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2020

RESIDENTIAL BUILDING DESIGN & CONSTRUCTION CONFERENCE PROCEEDINGS

MARCH 4–6, 2020

THE PENN STATER HOTEL & CONFERENCE CENTER
STATE COLLEGE, PENNSYLVANIA, USA

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State College, Pennsylvania, USA

Edited by
Dr. Ali M. Memari
Sarah Klinetob Lowe

Department of Architectural Engineering
Department of Civil & Environmental Engineering
The Pennsylvania State University, University Park, Pennsylvania, USA

PennState College of Engineering | PENNSYLVANIA HOUSING RESEARCH CENTER

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Ali M. Memari
Director, Bernard and Henrietta Hankin Chair in Residential Building Construction
PHRC
222 Sackett Building
University Park, PA 16802

CONFERENCE ORGANIZATION

CONFERENCE CHAIR

Dr. Ali Memari
Bernard and Henrietta Hankin Chair in Residential Building Construction

Department of Architectural Engineering, Department of Civil & Environmental Engineering, PHRC, Penn State
amm7@psu.edu

CONFERENCE ORGANIZER

PHRC
PENNSYLVANIA HOUSING RESEARCH CENTER

206B Sackett Building
The Pennsylvania State University
University Park, PA 16802
T: 814-865-2341
phrc@psu.edu

CONFERENCE SECRETARIAT

Sarah Klinetob Lowe
Housing Systems Specialist, PHRC
SKLowe@psu.edu

CONFERENCE COORDINATOR

Rachel Fawcett
Budgets & Publications Coordinator, PHRC
RFawcett@psu.edu

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PREFACE

While home builders are continuously challenged to consider various criteria such as affordability, energy efficiency, sustainability, serviceability, aesthetic, utility, and resistance to natural hazards among others, there are varying degrees of adherence to such objectives. The more efforts are made for technology transfer and providing the residential construction industry with the latest advancements in construction materials, tools, methods, and code requirements, the more receptive will be the mainstream builders to incorporation of technological advancements. As always, the Pennsylvania Housing Research Center (PHRC) at The Pennsylvania State University considers knowledge sharing and dissemination of the results of recent advancements in the field as one of its primary responsibilities and is pleased to continue organizing the Residential Building Design and Construction Conference series to serve the housing and residential construction industry for this purpose.

It is with great pleasure that we share the proceedings of the 2020 Residential Building Design and Construction Conference that was held on March 4–6, 2020 at The Penn Stater Hotel and Conference Center in State College, Pennsylvania. As in the past four RBDC Conferences, this 5th conference provided an opportunity for researchers, design professionals, manufacturers, builders, and code officials to exchange the latest advancements in research and practice and to discuss and share their own findings, innovations, and projects related to residential buildings.

The 2020 RBDC Conference hosted 132 attendees and included 56 papers and 102 presentations on various issues related to residential buildings, which encompass single- and multi-family dwellings, mid-rise and high-rise structures, factory-built housing, dormitories, and hotels/motels. Papers and presentations related to the following areas and topics were invited in the conference call:

- Aging-in-Place and Senior Living Housing
- Alternative Renewable Energy Generating Systems
- Building Information Modeling (BIM) Application in Residential Construction
- Building Integrated Photovoltaic Systems
- Building Performance Assessment/Metrics/Verification Methods and Occupant Behavior
- Building Science and Building Enclosures
- Energy Efficient Building Components
- Fire Damage and Protection
- High Performance Residential Buildings
- Indoor Air Quality
- Innovations in Green Roofs and Façade/Envelope Systems
- Innovations in Residential Architecture and Design
- Innovations in Modular and Manufactured Housing
- Innovative and Emerging Housing Construction Methods/ Systems
- Innovative Wall, Floor, Roof, Window, and Siding Systems

- Learning from the Performance of Residential Buildings under Natural Disasters
- Low-Income and Affordable Housing
- Panelized Building Components
- Passive House Design Approach
- Resilient New Design and Retrofit of Existing Buildings under Natural Disasters
- Retrofit of Existing Buildings for Energy Efficiency
- Rural Housing Materials and Construction
- Serviceability and Life Safety Damage Aspects
- Smart Home Technologies, Design, and Construction
- Sustainable Housing Construction Materials and Methods
- Temporary Housing for Disaster Situations
- Whole Building Design Approach
- Zero-Net Energy Homes

As the following Conference Schedule and Table of Contents of these proceedings show, many of the above areas were among the papers and presentations at the conference. In particular, there was considerable interest in Passive House Design and Retrofit, Disaster Resilient Design, Building Envelope and Building Science, and Construction using Cross Laminated Timber. The conference also hosted six Special Session panel discussions, three evening networking events, and a tour of the Building Enclosure Testing Laboratory (BETL) and the ADDCON Laboratory for 3D Printing of concrete, both located in Civil Infrastructure Testing and Evaluation Laboratory (CITEL) at Penn State University.

Two keynote speakers were invited for the conference: David O. Prevatt, Ph.D., PE, FASCE, Associate Professor of Civil & Coastal Engineering, Associate Director NSF - NHERI Experimental Facility at University of Florida and Lois B. Arena, PE, Director of Passive House Services at Steven Winter Associates, Inc. Professor Prevatt discussed his presentation titled "Wind Hazard Resilient Residential Communities—When Engineering Isn't Enough." Lois B. Arena shared her presentation titled "Passive House: A Proven Path Toward Resilient, Affordable & Energy Efficient Housing." The conference also hosted a closing plenary session by Jay Arehart, Senior Research Fellow at Project Drawdown and Tom Richard, Director of Institutes Energy & the Environment at Penn State, entitled "Buildings as a Drawdown Solution: Getting to Zero and Beyond."

We wish to thank the members of the International Scientific Committee of the conference for their contributions in promoting the conference. The support of the PHRC staff for logistics is gratefully acknowledged. In particular, special thanks goes to Rachel Fawcett for her contribution as the Conference Coordinator.

Proceedings Editors:
Ali M. Memari and Sarah Klinetob Lowe
March 2020

CONFERENCE SCHEDULE

WEDNESDAY, MARCH 4

8:30am - 10:15am | ROOM 207

KEYNOTE David O. Prevatt | University of Florida
"Wind Hazard Resilient Residential Communities—When Engineering Isn't Enough"
Opening Remarks: Dr. Sez Atamturktur | Department Head, Architectural Engineering, Penn State

10:45am - 12:15pm **Conference Sessions A**

	Disaster-Resilient Design | Rm. 203	Building Envelope | Rm. 204	Adaptation & Retrofits | Rm. 205	The Big Picture | Rm. 211	Building Science/Education | Rm. 218
10:45-11:15	**Perceptions for Residential Resilience** *Sandeep Langar | University of Texas at San Antonio*	**Innovative Construction Products: From Qualification and Performance Assessment to Quality Control** *Marzieh Riahinezhad, J-F Masson, Peter Collins, Bruno Di Lenardo, Jocelyn Johansen, & Michael Lacasse | National Research Council of Canada & CSL Silicones, Inc.*	**Sustainability Charrettes and Penn State's Residence Halls Renovations: Improving Building Performance and the Student Experience** *John Bechtel & Yumna Kurdi | Penn State*	**Discussing Innovation in Residential Construction at the National Scale** *Frederick Paige, Andrew McCoy, & Carlos Martín | Virginia Tech & Urban Institute*	**Introductions + Overview** *Sam Taylor | Energy & Resource Efficiency*
11:15-11:45	**Single-Family Housing Construction Vs. Hazard Mitigation Cost Data In The State Of Kentucky Using Model-Based Cost Calculation** *Marlie Reneau & Fatemeh Orooji | Western Kentucky University*	**ASHRAE 90.1: Codified Condensation for Cold Climates** *David Finley & Manfred Kehrer | Wiss, Janney, Elstner Associates, Inc.*	**Passive House Retrofit: Breathing New Energy into Old Dorms** *Benedict H. Dubbs & William Trout | Murray Associates Architects*	**Building Industry: Trends in Sustainability and Building Science Applications** *Dorothy Gerring, Rob Wozniak, Thomas Brooks, Evan Klinger, Cole Moriarty, Jeffrey Sementelli, & Michael "Tanner" Reif | Pennsylvania College of Technology*	**Building Science Education: Evolving Approaches and Resources** *Sam Taylor | Energy & Resource Efficiency*
11:45-12:15	**Evaluation of Various Retrofit Strategies for Existing Residential Buildings in Hurricane Prone Coastal Regions** *Mehrshad Amini & Ali Memari | Penn State*	**Wall Upgrades for Deep Residential Energy Renovation: Interim Results from a Multi-Year Study** *Chrissi Antonopoulous, Cheryn Metzger, Jian Zhang, Michael Baechler, A.O. Desjarlais, Pat Huelman, & G. Mosiman | Pacific Northwest National Laboratory, Oak Ridge National Laboratory, & University of Minnesota*	**Trends and practices of retrofitting existing residential buildings to Passive House criteria and similar standards.** *Sophia Welch, Esther Obonyo, & Ali Memari | Penn State*	**A Path to Zero Energy Ready Home Construction** *Theresa Gilbride, Michael Baechler, & Kiere Degrandchamp | Pacific Northwest National Laboratory & High Performance Homes*	**50 Shades of Building Science Education** *Georg Reichard, Zach Gould, & Dominick DeLeone | Virginia Tech*

12:15pm-1:15pm **LUNCH | PRESIDENTS HALL 1 & 2**

1:15pm - 2:45pm **Conference Sessions B**

	Disaster-Resilient Design | Rm. 203	Building Envelope | Rm. 204	Adaptation & Retrofits | Rm. 205	MEP | Rm. 211	Building Science/Education | Rm. 218
1:15-1:45	**Assessing the Performance of Elevated Wood Buildings in the Wake of Hurricane Michael** *Jae Kim, Elaina Sutley, & Thang Dao | University of Kansas & University of Alabama*	**High-Performance Windows – More than just a Pretty Hole in the Wall** *Katherine Cort & Theresa Gilbride | Pacific Northwest National Laboratory*	**Market Transformation: How Far, How Fast** *Rob Bernhardt | Passive House Canada*	**A New Standard to Evaluate the Installation Quality of Residential HVAC Systems** *Dean Gamble | EPA ENERGY STAR Certified Homes*	**Teaching Passive House in Academia** *Walter Grondzik, Alison Kwok, Mary Rogero, & Katrin Klingenberg | Ball State University, PHIUS, University of Oregon, & Miami University of Ohio*
1:45-2:15	**Wind Induced Effects on Roof-to-Wall Connections of Residential Buildings** *Amal Elawady, Arindam Chowdhury, & Ehssan Sayyafi | Florida International University*	**Low-Slope Roofing Systems for Multi-Story Residential and Commercial Buildings** *Rowland Smith | Wiss, Janney, Elstner Associates, Inc.*	**Repurposing Everyday Buildings: Extraordinary Renovations of Ordinary Structures** *Eric Fisher & Bea Spolidoro | Fisher ARCHitecture*	**Monitoring HVAC System Performance for Affordable Housing Units** *Fatemah Ebrahim, Frederick Paige, Farrokh Jazizadeh, & Quinton Nottingham | Virginia Tech*	**NAHB Career Pathways: Early Career Home Builders Findings & Mapping Career Pathways in Homebuilding** *Eric Holt | University of Denver*
2:15-2:45	**Wind hazard resilient construction mitigation decision-making framework** *Fatemeh Orooji | Western Kentucky University*	**Thin shell concrete enclosures in residential buildings** *Pablo Moyano Fernandez | Washington University in St. Louis*	**OPEN BUILDING: Planning Multi-unit Residential Buildings for Change** *Stephen Kendall | Council on Open Building*	**Indoor Air Quality and Energy Use in Passive Houses** *Xinyi Lily Li & Donghyun Rim | Penn State*	**One Book with Many Topics: But Are They Enough?** *Walter Grondzik | Ball State University*

3:00pm - 4:30pm **Conference Sessions C**

	Disaster-Resilient Design | Rm. 203	Senior Housing | Rm. 204	Adaptation & Retrofits | Rm. 205	Lab Tour	Building Science/Education | Rm. 218
3:00-3:30	**UN Sustainable Development and the Cool Roofs Challenge** *Kariuki Mbugua | Steam Plant Ltd*	**Tailoring Environments for Active Life Engagement (TEALE) Study: Preliminary Findings on Older Adults' Perceptions of the Functionality of their Housing Environment** *Angela L. Sardina, Shyuan Ching Tan, & Alyssa A. Gamaldo | University of North Carolina Wilmington & Penn State*	Presentation and Q&A Forum : **Scalable Retrofit Strategies for Net Zero Energy Performance in the United States & Beyond** *Moderator: Sarah Klinetob Lowe | Penn State* *Panelists:* *Lois B. Arena | Steven Winter Associates* *Saul Brown | RetrofitNY* *Dario Giandomenico | Green Building Alliance*	**Tour of Building Envelope Testing Laboratory (BeTL) + AddCon Lab Tours** [offsite + preregistration required] Meet at the Hotel Lobby at 3:00pm Return to Penn Stater by 5:00pm	**Mojave Bloom: Designing a Net-Zero Veteran's Transitional Home** *Eric Weber & Dak Kopec | University of Nevada Las Vegas*
3:30-4:00	**Modelling tropical cyclone vulnerability and the development of new insurance coverage programs for housing in Fiji** *Daniel J. Smith & Geoff Boughton | James Cook University, Cyclone Testing Station*	**Educating for Energy Efficiency: Educating Senior Residents Towards Net Zero Energy Goals** *Frederick Paige | Virginia Tech*			**Experiences with the Race to Zero/Solar Decathlon Design Challenge** *Tom Collins & Walter Grondzik | Ball State University*
4:00-4:30	**Kentucky Flood Resistant House: Integrating Resilience into Architectural Design** *Kyle Choate & Fatemeh Orooji | Western Kentucky University*	**Housing for Adults Facing Shifting Demographics in Japan** *Yoko Crume | Consultant (Aging & Society)*			**High Performance for Habitat for Humanity: Penn State's 2018-2019 Solar Decathlon Design Competition Entry** *Puja Bhagat & Jonathan Wong | Penn State*

6:00pm - 8:30pm **HAPPY HOUR ON THE EXHIBIT FLOOR | PRESIDENTS HALL 1 & 2**

THURSDAY, MARCH 5

8:30am - 10:15am | Presidents Hall

KEYNOTE: Lois B. Arena | Steven Winter Associates
"Passive House: A Proven Path Toward Resilient, Affordable & Energy Efficient Housing"
Opening Remarks: Dr. Christopher Rahn | Associate Dean for Innovation, Penn State College of Engineering

10:45am - 12:15pm — Conference Sessions D

	Concrete | Rm. 203	Building Envelope | Rm. 204	Passive House | Rm. 205	Microgrids | Rm. 218
10:45-11:15	**Hempcrete as a Residential Construction Material: State-of-the-art and Challenges** *Hojae Yi, Corey Griffin, Ali Memari, David Lanning, & James Dooley | Penn State & Forest Concepts LLC*	**Long-Term Exposure Data Analysis of Residential High Performance Wall Assemblies Exposed to Real Climate** *Michal Bartko, Travis V. Moore, & Michael A. Lacasse | National Research Council of Canada*	**Panelized Multifamily Passive House: Less Cost & More Profit Than Code** *Paul Grahovac | Build SMART, LLC*	**The Mycorrho-grid: A Blockchain-based Mycorrhizal Model for Smart Solar Microgrids** *Zachary Gould, Susan Day, Georg Reichard, Ikechukwu Dimobi, & Arjun Choudhry | Virginia Tech & the University of British Columbia*
11:15-11:45	**Accounting for the carbon sequestration potential of concrete systems: OPC and Hempcrete** *Jay Arehart | University of Colorado Boulder*	**Multifamily case study in Midland, MI compares different construction strategies for cost, durability, energy transfer and comfort.** *Brian Lieburn | DuPont Performance Building Systems*	**FRONT FLATS: A Net Positive, Carbon-Neutral, Multi-Family Experiment……and Fashion Statement** *Timothy McDonald | Onion Flats*	**Mining the Impact of Urban Form on Energy Performance in Community Microgrids** *Mina Rahimian | Penn State*
11:45-12:15	**Mitigating pyrrhotite-induced damage in residential concrete construction** *Jonathon Piasente & Aleksandra Radlinska | Penn State*	**Field Evaluation of an Affordable Solid Panel Structural Building System** *Pat Huelman, Tom Schirber, Garrett Mosiman, Dan Hendeen, & Rolf Jacobson | University of Minnesota*	**Bridging the Communication Gap Between Design and Construction** *Thiel Butner | Pando Alliance*	**TBD**

12:15pm-1:15pm — LUNCH | PRESIDENTS HALL 1 & 2

1:15pm - 2:45pm — Conference Sessions E

	Occupant Behavior| Rm. 203	Wood & CLT | Rm. 204	Passive House | Rm. 205	Community Design | Rm. 211	Building Science/Education | Rm. 218
1:15-1:45	**Personalizing occupant comfort using bio-sensing techniques** *Erica Cochran & James Katungyi | Carnegie Mellon University Center for Building Performance & Diagnostics*	**Mid-Rise Wood Frame Construction: A Good Idea or Are We Asking for Trouble?** *Derek Hodgin | Construction Science & Engineering, Inc.*	**A Couple's Passive House - Environmental Sustainability Without City Living** *Gary Gardner | Passive House Western PA*	**Participatory Design in Housing** *Joe Colistra & Nilou Vakilbahrami | University of Kansas*	**Introductions & Reflections** *Sam Taylor | Energy & Resource Efficiency* **IEA EBC Annex 74: International Information-Sharing Platform for Building Competitions and Living Labs** *Holly Carr | US Department of Energy*
1:45-2:15	**Message Design for Residential Energy Feedback** *Wendell Grinton & Frederick Paige | Virginia Tech*	**Using Truss Rafting to Create Safer, More Efficient Construction Sites** *Daniel Hindman | Virginia Tech*	**Master Planning a Phased Passive House Retrofit** *Laura Blau | BluPath Design*	**Green Social Services Buildings in Japan: Engaging Clients and Inspiring the Community** *Richard Crume | American Public Health Association*	**Solar Decathlon winning design entries - how to get projects built** *Paul Crovella, Michael Schmidt, & Noah Townsend | SUNY ESF*
2:15-2:45	**Energy Efficiency Rebate Programs: An assessment of investment behaviors by homeowners** *Celso Santos & Kristen Cetin | Iowa State University & Michigan State University*	**Resurrecting Fire-Damaged, Glued Laminated Beams from Beyond the Grave: A Pilot for Attaining Serviceability Requirements** *Cole Moller & Brian Kukay | Cushing Terrell & Montana Technological University*	**On the Way to Zero: Exploring A Path to Cost Efficient, Energy Efficient Affordable Housing** *Mike Steffen | Walsh Construction*	**Penn State Initiative for Resilient Communities (PSIRC): pilot study for community flood resilience** *Lisa D. Iulo | Penn State*	**Envelope and Systems Synergy for High Performance, Affordable Housing** *Michael Gibson & Paul Karr | Kansas State University*

3:00pm - 4:30pm — Conference Sessions F

	Healthy Homes | Rm. 203	Wood & CLT | Rm. 204	Passive House | Rm. 205	3D Printing & Modular | Rm. 211	Building Science/Education | Rm. 218
3:00-3:30	**Residential Indoor Air Quality Update – Contaminant Exposures, Standards, & Control Technologies** *William Bahnfleth | Penn State*	**The Burwell Center: A CLT Construction Case Study on the Campus of The University of Denver** *Eric Holt | University of Denver*	**PHFA Passive House Addition | The Design – Product Research and Existing Modeling** *Benedict H. Dubbs, Jr. & Wade Romberger | Murray Associates Architects & Pennsylvania Housing Finance Agency*	**The Potential of Additive Manufactured Housing** *Joe Colistra & Paola Sanguinetti | University of Kansas*	(continued)
3:30-4:00	**Residential Indoor Air Quality Assessment: An Evaluation of the Built Environment and Quality of Life in Communities** *Jessica Vaden & Melissa Bilec | University of Pittsburgh*	**Mass Customized Cross-Laminated Timber Elements for Residential Construction** *Daniel Hindman & Ali Memari | Virginia Tech & Penn State*	**PHFA Passive House Addition | The Documentation – "The Devil is in the Details"** *Benedict H. Dubbs, Jr. & Wade Romberger | Murray Associates Architects & Pennsylvania Housing Finance Agency*	**Market Driven Collaboration & Innovation in Modular Construction** *Frank Yang | ADL Ventures*	**Building Science Education Panel Discussion** *Moderator: Sam Taylor | Energy & Resource Efficiency* *Panelists: Holly Carr | US Department of Energy* *Chrissi Antonopoulous | Pacific Northwest National Laboratory* *Pat Huelman | University of Minnesota* *Georg Reichard | Virginia Tech*
4:00-4:30	**Barriers in Implementing Material Transparency in LEED® v4.0 projects** *Susan Thomas & Paul Crovella | SUNY ESF*	**Shake Table Testing of a 10-story Mass Timber Building with Nonstructural Components** *Keri Ryan, Shiling Pei, & Tara Hutchinson | University of Nevada Reno, Colorado School of Mines, & University of California San Diego*	**PHFA Passive House Addition | The Build – Contractor Selection, Sequencing and Collaboration** *Benedict H. Dubbs, Jr. & Wade Romberger | Murray Associates Architects & Pennsylvania Housing Finance Agency*	**TBD**	(continued)

6:30pm - ? — RELAX & UNWIND DOWNTOWN | SPONSORED BY THE GLOBAL BUILDING NETWORK

FRIDAY, MARCH 6

8:30am - 10:00am — Conference Sessions G

Time	Affordable Housing | Rm. 203	Building Envelope | Rm. 204	Passive House + Education | Rm. 205	Energy Usage | Rm. 218
8:30-9:00	**Evaluating Inclusionary Zoning in Centre County, PA as a Tool to Increase the Supply of Affordable Housing Stock and to Mitigate Housing Segregation** *Rachel Fawcett | Penn State*	**Stucco – the Once and Future Cladding: Design Options to Meet Industry Codes and Standards** *Theresa Weston | DuPont Performance Building Systems*	Panel Discussion & Moderated Forum : **Passive House & the Nexus between Academia, Practice, Construction, and Research** *Moderator: Walter Grondzik |PHIUS & Ball State University* *Panelists:* *Laura Blau | BluPath* *Tim McDonald | Onion Flats* *Mary Rogero | Miami University* *Mike Steffen | Walsh Construction*	**Characteristics of Typical Occupancy Schedules for Residential Buildings in the United States** *Debrudra Mitra, Nicholas Steinmetz, Yiyi Chu, & Kristen Cetin | Iowa State University & Michigan State University*
9:00-9:30	**The Challenges of Creating Resilient Housing at Affordable Cost – A "Lessons Learned" Report on The Field of Dreams EcoCommunity** *Jörg Rügemer | University of Utah*	**Performance of PCMs in Different Building Envelope Configurations, Climate Zones and Building Operating Scenarios** *Hyejoo Koh & Fitsum Tariku | British Columbia Institute of Technology*		**An Evaluation of Electrical Energy Usage Comparing Homes With and Without Building Code Enforcement** *Ben Bigelow & Melina Cedillo | University of Oklahoma & Holder Construction*
9:30-10:00	**Integrating Flexible Human-Activity in Modular Space Design for Affordable Mass Housing in Asia** *Atul Biltoria & Uttam Roy | Indian Institute of Technology Roorkee*	**The Interface** *Adam Ugliuzza | Intertek*		**The Home as a Concrete Example for Energy Education** *Frederick Paige | Virginia Tech*

10:15am - 11:45am — Conference Sessions H

Time	Disaster-Resilient Design | Rm. 203	3D Printing on Mars | Rm. 204	Local Communities + Education | Rm. 205	High Performance Housing | Rm. 218
10:15-10:45	**Wind Pressure Distribution on Single-Story and Two-Story Elevated Structures** *Nourhan Abdelfatah, Amal Elawady, Peter Irwin, & Arindam Chowdhury | Florida International University*	**An Overview of the Execution of 3D-Printed Subscale Habitat on Mars: A Case Study to Exemplify the Automated Construction Process** *Shadi Nazarian, Jose Duarte, Sven Bilén, Ali Memari, Naveen Kumar Muthumanickam, Nathan D. Watson, Aleksandra Radlinska, Negar Ashrafi, & Maryam Hojati | Penn State*	Panel Discussion & Moderated Forum : **Community-University Partnerships for High Performance Homes** *Moderator: Dr. Meghan Hoskins | Penn State* *Panelists:* *Ilona Ballreich | Penn State* *Jasmine Fields | State College Borough* *Lisa D. Iulo | Penn State* *Sarah Klinetob Lowe | Penn State* *Colleen Ritter | State College Community Land Trust* *Maureen Safko | State College Borough* *Alan Sam | State College Borough*	**Managing Building Pressure Differentials in High-Performance, Low-Load Homes** *Pat Huelman & Marilou Cheple | University of Minnesota*
10:45-11:15	**Conceptual Geometric Design for U.S. Coastal Homes to Resist Hurricane Surge Forces** *Julie Bates & Ali Memari | Penn State*	**Structural Analysis of Full-Scale and Sub-Scale Structure for Digitally Designed Martian Habitat** *Keunhyoung Park, Ali Memari, Shadi Nazarian, Jose Duarte & Maryam Hojati | Penn State & University of New Mexico*		**Whole Building Airtightness Testing at Penn State** *Adam Ugliuzza | Intertek*
11:15-11:45	**Performance of Residential Buildings in Hurricane Prone Coastal Regions and Lessons Learned for Damage Mitigation** *Mehrshad Amini & Ali Memari | Penn State*	**Experimental Testing and Finite Element Modeling of 3D-Printed Reinforced Concrete Beams** *Keunhyoung Park, Ali Memari, Maryam Hojati, Mehrzad Zahabi, Shadi Nazarian, and Jose Duarte | Penn State & University of New Mexico*		**A Method for Evaluating Whole-building Energy Use of Two Adjacent Multifamily Residential Buildings in Pennsylvania: A Comparative Case Study on Passive House and Conventional Buildings** *Homeira Mirhosseini, Xinyi Lily Li, Lisa D. Iulo, & Jim Freihaut | Penn State*

11:45am-12:45pm — LUNCH | THE GARDENS RESTAURANT (PENN STATER)

12:45pm - 2:15pm — Conference Sessions I

Time	Infrastructure | Rm. 203	BIM | Rm. 204	Global Communities + Education | Rm. 207
12:45-1:15	**Role of Infrastructure in the Success of Urban Housing Developments** *Shay Chakraborty, M.G. Matt Syal, & Sinem Mollaoglu | Michigan State University*	**BIM for parametric problem formulation, optioneering, and 4D simulation of 3D-printed Martian habitat: A case study of NASA's 3D Printed Habitat Challenge** *Naveen Kumar Muthumanickam, Keunhyoung Park, Jose Duarte, Shadi Nazarian, Ali Memari, & Sven Bilén | Penn State*	Panel Discussion & Moderated Forum : **Global Building Network Panel Discussion** *Moderators: Dr. Esther Obonyo & Sarah Klinetob Lowe | Penn State* *Panelists:* *Rob Bernhardt | Passive House Canada* *Jenna Cramer | Green Building Alliance* *Richard Crume | American Public Health Association* *Dario Giandomenico | Green Building Alliance* *Dr. Esther Obonyo | Penn State*
1:15-1:45	**Improving the User Experience (UX) of Green Building Certification Resources for Multifamily Housing Units** *Dwayne Jefferson & Frederick Paige | Virginia Tech*	**The Value and Use of National Building Information Modeling Standards** *John Messner | Penn State*	
1:45-2:15	**TBD**	**TBD**	

2:30pm - 4:00pm — CLOSING PLENARY & CLOSING REMARKS | ROOM 207

"Buildings as a Drawdown Solution: Getting to Zero *and* Beyond"

Jay Arehart | Project Drawdown & Tom Richard | Penn State

Opening Remarks: Dr. Patrick Fox | Department Head, Civil & Environmental Engineering, Penn State

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206B Sackett Building
The Pennsylvania State University
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T: 814-865-2341
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Perceptions for Residential Resilience

Sandeep Langar, Ph.D., LEED AP[1]

[1]Assistant Professor, Department of Construction Science, The University of Texas at San Antonio, 501 W. Cesar E. Chavez Blvd, San Antonio, TX 78207; e-mail: sandeep.langar@utsa.edu

ABSTRACT

Texas has endured the most Billion-Dollar weather and climate disasters in the last two decades, making it the state within the US with the highest disaster incident rate. The increasing natural disasters can impact the housing stock and, in the process influence how people accumulate wealth. Given the intensity and frequency of natural disasters, its impact on housing stock, and the susceptibility of the state to be impacted, it is imperative to ensure that residential units are resilient to natural disasters. The initial step in constructing residential units that are resilient to natural disasters is assessing current perceptions among homeowners and homebuilders. The study used an online survey method to identify the perceptions. The research involved the following steps: sample selection (homebuilders and homeowners), survey instrument development (online), pilot testing the instrument, survey administration, data collection, and data analysis. The results were statistically analyzed to identify the perceptions among homeowners and homebuilders for resiliency within the state of Texas. The study found that the majority of responding homeowners perceive the need for resilient residential units. The study also found a misalignment of perceptions between the responding homeowners and homebuilders in terms of perceptions for the resilient residential unit and the stakeholders perceived to be receptive to the residential unit's resilience.

INTRODUCTION

The impacts of climate change on the ecosystem and the built environment can no longer be ignored. The changes in climate are not only contributing to the rise in sea-level but also have the potential of generating extreme events in the near future (GFDL, 2019; Mudd et al., 2014; IPCC, 2019). From 1996 to 2015, 11,000 extreme events occurred globally, resulting in more than half a million fatalities, and direct losses exceeding three Trillion USD (Kreft et al., 2016). Approximately 24 million people across the globe were displaced due to natural events such as floods, typhoons, and others (Stapleton et al., 2017). The impacts of extreme natural events have been observed in the US. The US, along with China, India, Indonesia, and the Philippines, were the top five countries around the globe that were impacted by natural disasters between 2006 and 2015 (Guha-Sapir et al., 2016). Within the US, between 1980 and 2018, the most frequent and most expensive Billion-Dollar disaster events occurred in the last decade (NCDC-NCEI, 2019). The year of 2019 is the fifth consecutive year in 2015-2019, where climatic event losses exceeding ten billion dollars have impacted the US (NCDC-NCEI, 2019). Given the scale and intensity, it is evident that natural disasters and their impacts are increasing continuously and will continue to impact the people and the economy. The residential sector within the US is particularly vulnerable to natural disasters (FEMA, 2005; Kunreuther et al., 2019; Mozumder et al., 2015) and the future climatic events can severely impact the residential structures if the current developmental and construction paradigm is continued (Dong and Li, 2016).

Along with the structural impacts, the impacts of natural disasters can be felt on the economy associated with the residential units. The response of households to changing climate can significantly impact the housing markets, the relocation areas, and the composition of housing stocks (Sheldon and Zhan 2019). Natural disasters impact the housing industry in terms of delayed or disrupted sales post-disasters, reduced inventory, increased demand for rental properties (Forbes 2018), with increased rents for the properties and a decline in homeownership rates (Dillon-Merrill et al. 2018). Also, post-disasters, the property prices of the impacted areas can decrease for a few years, thereby impacting how people accumulate wealth (Sheldon and Zhan 2019), and in the process impact on the financial independence of the society (Goodman and Mayer 2018). The societal paradigm for housing choices, in response to natural disasters, can have a ripple effect on social, economic, and racial equity (Sheldon and Zhan 2019). Therefore given the impact of the increasing natural disasters on not only the social and economic systems but also the built environment, the study aims to assess the perceptions for resilience within the residential industry for homeowners and home builders geographically located within the state of Texas.

The state of Texas was selected as the geographical location of the state resulted in it being impacted by natural disasters frequently. For Example, the US for the last two decades (1989-2019) suffered 227 natural disaster events where losses for each event exceeded One Billion Dollars. (NCDC-NCEI 2019). When reviewing the impacts of the 227 natural disaster events, the state of Texas was impacted the most in terms of the number of Billion Dollar Natural Disaster, resulting in nearly 5,172 fatalities and was followed only by Illinois and Georgia. In addition, the impact of Harvey alone resulted in 354,000 residential property claims, as per the Texas Department of Insurance (Insurance Journal, 2018). At the same time, the state has been identified as one of the states with the most growth in the housing market for 2018 and 2019 (USA Today, 2018; Smartasset, 2019). Thus given the intensity and frequency of natural disasters, its impact on housing stock, and susceptibility of the state to be impacted, it is imperative to identify the perception of the homeowners and homebuilders within Texas for enhancing the resilience of the residential units.

METHODOLOGY

The general population for the study was the homeowners and homebuilders geographically located within Texas. The survey method was selected as it enabled researchers to collect data and, in the process, identify trends and determine relationships at the time of the study (Gable, 1994). Among the various survey methods available, online survey method was selected as it allowed: data collection from significant respondents to identify trends and determine the existence of relationships between variables at a given point of time (Gable, 1994), higher likelihood of prompt responses (Faherty et al., 1998), and the value generated by the online survey outweighed other survey methods (Sheehan, 2001). The online survey was hosted on the Qualtrics website and had sections that aimed to measure the perceptions and knowledge of responding homeowners and homebuilders for resilient residential units, apart from the section that assessed the respondent demographics. The survey was designed in such a manner that it could be completed within 10-15 minutes, provided that the respondents possessed all the required information. The study was subjected to a pilot test, and all recommendations were analyzed before they were incorporated into the study. Email information about the sampling frame representing the homeowners and homebuilders was obtained from publicly available sources, personal contacts, student participation, and in collaboration with Qualtrics. After obtaining the contact information, a cover letter with a Qualtrics survey link was emailed.

All initial responses were collected and stored on the Qualtrics site. After the survey was deactivated, all responses were downloaded from the Qualtrics site for initial data cleaning. At this point, any incomplete and duplicate response was deleted. During the initial analysis, it was also determined that the average time to complete the study was approximately ten minutes, thereby validating one of the parameters of the survey design (survey completion time). For homeowners, a total of 161 completed responses were recorded, out of which 97 indicated property ownership at the time of the study. Thus resulting in 97 homeowners whose responses were statistically analyzed for the study. For homebuilders, responses from seven companies, geographically located in Texas, were used for statistical analysis. All compiled data was subjected to inferential statistical analysis to ascertain the trends discussed in the subsequent section.

RESULTS

The research aimed to assess the perception of the homeowners and homebuilders within Texas for enhancing the resilience of the residential units.

Homeowner demographics:

Langar et al. (2019) identified education as one of the eleven factors that determine how a family would choose to respond while facing a natural disaster. For the study, when asked about the highest level of education in the household of the responding homeowner, approximately 38 respondents (39.2%) indicated Bachelors to be the highest followed by 34 respondents (35.1%) that indicated High School to be highest, followed by 19 respondents (19.6%) that indicated Masters to be highest, followed by 6 respondents (6.2%) that indicated Doctoral to be highest educational qualification within the household and as depicted by Figure 1. Thus indicating that the majority of respondents (74.3%) had either a high school or Bachelor’s degree as the highest level of education with the household. Along with the education, respondents were also asked about their annual household income. Using household tax slabs from the IRS (2019) as the basis, five groups for the annual household incomes were identified. These five groups were: Group 1 - up to $19,400, Group 2 - $19,401 to $78,950, Group 3 - $78,951 to $168,400, Group 4 - $168,401 to $321,450, and Group 5 - above $321,450. The income distribution, represented in Figure 2, depicts majority of the respondents (53%) indicated a household income from $19,401 - $78,950, followed by 21% respondents representing the income Group 3 ($78,951 - $168,400).

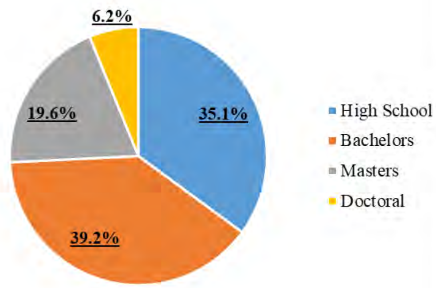

Figure 1: Respondent education level

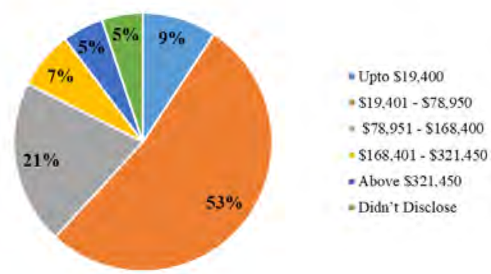

Figure 2: Respondent household income

Homeowner's knowledge and perceptions:

The section aimed at measuring homeowner's perception of the need for resilient residential units, the familiarity of the household for resilient units, decision-makers in the household, training with regard to design and construction of residential units, and perception about stakeholder's receptiveness towards enhancing the resilience of residential project(s). When asked if responsive design to natural disasters can reduce challenges imposed by recent natural disasters to the residential industry, approximately 32.0% of respondents indicated "*definitely yes*," followed by 44.3% indicating "*probably yes*," and 23.7% indicated "*might or might not.*" Therefore, more than three-fourths of the responding homeowners' perceived responsive design to natural disasters can alleviate challenges imposed by the recent events for the residential industry.

When asked about the importance of ensuring the design of a residential unit is resilient to natural disasters, about 29.9% indicated as "*extremely important,*" 19.6% as "*very important,*" 47% as "*moderately important,*" and 3.1% "*slightly important*." Thus, indicating that nearly half of the responding homeowners felt the need to ensure that the residential unit design should be resilient to natural disasters. The respondents were followed-up with the question if they or anyone in the household possessed familiarity with the concept of resilient housing, and about 27.8% of the respondents claimed to possess or have someone within the household possessing familiarity.

Further, 76.3% of the respondents claimed to be decision-makers for the household. For the respondents claiming to be decision-makers, about 23% claimed to have some familiarity, and 77% claimed to have no familiarity with the concept of resilient housing. Thus, highlighting the lack of awareness and knowledge, especially for people that are decision-makers for households. Further, even though the majority of the responding decision-makers (64.5%) claimed to have someone in the household (including themselves) familiar with the concept of resiliency and had received training, however, most of the identified training sources could not be connected to formal sources. Thereby indicating the need for providing knowledge, information, and formal training to the homeowners (especially decision-makers in households) so that informed decisions for residential unit's resilience are incorporated. Such an intervention is critical, especially when a significant portion of the population has no formal training or knowledge for the design and/or construction of a resilient residential unit. When asked about the homeowner's level of confidence possessed to make decisions for residential units that are resilient to natural disasters, 46.4% of respondents were "*neutral*," followed by 24.7% of respondents that felt "*somewhat comfortable,*" 18.6% felt "*extremely comfortable*," as indicated in Figure 3. Thus, indicating a concern as more than 43% of responding homeowners are comfortable to a certain degree with making decisions for the residential unit(s) that are resilient to Natural Disasters, but lack training and awareness about the same.

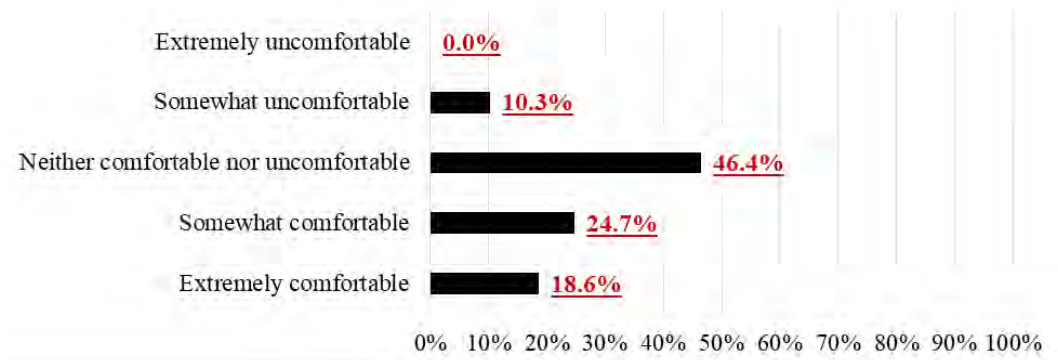

Figure 3: Perception about the level of confidence possessed to make decisions for a residential unit resilient to natural disasters

Further, 43.3% of the responding homeowners claimed to have faced natural disasters in the last ten years implying that the majority of the respondents (56.7%) were inexperienced to the natural disasters and could impact on the course of actions (including mitigation strategies) that could be implemented to alleviate the impacts of natural disasters. This information is critical when 44% of the respondents made decisions for the design or construction of the residential projects, and 36.1% of the respondents claimed to have been associated with the design or construction of the residential project(s) during the last ten years. Thus, highlighting the need for educating homeowners about the ways in which they can enhance the resilience of the residential units, especially when there is an inclination of the population to be associated with the design and construction of such projects.

Residential projects have numerous stakeholders or participants associated with the project across the life of the project, with each having an ability to impact project resilience. When asked about the project stakeholder that were most receptive to enhancing the resilience of a residential project, the top three were- *Owners* (24%), *Designer* (22.9%), and *Insurance Companies* (17.7%), as indicated in Figure 4. Also, 32%, 19.6%, and 13.4% of the respondents identified *Engineers*, *Owners*, and *Insurance Companies* respectively as the top three project stakeholders that were most receptive towards the implementation of technologies and strategies that enhance the resilience of residential units, as identified in Figure 5. For both questions, municipal authorities and sub-contractors were identified as the least receptive stakeholders. Therefore, indicating that local/municipal authorities, especially in Texas, need to play a more significant and proactive role in enhancing the resilience of the residential units. Such as measure is critical, especially when states such as Florida have required building elements (windows, roofs, and others) to withstand hurricane-force winds (Joint Center for Housing Studies of Harvard University, 2018).

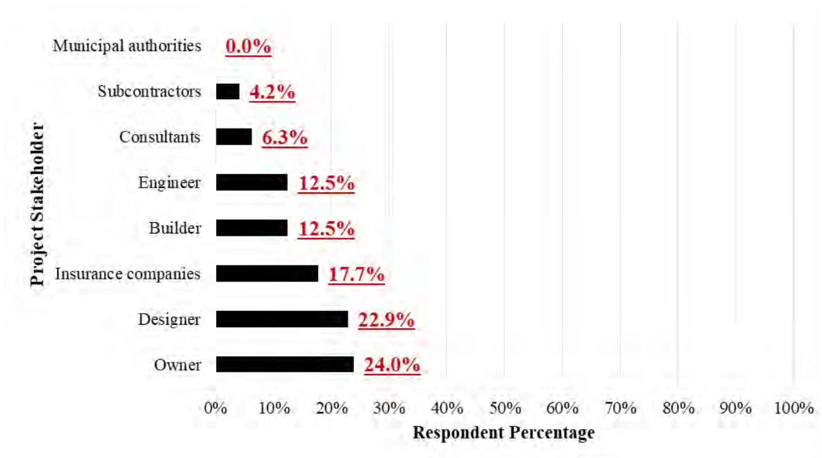

Figure 4: Stakeholder's receptiveness towards enhancing the resilience of a residential project

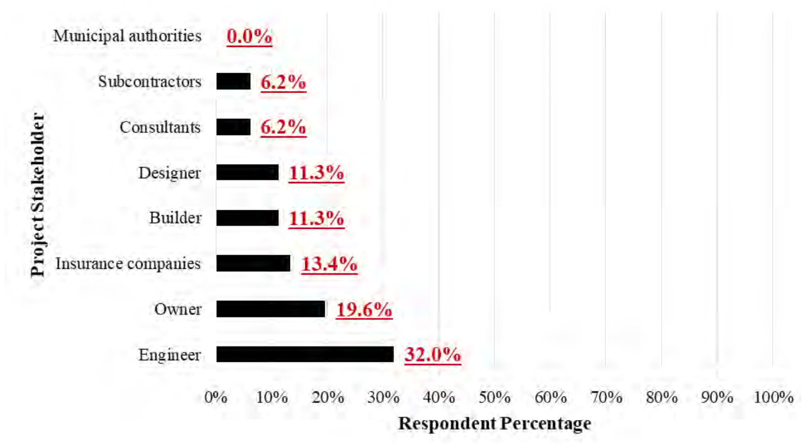

Figure 5: Stakeholder's receptiveness towards the implementation of technologies and strategies that enhance the resilience of a residential project

<u>Homebuilder demographics:</u>

Respondent demographics were assessed in the categories of the respondent title/position within the company, company size, annual company revenue, company's branches within the state and the country, and residential project types executed. Regarding the profile of the respondents, 42.9% of the respondents were company owners, as indicated in Figure 6.

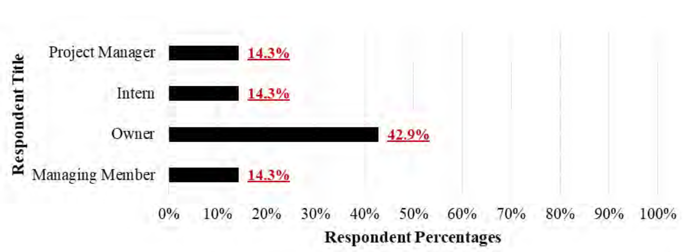

Figure 6: Respondent job title

The experience of the responding homebuilders varied with maximum to be 41 years and minimum to be less than one year of experience, indicating a wide range of respondent experience. For company size, the majority of the respondents (57.1%) had less than five Full-Time Employees (FTE), indicating that the majority of responding builders were small businesses. Also, approximately 14.3% of the respondents indicated employing more than 50 FTE. The annual company revenue among the responding homebuilders also varied with a maximum reported revenue of 134.0 Million USD and a minimum of 500,000 USD. Also, maximum respondents were in the category of 1-5 Million and 5.01-10 Million USD Category representing 28.6% of the respondents equally. Also, 28.6% of the respondents reported having more than one branch within the state and the country.

When asked about the project types executed by the responding homebuilders, single-family detached was executed by 41.7% of the respondents. For the question, the respondents possessed the ability to select more than one project type, as a homebuilder could execute more than one project type. Figure 7 represents the distribution of the responses for project types executed by the responding homebuilder.

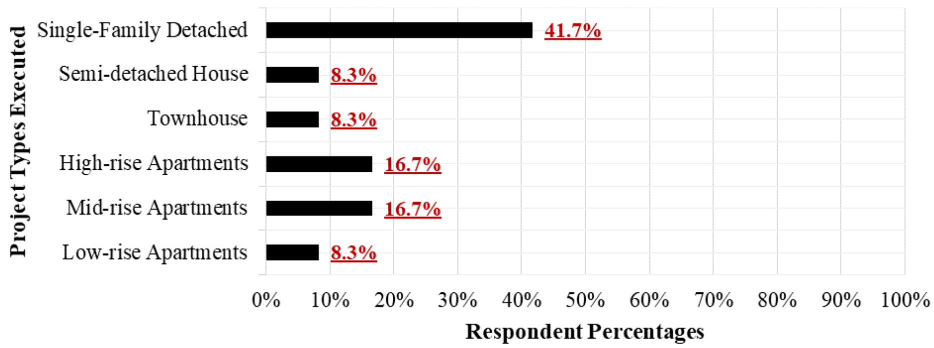

Figure 7: Project type executed by responding homebuilders

<u>Homebuilder perception and measurement of resilient residential unit:</u>

The section assessed the perceptions of the responding homebuilders for the importance of resilience within the residential industry, resources utilized to construct residential units that were resilient to the natural disasters, measurement criterion used to assess the resilience of residential units, and stakeholders perceived to be responsive to the incorporation of resilient technologies and strategies.

When asked if responsive design to natural disasters in the residential projects can reduce challenges imposed by recent natural disasters, a majority (71.4%) of respondents indicated as "*definitely yes*," followed by 14.3% of respondents indicating *"probably yes*" and "*might or might not*." Thereby, indicating that the majority of the respondents perceived responsive design to natural disasters can reduce challenges within the residential industry. When asked about the importance of ensuring the design of a residential unit is resilient to natural disasters, no clear response could emerge. Approximately 28.6% of respondents equally identified it as "*extremely important, very important,* and *moderately important*." At the same time, 14.3% indicated that it was "*not at all important.*" Therefore, even though the majority of the responding homebuilders perceived that it is crucial to ensure residential units are resilient to natural disasters, it could not be ascertained the level of importance perceived by the responding homebuilders. The respondents were followed-up with the question if their company was familiar with the concept of resiliency within the residential sector. A majority of respondents (71.4%) claimed to possess the familiarity. For the companies indicating familiarity, the majority (60%) of the responding homebuilders claimed to have less than 10% of the employees possessing the familiarity with the design and/or construction of resilient residential units, and only 40% of the responding home builders offered training about the same to their employees. Therefore, indicating that the majority of the respondents (71.4%) although claimed to have familiarity but did not offer any training for their employees. Further, when asked if a company needed to provide training that improves the knowledge of employees to build residential units that are resilient to natural disasters, a majority (60%) somewhat agreed with the need for education of their employees provided by the company owners. Therefore, indicating a need for employee-education or continuing education of employees within the homebuilders.

When asked about the respondent's level of confidence possessed to design a residential unit that was resilient to natural disasters, a majority of the respondents (57.1%) indicated that they were "*neither comfortable nor uncomfortable*" followed by 28.6% of the respondents that indicated they were "*extremely comfortable*." Further, a majority of the respondents (71.4%) indicated that their company did not have an in-house architect and external designers designed the projects. The study could not ascertain the selection process for external designers in such a scenario. The remaining respondents (28.6%) indicated that their company had an in-house architect(s). When asked if the company had constructed any resilient residential project, during the last ten years, about 57.1% of the responding homebuilders indicated that they had constructed a resilient residential unit(s), as depicted in Figure 8. At the same time, it is evident that a substantial percentage of the respondents (42.9%) had not constructed any resilient residential project in the last decade.

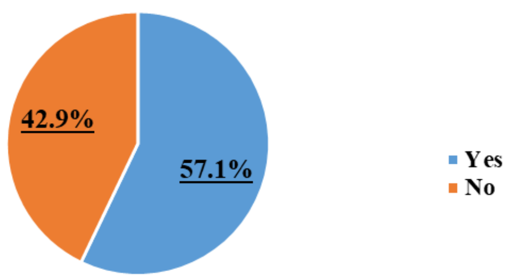

Figure 8: Construction of resilient residential projects in the last decade by responding homebuilders

Also, the majority of the responding homebuilders confirmed that they had used specific ways to enhance the resilience of the executed residential projects. The responding homebuilders were provided seven strategies along with the option of inputting a strategy based on the experience. Following is the list of strategies (1- Most Important; 7- Least Important) identified by the homebuilders used to enhance the residential unit resilience:

1. Ensure that the designers associated with the project are trained

2. Integrate building resiliency into the project vision
3. Integrate building resiliency into Owner Project Requirements and Basis of Design
4. Use building measurement systems that can measure building resiliency for particular natural hazards
5. Encourage design charrettes to identify potential natural hazards
6. Encourage design charrettes to identify potential mitigation strategies
7. Use of specialized software

Further, when followed-up with the measurement criterion used to assess the resilience of a constructed residential unit, the top three identified by the responding homebuilders (in order of importance) were- *building to requirements/specifications, testing the materials in a controlled environment,* and *paying someone to assess*. Even though the majority of the respondents for this questions claimed that they were constructing to codes/requirements/specifications, but studies have indicated that the severity of storms is increasing (NSF, 2018) and so the question that remains unanswered is if the local codes and requirements are robust enough to foster residential units that are resilient to the increasingly severe weather patterns.

In order to identify the stakeholder perceived to be most receptive towards the implementation of technologies and strategies that enhance the resilience of a residential unit, *Designers* (20%) and *Engineers* (15%) emerged as the most receptive, as indicated in Figure 9. The figure also indicates that *Insurance Companies* (0%) and *Owners* (5%) were perceived as least receptive towards the implementation of technologies and strategies that enhance the resilience of a residential unit.

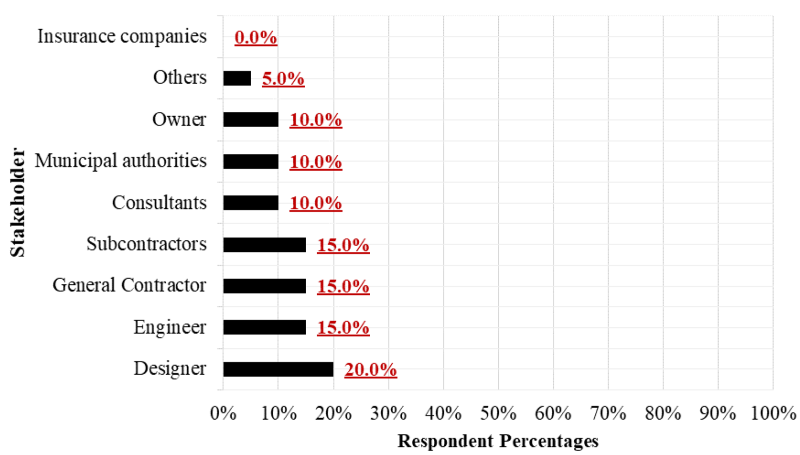

Figure 9: Stakeholder receptiveness for the implementation of technologies and strategies that enhance the resilience of a residential unit

The order of importance changed when respondents were asked about the stakeholder that was perceived as most receptive towards enhancing the residential unit's resilience — thereby indicating that the respondents felt that incorporating technologies and strategies do not always lead to resilient projects. For the question, the respondents identified *General Contractors* (25%) as most receptive to enhancing the resilience of the residential unit. At the same time, *Insurance Companies* (0%) and *Owners* (8.3%) were perceived as least receptive towards enhancing the resilience of the residential unit, as indicated in Figure 10. Although the research did not investigate why the responding homebuilders felt that owners and insurance companies were least receptive towards enhancing the resilience of the residential unit and implementation of technologies and strategies that enhance the resilience of a residential unit. Such an observation was not expected from the homebuilders as the owners and insurance companies would be the primary beneficiaries with a resilient residential unit, in most of the cases. At the same time, the researcher would like to highlight this as a query that needs to be investigated in the future.

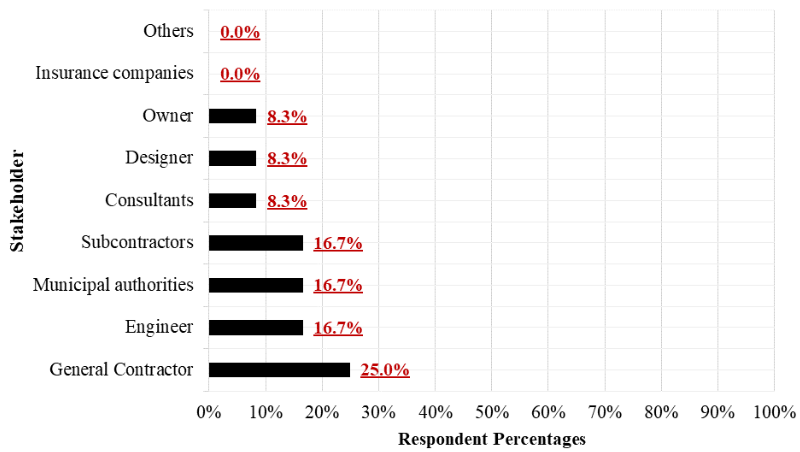

Figure 10: Stakeholder receptiveness for enhancing the resilience of a residential unit

CONCLUSION

The study identified perceptions for residential resilience among homeowners and homebuilders geographically located within the state of Texas. The study analyzed responses from 97 homeowners living in Texas, and the majority of the responding homeowners (76%) perceived responsive design to natural disasters can reduce challenges imposed by recent events within the residential industry. Also, the majority of the responding homeowners (96%) indicated the importance of ensuring the design of a resilient residential unit to natural disasters as "*extremely, very, or moderately important*." Therefore, indicating that the responding homeowners not only feel that responsive design can offset the challenges imposed by recent natural disasters to the residential units but also perceive it to be critical. Even though the responding homeowners perceived the need for resilient residential unit(s), they lacked the knowledge, with only 27.8% of the respondents claimed to be familiar with the concept of resilient residential units. The issue is complicated by the fact that the majority (56.7%) of the respondents had not faced natural disasters in the last ten years, thereby making them inexperienced in terms of responding to the occurrence of such event(s). Given the need, education, experience, and perceptions of homeowners, there is a critical need for educating the homeowners about how technologies and strategies can be adopted and implemented to make the residential units resilient. The responding homeowners also identified *Owners* (24%), *Designer* (22.9%), and *Insurance*

Companies (17.7%) most receptive stakeholders towards enhancing the resilience of residential projects towards natural disasters.

For the responding homebuilders, the study utilized the responses from seven homebuilders geographically located and operating in Texas. The majority of the responding homebuilders (71.4%) perceived responsive design could reduce challenges imposed by recent natural disasters within the residential industry. At the same time, when asked if responsive design to natural disasters can reduce challenges imposed by recent events within the residential industry, no clear response emerged. Nearly 14.3% of the responding homebuilders indicated that it was not at all essential to have designs that are responsive to natural disaster, which is in contrast to the perceptions for the homeowners where 96% of the respondents indicated the importance of ensuring the design of a house/apartment resilient to natural disasters as "*extremely, very, or moderately important*" — thus indicating misalignment of perceptions between the responding homeowners and homebuilders. Also, the majority of the responding homebuilders (71.4%) claimed that their company possessed familiarity with the concept of resiliency within the residential sector. For the companies indicating familiarity with the concept, the majority of the responding homebuilders claimed to have less than 10% of the employees possessing the familiarity with the design and/or construction of resilient residential units, and only 40% of the responding homebuilders offered training to their employees. A majority (60%) somewhat agreed with the need for the education of their employees. To summarize, majority of the homebuilders indicated their company's familiarity with building resiliency but at the same time had very few employees familiar with the concept and did not offer any in-house training to improve/enhance the employee knowledge in the area even when they felt that there is a need for the employees to be trained. Also, 42.9% of the respondents had not constructed any resilient residential project in the last decade. The percentage could also be attributed to the lack of demand for such projects and needs to be explored in future studies. "*Ensuring designers associated with the project are trained, integrating building resiliency into the project vision,* and *integrate building resiliency into Owner Project Requirements and Basis of Design*" emerged as the top three strategies implemented by the homebuilders used to enhance the residential unit's resilience. Also, responding homebuilders identified "*building to requirements/specifications, testing the materials in a controlled environment,* and *paying someone to assess*" as the resilience measurement criterion for the residential projects. The responding homebuilders identified *Insurance Companies* and *Owners* as the least receptive stakeholders for enhancing the resilience of residential units. The findings are unexpected as the two stakeholders would be primary beneficiaries with a resilient residential unit.

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Evaluation of Various Retrofit Strategies for Existing Residential Buildings in Hurricane Prone Coastal Regions

Mehrshad Amini[1] and Ali M. Memari[2]

[1]Ph.D. Candidate, Department of Civil and Environmental Engineering, Penn State University, e-mail: mxa261@psu.edu

[2]Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering, Penn State University, e-mail: amm7@psu.edu

1. Abstract

Among hurricane related hazards, surge and subsequent flood waves due to high wind are the most destructive and costly phenomena during hurricanes for residential buildings in coastal areas. This potential damage has been increased over the past 30 years due to increase in intensity of storms, residential population, and age of existing homes in coastal regions. As remedial measures to mitigate flood related hazards for homes in coastal areas, FEMA has developed six major retrofitting methods, namely elevation, relocation, demolition, wet floodproofing, dry floodproofing, and barrier systems. Although elevating the first floor above base flood elevation is the most effective method to mitigate flood-related damage, other methods would be needed for buildings that cannot be elevated. However, there is still lack of sufficient understanding of the performance of retrofitted homes, which are still potentially exposed to damage under hurricane flood conditions.

This paper presents a review of the performance of retrofitted residential buildings in past hurricanes, and potential wind and flood-induced damage and subsequent risk mitigation techniques are discussed. The results show that structural characteristics such as superstructure or foundation system type, specific flood-prone zone construction, and total cost play a prominent role in selecting the appropriate retrofit method by homeowners and engineers. Study of actual damage shows that although elevating the house can potentially reduce the direct damage from flood and surge, it can impose severe wind-induced damage to roof structural members, envelope systems, and foundation due to higher lateral wind loads and subsequent higher overturning moment. The performance of breakaway walls below the BFE strongly depends on connections between the wall and structural members, which needs to be designed properly to ensure that the breakaway walls breach clearly during the flood. Furthermore, the performance of houses with dry floodproofing depends on several factors, including quality of materials below the BFE, appropriate installation (sealant and shield systems), and drainage system for potential seepage. Last but not least, regardless of retrofit strategies, the lack of flood damage-resistant material below the BFE and ongoing maintenance cause severe damage to residential buildings in coastal areas during the hurricanes.

Keywords: Hurricane Hazards, Residential Buildings, Retrofit Strategies.

2. Introduction

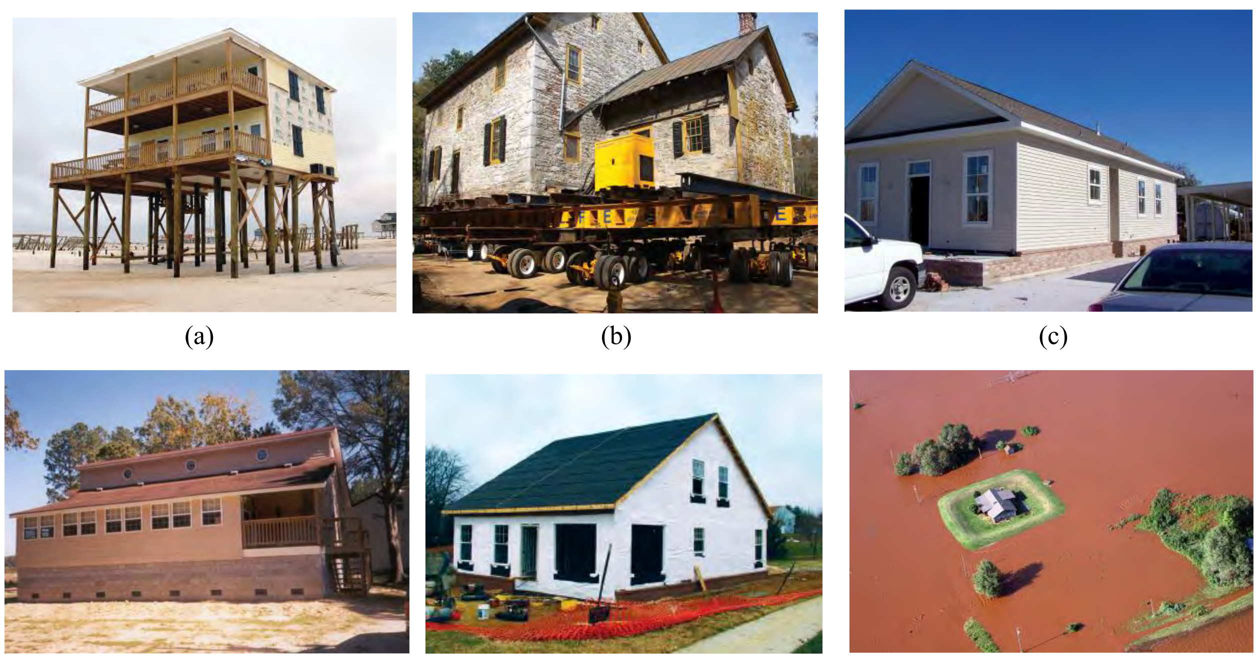
Due to significant structural damage and fatalities, interest in understanding the performance of residential buildings under hurricane hazards has been increasing in the U.S. over the past few decades. Many studies have contributed to better understanding of the problem and attempts have been made to protect communities and existing or new homes against flooding and subsequent hazards (e.g., White, 1945; Laska, 1991; Vickery et al., 2000; Wilson, 2008; Thampi et al., 2011; Xian et al., 2015). Based on performance of coastal residential buildings in past hurricanes, elevating the lowest floor above the expected Base Flood Elevation (BFE) is thought to be the most effective strategy to reduce direct damage caused by flood and storm surge. However, it might increase the wind-induced damage due to higher elevation and subsequent higher wind forces in the atmospheric boundary layer. Literature review shows that there is still a lack of sufficient understanding of the performance of elevated homes subjected to higher wind forces/effects in hurricane prone coastal areas. In addition, past hurricanes have shown that the actual flood levels can be several feet higher than the BFE, which means elevated houses are still vulnerable to direct flood damage. As a result, FEMA retrofit strategies need to be evaluated in terms of effectiveness to resist realistic combined hurricane wind and storm surge loadings.

Federal Emergency Management Agency (FEMA) has developed different retrofit guidelines for new and existing buildings that cannot be elevated, including relocation, demolition, wet floodproofing, dry floodproofing, and barrier systems. In addition, FEMA developed guidelines and recommendations such as minimum lowest floor elevation, foundation type, suitable retrofit techniques, and other requirements for new and existing buildings based on specific flood zones and structural characteristics. However, poor performance of retrofitted residential buildings in past hurricanes requires that these retrofit methods need to be evaluated in terms of effectiveness to resist hurricane wind and storm surge loads. In addition, the inefficiency of the FEMA strategy would be more fundamental when the effects of storm climatology change, sea-level rise, and coastal developments were considered by advanced dynamic models (Lin and Shullman, 2017).

This paper presents a review of the performance of retrofitted residential buildings in past hurricanes in coastal areas. The potential wind and flood-induced damage and subsequent risk mitigation techniques are discussed with respect to each retrofit method. The summary of current FEMA retrofitting strategies is presented in order to obtain better understanding in terms of details and limitations. The paper also investigates the role of different variables such as superstructure and foundation system construction types, choice of retrofitting measure, flood-prone zone construction, and overall retrofit cost (initial, operating, and long-term costs) as an important decision variable for builders and homeowners. Finally, the results provide an overall evaluation of the effectiveness of different FEMA retrofit strategies and an assessment of their strengths and weaknesses against hurricane hazards. This can help in modification of current retrofit solutions, or development of new retrofit techniques, which will contribute to the overall resiliency of coastal residential communities.

3. Literature review on flood retrofit strategies

Among hurricane related hazards, flood and subsequent waves due to high wind are the most destructive and costly phenomena during hurricanes for residential buildings in coastal areas. Flooding causes approximately 90% of the disaster-related property damage in the United States: for example, 186,000 homes were flooded more than once between 1978 and 2014 (FEMA P-312). Therefore, FEMA has developed six major retrofitting methods, namely, elevation, relocation, demolition, wet floodproofing, dry floodproofing, and barrier systems in order to mitigate flood-related hazards for homes in coastal areas (Figure 1). Nevertheless, only elevation, relocation, limited wet floodproofing, and demolition methods are acceptable by National Flood Insurance Program (NFIP) as minimum requirements for homes in order to be eligible for flood insurance and premium reductions. Although elevating the first floor above BFE is the most effective method to mitigate flood-related damage, other methods should be used for buildings that cannot be elevated. Each method can protect the house against flood in different ways, and choosing the appropriate one for homes depends on cost (initial, operating, and long-term costs), risk reduction, and annual cost of insurance premiums (FEMA P-499). For example, not only light-wooden structures are cheaper to elevate than masonry structures, the latter are highly prone to cracks during the necessary retrofitting constructions (FEMA P-259).



(a) (b) (c) (d) (e) (f)

Figure 1. Practical examples for six available retrofit methods recommended by FEMA (FEMA P-312): (a) elevation; (b) relocation; (c) demolition; (d) wet floodproofing; (e) dry floodproofing; (f) barrier system.

Retrofiring methods can also be classified into two categories based on the level of human intervention, including passive and active methods (FEMA P-259). For example, elevating the house above the BFE and using a floodwall with an opening system for cars are considered as passive and active retrofiring methods, respectively. The former is a passive method due to the fact that it can be effective without any human interventions. However, the latter is an active method because it requires adequate warning time in advance for implementing necessary measures before flood occurs (e.g., the door has to be securely closed before the flood). It should be noted that there are some restrictions and limitations for active methods to be considered as appropriate flood protection for NFIP requirements (FEMA P-312). For example, all enclosures below elevated buildings in Zone V must have breakaway walls. However, enclosures and closed foundations without breakaway walls can be constructed in Zone A but are not recommended in Coastal A Zones (A zones where breaking wave heights may be between 1.5 and 3.0 feet). However, they must have flood openings to allow the water passes through the buildings in order to comply with NFIP requirements. It should be noted that selecting appropriate types of breakaway walls (e.g., solid panels, louvered panels, and open lattice) significantly affects their performance during flood events. For instance, louvered panels remain more intact with subsequent less floodborne debris, which results in lower repair costs and final flood insurance premium for homeowners. Figure 2 illustrates a typical home elevated on continuous foundation walls with all additional requirements defined by NFIP.

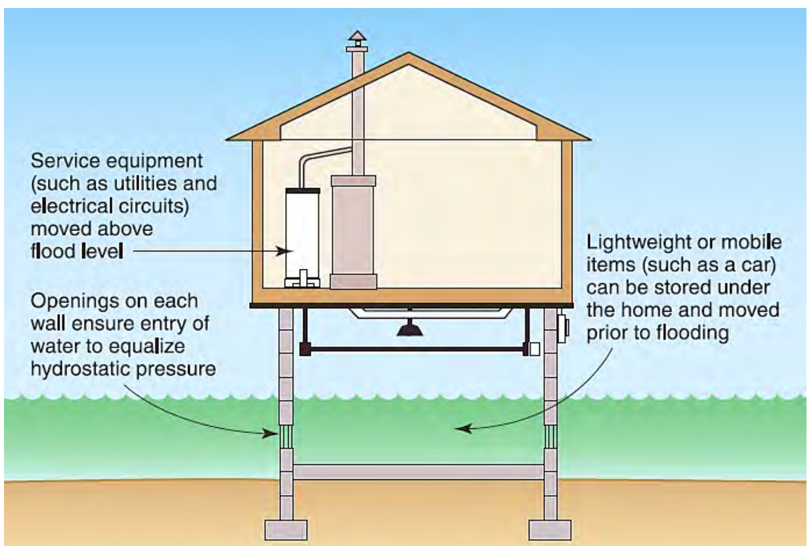
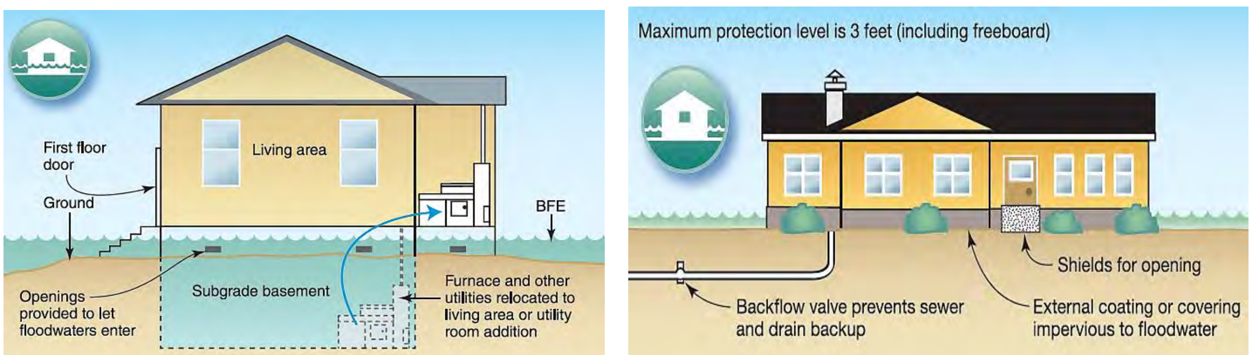


Figure 2. Home elevated on continuous foundation wall (FEMA P-312).

Elevating the lowest floor of a house to or above DFE (BFE + additional freeboard) is the most effective retrofitting method to mitigate flood associated hazards particularly in areas near shoreline. The method of modification of existing foundation, however, could vary from extending to demolition to rebuilding (FEMA P-312). In other words, when the house is separated from its foundation to be elevated, the existing foundation can be extended vertically by building continuous foundation walls on top of existing foundation walls or by adding piers on top of existing foundation walls to support the elevated house with open areas between piers. Although elevating the first floor above BFE is the most effective method to mitigate flood-related damage, other methods should be used for buildings that cannot be elevated.

The wet/dry floodproofing is an alternative retrofitting method when elevating or relocating the structure is not feasible or cost effective (Figure 3). While wet floodproofing decreases hydrostatic pressures (not hydrodynamics) by passing the water thought the appropriate opening in the building, dry floodproofing aims to keep the house watertight so that the floodwater is not allowed to enter the house within limited time (a few hours) and depth (less than 2-3 feet). The NFIP requires that the retrofitted enclosure with wet floodproofing methods only be used for parking, access, and storage (FEMA P-55). In addition, subgrade basement is to be filled if the house is to meet the requirements. Regarding dry floodproofing, this method has not been recommended by NFIP for houses with basements due to the fact that lack of hydrostatic pressure equalization will result in significant lateral and uplift forces from the saturated soil to basement walls and floors (FEMA P-312).



(a) (b)

Figure 3. Schematic of wet/dry floodproofing strategy (FEMA P-312): (a) home with subgrade basement using wet floodproofing; (b) typical details for dry floodproofing techniques.

Last but not least, construction terminology (construction and foundation type), choice of retrofitting measure, and flood-prone zone play prominent role in the decision-making process, particularly, the cost for choosing the best retrofit method. Typical construction consists of frame, masonry veneer, masonry, modular, and manufactured home. In addition, common foundation types consist of basement, crawlspace, slab-on-grade, and open foundation. Regardless of construction type and foundation system, it may be said that wet and dry floodproofing methods are the most affordable method, while elevation, relocation and demolition are the three most expensive retrofit methods (FEMA P-312). However, there is always a tradeoff between alternative methods due to other influential factors such as hazard intensities, house characteristics, freeboard, and corresponding insurance premium rates (Czajkowski et al., 2013; Xian et al., 2017). It can be concluded that more accurate cost evaluation is needed in decision-making process in order to select the best retrofit method for residential houses in coastal areas.

4. Performance of various retrofit methods during past hurricanes

Based on the performance of coastal residential buildings in past hurricanes, elevating the lowest floor above the expected BFE is thought to be the most effective strategy to reduce direct damage caused by flood and storm surge (Kreibich et al., 2005; Bin et al., 2008). However, it might increase the wind-induced damage due to the fact that the structure will be exposed to higher wind forces in the atmospheric boundary layer (Holmes, 1994; English et al., 2015). It is important to mention that currently there are no requirements to consider their elevated height into the wind design procedure (English et al., 2017; FEMA P-762). Actual observations show that wind-induced damage to elevated residential houses can be categorized into three main groups, including structural damage, direct envelope damage, and subsequent indirect water intrusion damage. The envelope systems have experienced more damage compared to structural systems in elevated houses in coastal areas.

Review of FEMA reconnaissance reports shows that the structural system of elevated houses mainly suffers extensive damage to roof members, external wall members, and excessive lateral displacement due to insufficient connections. The most severe damage has been observed as loss of roof sheathing and subsequent progressive damage to structural roof trusses (Figure 4a). Gable end wall failures have also been observed due to higher exposure to positive/negative pressures and insufficient lateral bracing, particularly after the roof covering losses. Furthermore, foundations of elevated houses have experienced failures due to higher wind loads and subsequent higher overturning moments acting on the house. Figure 4b shows an elevated house suffering excessive lateral displacement caused by wind and surge concurrently due to lack of pile bracing or insufficient pile embedment length during Hurricane Katrina (2005). It can be concluded that sufficient connections between the elevated structure with floor system/beams and between the piles/piers with foundation system can significantly reduce the lateral drift and subsequent wind-induced damage (FEMA 549).

(a) (b)

Figure 4. Structural damage to elevated houses due to the wind during Hurricane Katrina, 2005 (FEMA 549): (a) severe damage to the roof framings and gable end wall; (b) excessive lateral displacement due to the insufficient pile embedment.

Extensive damage to envelope systems including, roof/wall coverings and sheathings, soffits, and windows has been observed mainly due to lack of sufficient connections (types of fastener or spacing) or inappropriate installation. These types of failures have occurred typically near roof/wall corners, roof edges, and overhangs due to increased negative and positive wind pressures resulting from the higher elevation (FEMA P-499). Figure 5a and 5b show how an elevated residential building has suffered extensive damage to the roof and wall coverings (siding and housewrap) during Hurricane Ike (2008) and Ivan (2004), respectively. In addition, extensive damage to soffits and windows is another common failure mode for elevated houses in coastal areas (Figure 5c). Furthermore, many elevated houses have sustained severe damage to sheathing panels underside of the floor system due to higher negative pressure resulting from higher wind speed passing under the house (Figure 5d). This type of damage was frequently observed for sheathing panels with different materials, including vinyl siding, gypsum boards, and plywood panels (FEMA P-489). As a consequence of direct wind-induced damage to envelope systems, one can expect subsequent water penetration, which causes serious damage to interior components such as insulations or drywalls.

(a)

(b)

(c)

(d)

Figure 5. Typical wind-induced damage to the envelope system for elevated houses: (a) extensive damage to roof coverings during Hurricane Ike, 2008 (FEMA P-499); (b) extensive losses of wall sidings and housewrap during Hurricane Ivan, 2004 (FEMA P-489); (c) serios damage to windows and soffits during Hurricane Charley, 2004 (FEMA P-488); (d) loss of plywood panels underside of the house during Hurricane Ivan, 2004 (FEMA P 489).

As it was mentioned earlier, all enclosures below elevated buildings in Zone V must have breakaway walls based on the NFIP requirements due to the fact that building components below the BFE are vulnerable to sever damage due to high floodwater velocity and high waves. Furthermore, additional requirements such as using appropriate connections between breakaway walls and the main structure, utilizing waterproof materials for interior components below the BFE, and limiting the use of corresponding garage (only for parking or storage) need to be considered. Figure 6 clearly illustrates the advantage of breakaway walls by comparing the performance of two adjacent houses with/without breakaway walls during Hurricane Irma (2017). As shown in Figure 6a, the slab-on-grade house without breakaway walls suffered severe damage to exterior masonry walls due to flood surge and waves. However, as shown in Figure 6b, the use of breakaway walls below the BFE not only could reduce direct damage to the house but also could decrease lateral loads on the foundation providing overall better performance during the flood. However, it should be noted that lack of appropriate connections between breakaway walls with structural members such as wall sheathing above the floor beam, piers, or piles can result in unclear breaches during the flood, which causes severe damage to the main structure (Figure 7).

(a) (b)

Figure 6. Performance of breakaway walls for houses located in Big Pine Key, FL during Hurricane Irma, 2017 (FEMA P-2023): (a) sever damage to masonry walls of a slab-on-grade house due to lack of breakaway walls; (b) limited damage to the house due to the role of breakaway walls during the flood event.

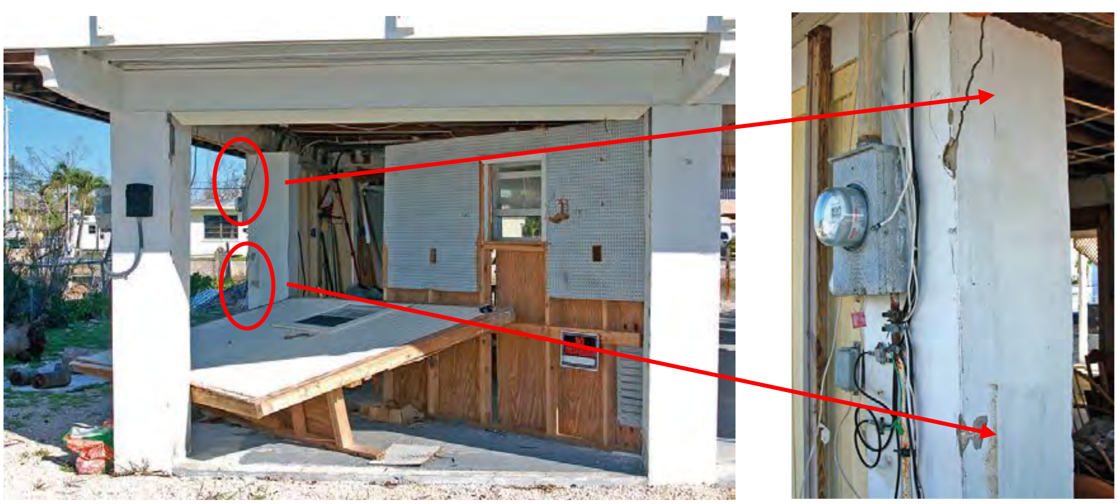


Figure 7. Sever damage to columns due to inappropriate connections between the breakaway wall and main structural members during Hurricane Irma, 2017 (FEMA P-2023).

As it was mentioned, based on NFIP requirements for A zones, all enclosures below the BFE must be built with flood damage-resistant materials and have enough flood openings to allow the water pass through during flood events. Furthermore, lack of sufficient openings and inappropriate designs (such as using covers that can impede the free flow) can transfer the flood loads to the structural members, which may lead to partial damage or total collapse of the building. Figure 8a shows an elevated residential building located in Zone AE suffering severe flood-induced damage to the enclosure below the BFE due to lack of flood openings during Hurricane Harvey (2017). On the other hand, Figure 8b shows another elevated building located almost 300 feet away, which sustained only minor damage due to having flood openings as part of the wet floodproofing system.

The performance of residential houses retrofitted by using flood openings depends on several factors, including number of openings, total net area of openings, height of openings above the grade, and installation methods. For example, NFIP requires that each enclosed area needs to have a minimum of two openings on exterior walls. On the other hand, maintenance is needed in such cases since normally opening are susceptible to clogging due to various types of flood-borne debris, which may cause unanticipated damage to the building during the flood (Figure 9).

(a) (b)

Figure 8. Performance of elevated houses with enclosure with/without openings during Hurricane Harvey, 2017 (FEMA P2022): (a) extensive damage to the enclosure due to lack of flood openings; (b) elevated house suffered minor damage due to having flood openings for enclosures below the BFE.

Figure 9. Typical flood opening clogged by flood-born debris (FEMA 2008).

Dry floodproofing is another possible retrofit measure when elevating or wet floodproofing is not feasible or cost effective. However, this retrofit method is not allowed in V zones and is not recommended in Coastal A Zones due to its vulnerability to hydrodynamic forces. In addition, dry floodproofing is only allowed to be applied for homes with masonry or poured concrete walls due to high hydrostatic pressure resulting from floodwater and saturated soil. The performance of houses with dry floodproofing depends on several factors, including quality of materials below the BFE, appropriate installation (sealant and waterproof shield systems), drainage system for potential seepage, protection of service equipment, and maintenance methods. It should also be noted that lack of flood damage-resistant materials for exterior walls and also interior partition walls below the elevated floor can cause significant damage to the building during the flood event (FEMA P-259).

Residential houses retrofitted by dry floodproofing have sustained various types of damage, including floatation of structure, slab uplift failure, inward collapse of openings and walls, extensive water intrusion, and subsequent indirect indoor failures (FEMA P-312). Among these failure modes, partial or severe water intrusion through walls and openings is most common during flood events. As a result, an efficient drainage system such as sump pumps alongside a well-designed sealant and shield systems can mitigate the damage to structural members and also interior components during the flood time. Furthermore, failure in the bottom connection of shield systems (location with highest hydrostatic pressure) is another common failure mode. Figure 10a shows a house swept away its foundation due to vertical buoyancy forces resulting from the underneath saturated soil. This vertical force is also able to compromise floor slab in terms of cracks or floatation. Figure 10b shows severe damage to wall foundations of a residential house equipped with dry floodproofing measures due to excessively high hydrostatic and hydrodynamic pressures of standing and moving floodwater, respectively. It can be concluded that wall foundation, external wall, and corresponding connections need to be carefully designed. Last but not least, appropriate protection of service equipment is another challenging requirement for dry floodproofing, which can significantly affect the performance of the house during the flood event.

(a) (b)

Figure 10. Various types of damage to residential houses retrofitted by dry floodproofing (FEMA P-312): (a) floatation of the house due to buoyancy forces; (b) collapse of wall foundation due to lack of strength and insufficient connections.

5. Conclusions

This paper presented a review of the performance of retrofitted residential buildings in past hurricanes in coastal areas. The summary of current FEMA retrofitting strategies was presented in terms of details and limitations. Furthermore, actual wind and flood-induced damage and subsequent risk mitigation techniques were discussed with respect to each retrofit method. The following conclusions are drawn from this study:

- The result of literature review indicates that retrofitted buildings generally experience less wind or flood-induced damage during hurricanes. However, there are several factors, including superstructure and foundation system types, flood-prone zone construction, flood insurance primum, and overall retrofit cost that should be considered in order to select an appropriate retrofit measure and to mitigate known types of damage to retrofitted residential buildings. Needless to say, regardless of retrofit methods, the use of flood damage-resistant materials below the BFE and ongoing maintenance can significantly reduce the damage during hurricanes.

- Past performance of buildings during such events show that elevated residential buildings experience severe wind-induced damage to roof structural members, envelope system, and also suffer excessive lateral displacement particularly due to insufficient connections between piers or piles with superstructure or foundation. Thus, even elevated buildings may need to be retrofitted to resist higher levels of wind forces considering the final elevation and configuration.

- Documented actual damage types to retrofitted residential buildings show that the use of breakaway walls below the BFE can significantly reduce damage to the house and its foundation against high velocity floodwater and waves. However, inappropriate connections between breakaway walls and structural members may lead to partial wall breaking during the flood, which results in serious structural damage to the building. As a result, homeowners and builders need to select accurate design procedures and appropriate installation methods.

- The performance of residential houses retrofitted by using flood openings depends on several factors, including number of openings, total net area of openings, height of openings above grade, and installation methods. In addition, appropriate measures such as proper maintenance need to be considered to prevent clogging of engineered or non-engineered openings by flood-borne debris as a common failure mode observed in past flood events. Furthermore, the performance of houses with dry floodproofing depends on several factors, including quality of materials below the BFE, appropriate installation (sealant and shield systems), drainage system for potential seepage, protection of service equipment, and maintenance methods.

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Innovative Construction Products: From Qualification and Performance Assessment to Quality Control

M. Riahinezhad[1], J-F. Masson[2], P. Collins[3], B. Di Lenardo[4], J. Johansen[5], and M. A. Lacasse[6]

[1] Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6, +1-613-993-2433, Marzieh.Riahinezhad@nrc-cnrc.gc.ca
[2] Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6, +1-613-993-2144, Jean-Francois.Masson@nrc-cnrc.gc.ca
[3] Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6, +1-613-993-9721, Peter.Collins@nrc-cnrc.gc.ca
[4] Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6, +1-613-993-7769, Bruno.DiLenardo@nrc-cnrc.gc.ca
[5] CSL Silicones Inc., 144 Woodlawn Rd W, Guelph, ON, Canada N1H 1B5, +1-519.836.9044 X226, jjohansen@cslsilicones.com
[6] Construction Research Centre, National Research Council Canada, 1200 Montreal Road, Ottawa, ON, Canada K1A 0R6, +1-613-993-9611, Michael.Lacasse@nrc-cnrc.gc.ca

ABSTRACT

Air barrier systems (ABS) are essential elements in the performance of building envelopes and they are specified in National Building Code of Canada (NBC) to minimize the infiltration and exfiltration of air through the building envelope to control the risk of condensation. Although their primary function is to control the movement of air across the building envelope, when placed on the exterior side of the wall assembly, the barrier may also function as a water resistive membrane, thereby reducing, the movement of moisture towards the inside of the assembly.

Since the publication of the Energy Code of Canada in 2014, more attention has been given to the importance of ABS to control both heat flow and air transfer through the building envelope, which both contribute to rising costs of energy use in buildings. Recently, the Canadian Construction Material Centre (CCMC) developed performance criteria for liquid-applied ABS. The CCMC is a recognized accreditation body that provides guidance to building officials with respect to the conformity of innovative products as alternative solutions to the NBC.

In this paper four key items are presented. First a brief overview of liquid-applied ABS, their components and functions, and the motivation for use of this product in the construction industry will be reviewed. Second, the qualification process for this innovative product against requirements for compliance with the NBC in Canada and its market acceptance will be discussed. In doing so, the strategy recently adopted by the CCMC in the evaluation of innovative liquid-applied ABS will be reviewed. Third, the key performance criteria and the durability assessment for an expected 25 years of acceptable service life. Finally, the quality control process for acceptable field applications.

1. INTRODUCTION

The air barrier system (ABS) is an essential element in the performance of building envelopes. Its role in the control of air, heat, and moisture movement across the building envelope was identified by the Division of Building Research at the National Research Council of Canada (NRC) over 50 years ago [Wilson, A. G., 1961] and it first appeared in the National Building Code of Canada (NBC) in 1965.

1.1. Air barrier

Air barriers are found within the exterior side of wall assemblies, examples of which are provided in Figure 1 and Figure 2. Figure 1 shows the location of the air barrier within a brick veneer, steel-stud and concrete masonry block wall assemblies. Figure 2 shows a vertical sectional view of the wall in which the air barrier has been installed on the exterior wood or gypsum sheathing panel. Figure 2 also provides a typical winter temperature profile in the wall exposed to a cold climate such as Ottawa in January. The notional temperature difference between the exterior and interior of the wall is about 50 °C, with a mean temperature close to –5 °C. Consequently, a portion of the exterior sheathing panel is below freezing. As such, should any interior conditioned air find a way to the stud cavity by a diffuse or convective process, condensation is likely to occur on cold surfaces.

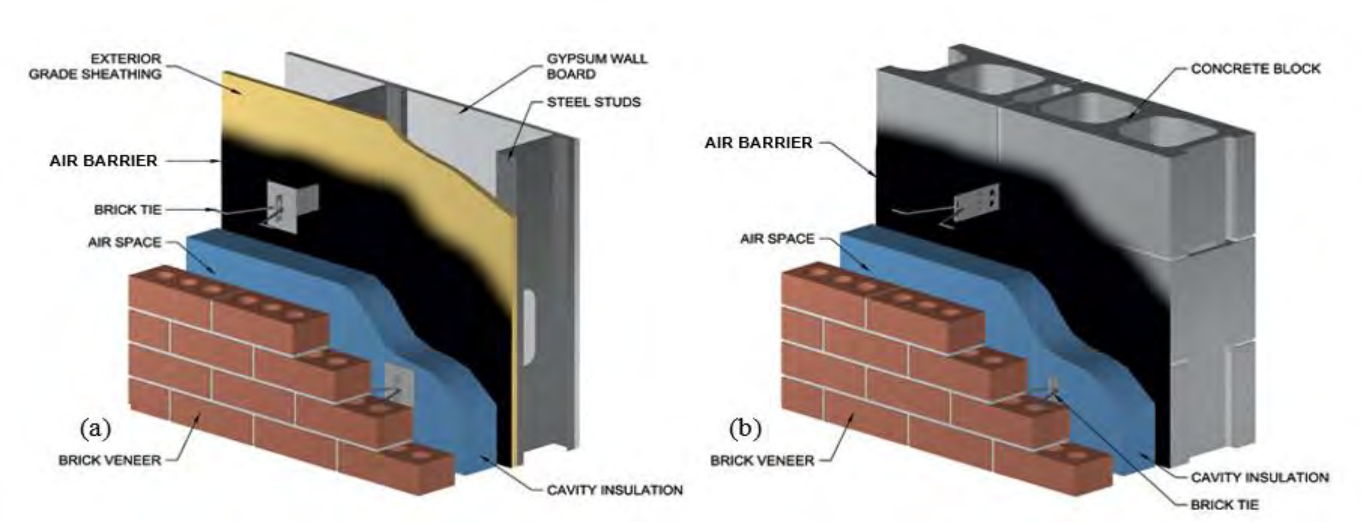

Figure 1: Location of air barrier within a brick veneer, steel-stud (a) and concrete masonry block (b) wall assemblies.

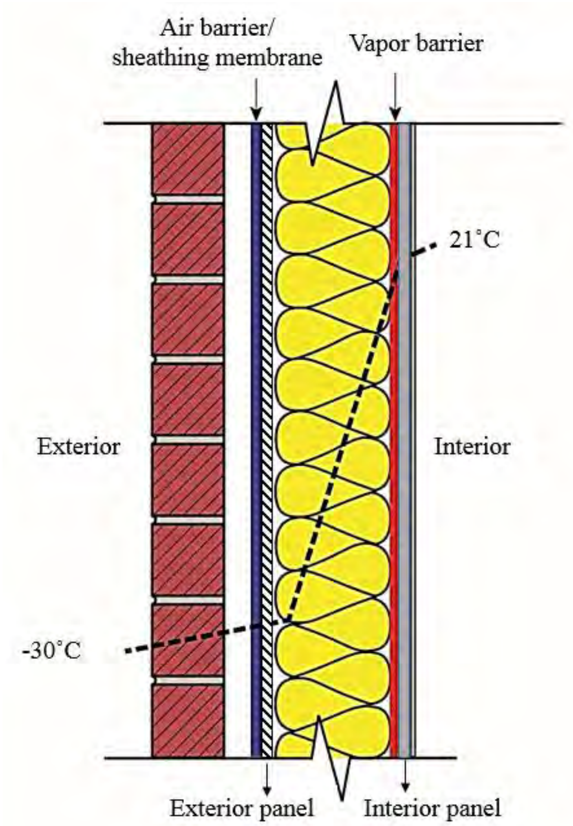

Figure 2: Vertical Sectional view of wall showing air barrier installed on exterior sheathing panel; Ottawa (cold climate), January conditions showing temperature profile through wall.

1.2. Problem definition and objective

The National Energy Code for Buildings (NECB) has been the impetus for the development and installation of an ABS. The NECB calls for the protection and continuity of insulation, together with effectiveness and continuity of air barriers. In effect, an ABS is to prevent air flow across all building envelope cavities, including panel joints, floor to wall joints, openings in the wall for windows, ducts, pipes and the like.

A lack in performance history for innovative products or indeed, the lack of performance standards to evaluate these products make it difficult for architects, building designers and engineers to specify and building officials and inspectors to accept materials for new construction. In such cases, the services offered by the Canadian Centre for Construction Materials (CCMC) help to fill the gap. The next section provides information on the qualification process of innovative products for the Canadian market, including a brief review of the function of CCMC in regards to the interpretation of the building code and also an overview of performance guidelines for barrier products and technical requirements for water and air barriers.

2. QUALIFICATION PROCESS

2.1. Role of the CCMC

The CCMC was established in 1988 under signed agreement with the majority of Provinces and Territories (P/T) whereby the P/T would support the CCMC to provide a centralized evaluation service that addressed the needs of the P/T and industry [Di Lenardo, B., 2005]. It was also agreed at that time that the CCMC would be located at the NRC in Ottawa. In this way, it was deemed essential that the evaluation Centre be able to benefit from NRC's building science expertise, and also in proximity to experts of the Canadian Codes Centre where the NBC is maintained and developed.

After the CCMC inception, the NRC moved to establish a Commission to oversee the Centre's policy direction. The members of the Canadian Commission on Construction Materials Evaluation (CCCME) is made up of representatives from across Canada as stakeholders from the construction industry, users, and regulators. The CCCME serves as the formal CCMC link to the Canadian Commission of Building and Fire Codes (CCBFC) and also links to the Provincial and Territorial Committees that represent the building regulatory system in Canada.

The NBC permits the use of products, systems, and methods not specifically mentioned in the code or the standards it references if it can be shown to the satisfaction of the "authority having jurisdiction" (AHJ) that the product, system, or method meets the intent of the code [Di Lenardo, B., 2000]. For proponents of innovative products this can be an issue given that: (i) it can be difficult to determine the specific intent of the code without some expertise in its use, and; (ii) across Canada there are a large number of AHJ to permit the use of new products in construction and they may apply different criteria for approval.

The CCMC provides an evaluation service for innovative products to determine whether they meet the intent of the NBC, and, if so, under what circumstances and limitations. These evaluations constitute advice from a credible source on which local building officials (i.e. AHJ) can base their decisions regarding a product, system or method and these evaluations do not usurp the official's authority to make such decisions. CCMC evaluations are thus widely accepted by municipal and provincial building officials in all parts of Canada.

Currently, the CCMC service produces a number of products to assist building officials in their decision making for acceptance of building products and systems that include, for example: Evaluation reports, Evaluation listings, and a Registry of product evaluations. CCMC Evaluation reports describe the evaluation process for innovative construction products. Where a product is so novel that no appropriate standard exist for the product, and where acceptance is being sought for its use in construction, building officials will typically assent to its suitability provided a third party technical opinion is submitted on the fitness of the product for its intended use [Poirier, G. et. al., 2004]. For these innovative products, all testing and performance criteria required for the evaluation, and which are to be met by the innovation, are provided in the CCMC Technical Guide.

The technical guide is a product-specific CCMC document not intended for general circulation. The Guide ensures a consistency in the evaluation of similar innovative products falling within that same class. Once the evaluation of the test results and product performance is complete, the published CCMC evaluation report provides the CCMC 'opinion' on the performance of the product with respect to 'equivalent' performance intended by the NBC. With this report, the AHJ is in a position to make an informed decision to determine 'approval' of the product for use in their jurisdiction. The AHJ may or may not agree with the CCMC opinion and has full discretion on the approval of the product for their use in their jurisdiction and may ask for more information on which to decide on the approval of the product for use in the field. The CCMC evaluation service is a voluntary program and becomes mandatory only when specified and mandated by others such as: AHJ, specifier, architect, engineer, or owner.

Evaluation reports describe the evaluation process for innovative construction products. Whereas, Evaluation listings provide a similar service for non-innovative products that fall within the scope of the standards referenced in the NBC. Specifically, when a product demonstrates compliance to a product standard (i.e., CSA, CGSB, ULC, or other standards) through third-party sampling and testing at an accredited lab, the CCMC publishes a listing on the product's demonstrated compliance to the standard referenced in the NBC. Compliance to a standard is a straightforward statement provided by the accredited testing laboratory and no judgment on product performance is involved. The registry of product evaluations is simply a web accessible database of all Evaluation reports and listings.

2.2. Technical requirements of NBC

The NBC 2015 defines the ABS as an assembly of materials installed in the building envelope that provides a continuous barrier to the movement of air and the principal resistance to air leakage. The primary technical requirements for the ABS and elements that ensure its effectiveness include:

i. Have an acceptable air leakage rate;
ii. Be continuous throughout the building envelope;
iii. Capable of withstanding expected structural wind loading during its service life;
iv. Be durable; and
v. Be buildable or reproducible in the field

As regards to item (ii), to constitute an air barrier 'system', the components (materials) of the ABS must be continuous [NBC, 2015]:

a) Across construction, control, and expansion joints;
b) Across junctions between different building assemblies, and;
c) Around penetrations through the building assembly.

The materials must be joined to each other to provide the required continuity and structural sufficiency. Failure to achieve such control can have adverse effects on building envelope components, assemblies and equipment, and it can lead to health and safety risks for occupants stemming from structural damage, compromised operation of building services and life safety systems, and air quality problems.

In respect to (iii) above, the structural design of ABS installed in assemblies subject to air pressure loads must be undertaken following the precepts set out in the NBC: Article 5.1.4.1. and Subsection 5.2.2 [NBC, 2015]. Thus to comply with NBC 2015 Part 5, the structural capacity of the ABS must be sufficient to resist 100% of the wind load for which the wall or roof structure is designed (as determined in NBC 2015 Part 4, Structural Design), and it must be supported and attached so that this load can be transferred to the structure [Di Lenardo, B., 2000]. In addition, deflections must not affect the non-structural elements of the wall assembly when the ABS system is subjected to wind loads of 1.5 times the specified wind load [Di Lenardo, B., 2000].

In addition, air barrier materials forming part of the ABS and providing the principal resistance to air leakage must [NBC, 2015]:

a) Have an air leakage characteristic not greater than 0.02 $L/(s \cdot m^2)$ measured at an air pressure difference of 75 Pa, when tested in accordance to ASTM E 2178-13, or;
b) Conform to CAN/ULC-S741-08 (R2016).

3. PERFORMANCE ASSESSMENT

It was recognized by the NBC standing committee for Part 5 that, ideally, the maximum air leakage rate of the complete ABS (including materials and joints) should be specified. However, at the time the 1995 NBC was finalized, there was insufficient knowledge of the performance of ABS to specify a limiting rate. It was also understood that determining the leakage rate of a particular assembly is, however, problematic. There is little information available on the airtightness of the many ABS used in building construction, and testing requires specialized equipment and expertise. Depending on the type of test [NBC 2015]:

- Testing may not represent the performance of the complete installed system;
- The location of deficiencies may be difficult to identify, and;
- Rectification of deficiencies may not be feasible.

Thus, only a ‘material’ air leakage rate was specified starting with NBC 1995, making it difficult to evaluate entire systems. Despite these difficulties, with a system whose performance is not known, it was recommended that tests nonetheless be conducted. Testing options include:

- Laboratory tests of small sections of the ABS, including the joints and intersections of different assemblies;
- Laboratory tests of large wall sections;
- In-situ tests of characteristic envelope areas.

Research and in-situ testing of installed ABS have shown that the bulk of air leakage occurs through joints (between air barrier materials) and junctions (between air barrier components). Ideally, a maximum air leakage rate for the complete ABS would be specified. The maximum acceptable rate will ultimately depend on warm and cold side temperatures and humidity conditions, and on the susceptibility of the environmental separator to moisture-related deterioration. Recommended maximum leakage rates for an ABS in an exterior envelope in most locations in Canada are shown in Table 1 [NBC, 2015]. The information provided in Table 1 is for guidance when testing the ABS as portions of an envelope. These values are for an ABS in opaque, insulated portions of the building envelope and not for whole buildings, as windows, doors, and other openings are not included.

NRC’s CCMC and Construction Research Centre have recently developed guidelines to evaluate liquid-applied membranes and systems that play a dual role in the building envelope;

that of a water resistive sheathing membrane and ABS. In the guidelines, further described in the subsequent sections, a performance-based approach is the basis for the evaluation of a liquid-applied ABS intended for buildings conforming to NBC Part-5. The focus is thus on buildings of more than 5 stories, typically having steel-stud framed walls and exterior grade sheathing panels behind code-prescribed claddings.

Table 1: Recommended Maximum Air Leakage Rates of ABS in Conformance with NBC 2015

Warm Side Relative Humidity at 21°C	Recommended Maximum System Air Leakage Rate, L/(s•m^2) at 75 Pa
< 27%	0.15
27 to 55%	0.10
> 55%	0.05

A performance-based approach to the evaluation of water resistive and air-barrier materials and system, whether liquid-applied or not, is focused on the material or system response to loads representative of in-service conditions. These specifically include climatic loads such as solar radiation, rain, relative humidity, and heat, in addition to mechanical loads induced by wind. For an effective protection of the building structure, as required by the NBC, the response of the materials or system to the following loads should be studied:

- Moisture protection and control: the sheathing membrane;
- Air-movement control: the air barrier material and system;
- Service-life and material durability, with a discussion of service loads.

3.1. Moisture control

Moisture control relates to the risk of moisture condensation within the building envelope, and also the protection from precipitation (i.e. rain and snow). With water sheathing membranes, the second line of protection behind cladding, the protection is more specifically against wind-driven rain, and, in sub-optimal cases, the retention of water that may collect behind cladding.

The NBC 2015 requires that the outermost layer of a wall assembly, the sheathing membrane, be "breathable" to allow condensation moisture trapped in the assembly to dissipate during the drying season. Therefore, the NBC has restrictions on the outermost layer having both low water-vapor permeance (WVP) and low air permeance (AP) materials installed on the cold side of the assembly. If the combination of sheathing panel and liquid-applied sheathing membrane lead to a WVP below 60 ng/(Pa·s·m^2) and AP below 0.1 L/(s·m^2), then thermal insulation must be installed outboard of the adhered membrane for demonstrating compliance with Subsection 9.25.5 of Division B of the NBC 2015.

After water vapor, liquid water must be considered. The liquid-applied sheathing membrane must prevent incidental rain penetration in the field of the wall, at brick tie locations, other cladding attachments, and at panel joints. These characteristics apply to the air-barrier materials and also to air-barrier system components when the latter also serve to protect against the intrusion of liquid water.

3.2. Air movement control

With respect to air control, there are progressive requirements for sheathing membranes that also double as air-barrier materials in ABS. The requirements include resistance to cracking upon wall bending (cracks would increase air permeance) and the need for acceptable air permeance and resistance to air leakage. Nonetheless, moisture and air movement controls always need to be considered together in the design of the building envelope and selection of sheathing membrane and ABS materials.

According to NBC Section 5.4., the air permeance of air-barrier materials must be below 0.02 L/(s.m^2). This is twice the benchmark value of 0.01 L/(s·m^2) for 11 mm thick oriented-strand board (OSB) [Di Lenardo, B., 1997]. With respect to the ABS, a value 10 times greater, 0.2 L/(s.m^2), is permitted to account for air leakage at wall openings, including for instance, windows, electrical outlets, pipes, and mechanical attachments that go through the air barrier. The ultimate requirement for air leakage can be lower than 0.2 L/(s.m^2), however, this depends on the WVP of the uninsulated layer (Table 2). The combination of air leakage rate and WVP determine the need for outboard insulation.

Table 2: Maximum permissible air leakage rates for ABS [Di Lenardo, 1997]

WVP of Outermost Uninsulated Layer of Wall Assembly ng/(Pa.s.m^2)	Maximum Permissible Air leakage Rates, L/(s.m^2) at 75 Pa
≤ 60	0.05
≤ 170	0.10
≤ 800	0.15
> 800	0.20

3.3. Service-life and durability

During material selection and evaluation, the basic properties are measured on unaged products. However, liquid-applied products within the building envelope must perform effectively for at least 25 years because they are defined as “non-accessible”. A non-accessible air barrier is a product difficult to replace, either because of its location in the building enclosure or because of the difficulty in removing it from the substrate to which it is applied. Given these expectations for service-life, these products must be evaluated for durability.

The four primary aging factors that are considered in durability assessments through the use of accelerated-aging tests include: UV irradiance, heat, humidity, and wind loading. The UV irradiance is meant to simulate and accelerate the effect of exposure to sunlight during the product’s’ early service-life and when the barrier is not yet covered with cladding. Aging using heat and humidity accounts for the in-service conditions that occur within the envelope upon repeated cycles of exposure to temperature fluctuations as occur on the surface of the wall cladding and the heat gain of the air barrier, sheathing membrane in the wall assembly.

How much aging and what method to use to perform accelerated aging is an important issue. It is a function of the material composition and the estimated loads that act to degrade the product over its service life. It is therefore not fixed, and the selection of accelerated aging conditions requires knowledge of product composition, materials chemistry, climatology, and building science. This is the reason why the development of meaningful accelerated aging conditions, and method for service-life prediction, are challenging. CCMC Technical Guides are developed to account for these conditions.

The effect of aging can conveniently be assessed by means of tensile or rheological characterization. The latter method is preferred because it can provide for moduli values over the entire range of in-service temperatures or beyond. Figure 3 shows an example of rheological characterization of a membrane product prior to and following UV aging. This type of characterization readily shows the effect of aging on fundamental material transition temperatures, material stiffness, and flow properties. In other words, it helps provide an understanding of the effects of aging arising from the action of UV radiation on the mechanical properties of the membrane. When the aging conditions are properly established, changes in rheological properties help in estimating the product's service-life.

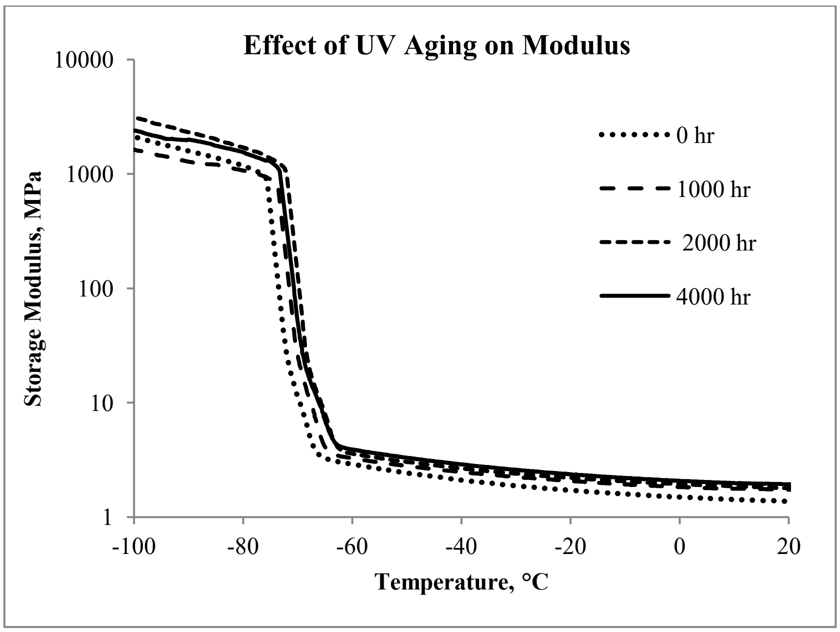

Figure 3: Rheological characterization of membranes, storage modulus versus temperature.

Another aging factor is aging due to wind loading and achieving acceptable performance is a necessary condition for the selection of sheathing membranes as air barriers. Wind pressures bring about the deflection of the wall, the extent of which depends on the wall structure. The limits to the amount of deflection, prescribed in the NBC, is L/360, where L is the height of the wall. Consequently, the testing of sheathing membranes and the ABS require that they be applied to wall panels over structural framing. When attempting to age and subject the product to wind loading, more precisely deflection aging, liquid-applied sheathing membranes and air-barriers are tested to meet increasingly demanding pressures differentials of increasing magnitude. In the evaluation of sheathing membranes, a single deflection loading to L/180 (twice the limit given in the NBC) is applied to a wall incorporating a membrane. Upon loading, the membrane must remain defect free, without splitting or debonding (Figure 4).

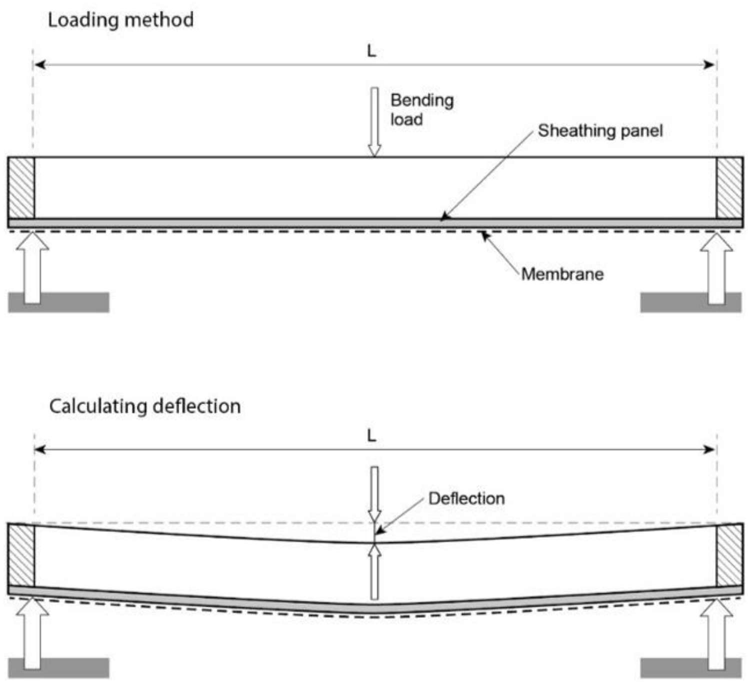

Figure 4: Details of wall-bending test serving to simulate deflection under action of wind loads.

The performance properties of liquid-applied membranes are related to application characteristics, namely, adhesion over various substrates, and control of material thickness during field application. Both of these parameters combine material properties and quality control during field application, which will be discussed in the next section.

4. QUALITY CONTROL

In contrast to prefabricated sheathing membranes and air barriers, the installation of liquid-applied products requires a more demanding set of quality control measures in the field as compared to prefabricated materials. This is to ascertain that the liquid-applied product meets specification and performs as expected after installation and curing. At a minimum, the installation must meet the requirements of standard ISO 12576-2 for field-applied products. In performance evaluations, the CCMC also requires quality control to include daily records to be filled out on-site with actual application details, including temperature, wind, relative humidity, and other factors that may affect installation. It also requires procedures for the correction of non-conforming installations, and the handling of rejected installations.

Two application-related quality control measures are specifically covered here, the adhesion of the membrane or barrier material to the substrate, and the control of liquid-applied material thickness.

4.1. Adhesion

Good adhesion is required for liquid applied products, and also self-adhered barriers. The fundamental adhesion mechanisms of these two types of products are significantly different, but what is not different is the need for a good quality substrate. This is to say, a dry substrate free of loose material on the surface (e.g. dust) would be required, and also a substrate free of materials that have already penetrated into the surface and which can interfere with the bonding of the membrane and substrate surfaces (e.g., oil). Most of adhesion failure issues are related to inadequate installation practice due to a poorly prepared substrate.

For the barrier to remain functional for a service-life of 25 years, the adhesion must override the tendency to failure over time. Unless repairs or rehabilitation is required, barrier adhesion is rarely, if ever, measured during service, because it is hidden under cladding. Consequently, adhesion is only measured in the field upon installation (as a quality control measure), and tested in the laboratory under conditions meant to simulate possible installation scenarios.

In testing for the adhesion strength of a liquid-applied product over gypsum panel (Figure 5), failure of the substrate is an indication of the development of proper adhesion, provided the substrate is sound. Substrate failure indicates that more than one adhesion mechanisms is likely at play and this provides significant insurance that proper adhesion will be maintained over an extended service life.

Figure 5: Pull-adhesion test result from a liquid-applied sheathing membrane/air barrier applied to a gypsum panel. Strong adhesion led to failure in the panel core.

4.2. Thickness

Sheathing membranes and air-barriers intended for spray-application will have an inherent variability in thickness. This variability could lead to inconsistent field performance. For example, a membrane sprayed too thin may not provide for appropriate protection against moisture ingress, whereas too thick a membrane may have too low of a water-vapor permeance to allow for effective drying and the escape of moisture trapped into the substrate. Membrane-barrier thickness must therefore only vary slightly from the specified thickness.

The minimum barrier thickness will depend on both the roughness of the substrate, and the intrinsic barrier permeability, e.g., the variability in WVP with thickness. On a fairly smooth surface such as a wall panel covered with a thin liquid-applied "breathing" membrane, the acceptable thickness might be 600 ± 125 µm, a variation of ±20%. In cases where the membrane is liquid-applied onto a rough surface, e.g., concrete blocks, the thickness must be greater to account for high points on the uneven surface. An appropriate thickness may then be 2000 ± 400 µm. In all cases, the appropriate variation in thickness will be established from the relationship between membrane transport properties and thickness, that is to say, the change in liquid water, water vapor, and air permeance through the membrane. During application, the measurement of the wet-film thickness (WFT) can be done with either a wheel gauge, as per ASTM D 1212, or a notch gauge as per ASTM D 4414 (Figure 6). The latter might be a little more precise, but it leaves large imprints on the wet barrier, which may be detrimental to the long-term mechanical performance of the barrier (Figure 6 (c)). Consequently, a comb gauge may be preferred.

Dry film thickness in the field may be obtained with an ultrasonic gauge as per ASTM D 6132. For development or laboratory work, membrane thickness may also be obtained from optical microscopy of membrane cross sections cored-out from the substrate. From thickness measurements taken across the field of the wall, adjustments to application conditions can be made and transferred to field practice so that thickness is maintained within 20% of the sought thickness.

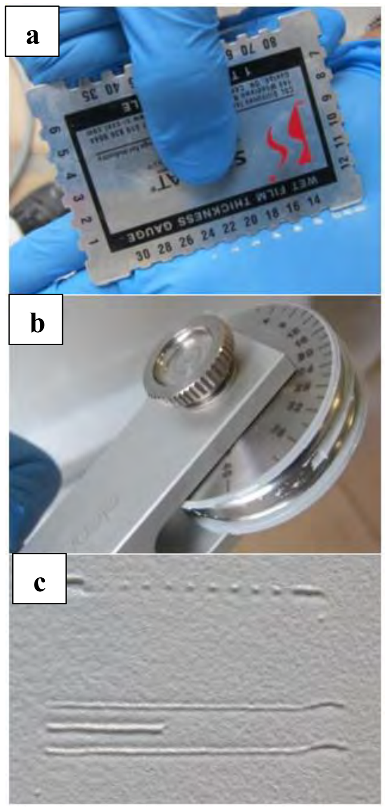

Figure 6: Notch (a) and wheel (b) gauges for liquid membrane thickness measurements, Imprint of the notch gage (c, top) and wheel gauge (c, bottom); Photos courtesy of CSL Silicones, Inc.

5. CONCLUSIONS

The National Building Code of Canada and the National Energy Code of Canada are designed to help improve the energy efficiency of buildings. A key aspect in this strategy is the continuity in measures to counter heat and air loss through the building envelope. Solutions to this strategy include continuous insulation and a barrier that protects the insulation from incoming moisture, and also prevents air movement across the wall. Liquid-applied products designed to perform both as sheathing membrane and air barrier are novel solutions being put forward by some providers of ABS. In this environment, the CCMC and the NRC provide building officials with opinions on the suitability of innovative products for the Canadian market.

This work presented in this paper provides an outlines of the strategy recently adopted by the CCMC in the evaluation of innovative liquid-applied barrier products. This strategy was based on the qualification of moisture and air transfer across the proposed materials and system, and the assessment of durability for an expected 25 years of acceptable service.

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ASHRAE 90.1: CODIFIED CONDENSATION FOR COLD CLIMATES

David S. Finley[1] and Manfred Kehrer[2]

[1]Senior Associate, Wiss, Janney, Elstner Associates, Inc., 9655 Sweet Valley Drive, Cleveland, Ohio 44125. 216.642.2300, dfinley@wje.com
[2]Senior Associate, Wiss, Janney, Elstner Associates, Inc., 330 Pfingsten Road, Northbrook, IL 60062. 847.272.7400, mkehrer@wje.com

ABSTRACT
To comply with the energy code, designers often utilize the Prescriptive Building Envelope Option described in ASHRAE 90.1 when determining the minimum amount of insulation required within a wall assembly. In cold climates, the minimum R-Value requirement for framed wall assemblies allows designers to utilize a split insulation arrangement to meet code requirements. However, these designs often carry an elevated risk of condensation which is not explained in the text of the standard and may lead a designer to unknowingly promote detrimental insulation combinations regarding convective condensation.

A design tool has been developed based on psychometrics and ASHRAE 90.1 requirements which illustrates the ratio of continuous insulation to total insulation. The design tool currently assumes a high leakage rate; therefore, values along the pass-fail line may be overly conservative. In order to incorporate a more realistic air leakage rate and develop a more defined pass-fail criteria, our research uses software tools, like WUFI, to study the requirements offered by 90.1 to evaluate the hygrothermal performance of insulation combinations for framed wall assemblies based on the simplified exfiltration model. Hygrothermal engineering principals and the results will be presented with future publication of the design tool for the design industry.

INTRODUCTION
To maximize the efficacy and performance of building enclosure walls, the four major building enclosure control layers (i.e., liquid water, air, water vapor, and thermal) should be designed and installed with continuity. The position of these control layers within a wall assembly can also significantly affect the hygrothermal performance (i.e., movement of heat and moisture) of an exterior wall. For buildings located in Climate Zones 4 and higher (Figure 1), insulation, which is the primary thermal control layer, should be ideally located outboard of the other control layers. However, to comply with energy code requirements, designers often utilize the Prescriptive Building Enclosure Option described in ASHRAE 90.1 or the minimum R-values required by the 2015 International Energy Conservation Code (IECC) to determine the minimum amount and location of thermal insulation required in an opaque wall assembly. The minimum R-Value requirement in these zones for both steel-framed and wood-framed opaque wall assemblies allows designers to utilize a split insulation arrangement to meet the minimum thermal requirement (Table 1). Split insulation designs utilize a certain amount of thermal resistance via continuous insulation outboard of the sheathing, where the air and water control layers are typically located, in addition to within the stud cavity inboard of the sheathing. The relative amount of continuous insulation outboard of the sheathing is expressed as an Insulation Ratio (Equation 1).

$$IR = \frac{R_{ci}}{R_{ci} + R_{batt}}$$

Equation 1: The Insulation Ratio (IR) is equal to the continuous insulation, R_{ci}, divided by the sum of the continuous insulation and discontinuous cavity (often batt) insulation, R_{batt}.

In certain circumstances, split insulation designs can be at risk of elevated relative humidity within the stud space or even at the first condensing surface, usually the interior side of the exterior sheathing. This risk is not explained in the text of the standard or the energy code and may lead a designer to unknowingly utilize split insulation assemblies without understanding their influence on the hygrothermal performance of the wall assembly. To compound the issues of split insulation assemblies, the introduction and placement of a vapor retarder within the wall system as mandated by code in some Climate Zones and local jurisdictions can result in trapped moisture and increased potential for condensation or microbial growth.

Careful analysis of the movement of heat and moisture through a wall assembly must be made when a portion of the thermal control is located inboard of the air, water, and water vapor control layers. The research project summarized in this document strives to use a hygrothermal software tool, such as WUFI (Künzel, 1995), to study the hygrothermal performance of the minimum R-value and distribution of wall insulation outlined in ASHRAE 90.1 and the IECC. Specifically, the moisture accumulation risk was evaluated for split insulation wall assemblies for steel stud framed walls as well as the remaining enclosure control layers, which are not fully prescribed by ASHRAE, but may be codified in the International Building Codes and by local municipalities. Similar studies have been carried out by (Finley and Kehrer, 2019)

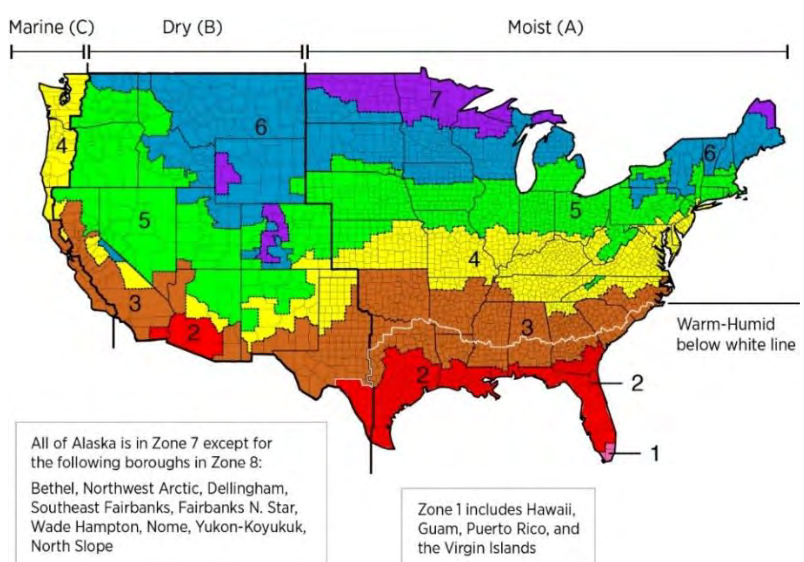


Figure 1: Climate Zone Map from International Energy Conservation Code

Climate Zones	
1-5	6-8
R-3.8ci + R-13	R-7.5ci + R-13
R-20	R-3.8ci + R-20

Table 1: 2015 IECC minimum R-values for wood stud framing

EFFECTS OF INSULATION

The introduction of insulation in any exterior wall system reduces the heat flow through the wall assembly; as such, the surface temperature of materials outboard of the insulation are reduced in cold weather. In addition to this temperature drop caused by the insulation, a subsequent and greater reduction in the saturation vapor pressure occurs, as shown in Equation 2, which can cause the development of condensation.

$$P_{ws} = 1000e^{\left(52.58 - \frac{6790.5}{T} - 5.028 \ln T\right)}$$

Equation 2: P_{ws} is the saturation vapor pressure and T is temperature in Kelvin. Note that the saturation pressure will drop exponentially relative to temperature.

Saturation vapor pressure is the maximum pressure of water vapor, or absolute humidity that can exist within the air. Relative humidity is the ratio of actual water vapor in the air to the maximum amount of water vapor at saturation (Equation 3). Therefore, the relative humidity (RH) of saturated air (i.e., actual vapor pressure equal to the saturation vapor pressure) is 100 percent.

$$RH = \frac{P_w}{P_{ws}}$$

Equation 3: P_w is the vapor pressure and P_{ws} is the saturation vapor pressure.

Because of the relationship between the significant drop in saturation vapor pressure associated with thermal gradients via insulation, increased relative humidity as well as the inherent reduction in surface temperatures outboard of the insulation layer is expected. As such, it is important and ideal to place the thermal control entirely outboard of the other building enclosure control layers in cold climates. However, when the thermal control layer is split and sandwiches some of the other control layers, it is imperative to control or reduce the vapor and air transport into and through the inboard insulation layer to avoid condensation development or increased surface relative humidity that can promote microbial growth.

Condensation can occur on surfaces when the surface temperature drops below the dew point temperature of the ambient air which occurs when the vapor pressure reaches the saturation vapor pressure, or a relative humidity of 100 percent (Equation 4).

$$T_{dp} = \frac{4030}{18.689 - \ln \frac{P_w}{133}} - 235$$

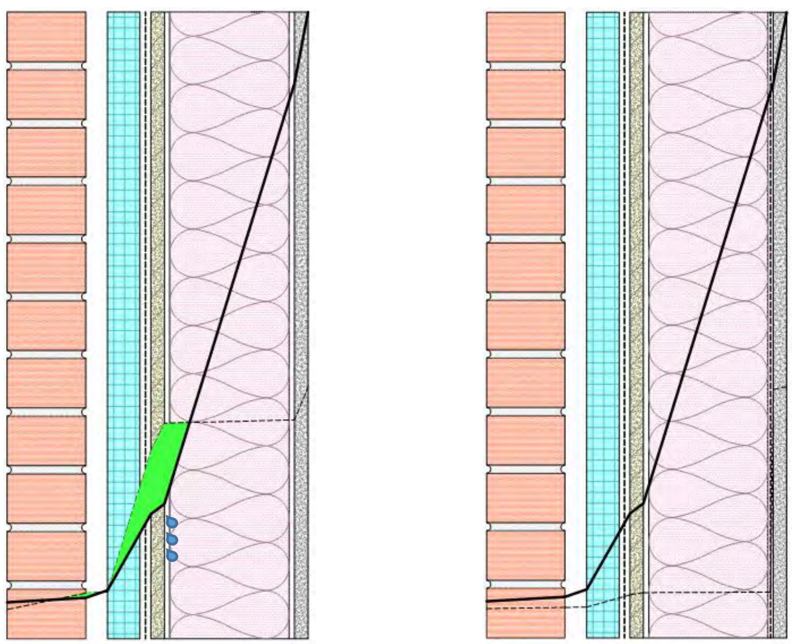
Equation 4: P_w is the vapor pressure and T_{dp} is the dew point temperature in Celsius.

For interstitial spaces, such as within a wall system, the necessary moisture (vapor) for condensation or elevated surface RH typically comes from two sources: vapor diffusion and air leakage. Both of these mechanisms should be considered when evaluating the anticipated hygrothermal performance of a proposed exterior wall assembly.

DIFFUSIVE CONDENSATION

Diffusive condensation occurs when moisture migrates from air with a higher vapor pressure to air with a lower vapor pressure. Diffusion is a much slower method of transferring moisture than airflow. As a result, it is typically a less significant contributor to moisture migration associated with condensation problems than is airflow. However, the placement of vapor retarders within an exterior wall assembly with respect to the location of the insulation nonetheless warrants careful consideration.

As previously discussed, insulation causes a significant change in the thermal gradient and a corresponding drop in saturation vapor pressure. If the predicted vapor pressure at any point across the moisture-sensitive portion of the wall assembly exceeds the saturation vapor pressure, condensation would be predicted to occur to satisfy equilibrium (Figure 2a). It should be noted that the rate of condensation development is typically extremely low. For example, the rate of condensate deposition in Figure 2a is about a droplet with 1/10-inch diameter per square foot per day.



(a) (b)

Figure 2: Predicted vapor pressure profile of a typical split insulation system during winter conditions. The dashed line represents the predicted vapor pressure and the solid line represents the saturation vapor pressure. The green shaded region (left) indicates the area where the predicted vapor pressure exceeds the saturation pressure or where the predicted RH exceeds 100 percent. The right graphic shows the pressure profiles for the same assembly but with a vapor retarder added between the studs and drywall.

As such, vapor retarders (in cases where needed), should be generally placed on the warm-side of all insulation, inboard of the inherent drop in saturation vapor pressure, to locally reduce vapor pressure (Figure 2b). When the insulation is not the outermost control layer, the vapor retarder is typically placed inboard of the insulation to alleviate potential wintertime diffusive condensation. The International Building Code (IBC) requires a Class I (e.g., polyethylene or foil sheet) or II (e.g., kraft paper) vapor retarder for Climate Zones 5 through 8 and Marine 4.

The use of vapor retarders with absorptive reservoir claddings (e.g., brick masonry, concrete, stucco) in certain climates, can result in summertime diffusive condensation on the outboard face of the vapor retarder as it is then located on the cold side of the insulation (Figure 3). The typical deposition rate of condensate during summertime conditions is even lower than the typical rate expected during winter conditions.

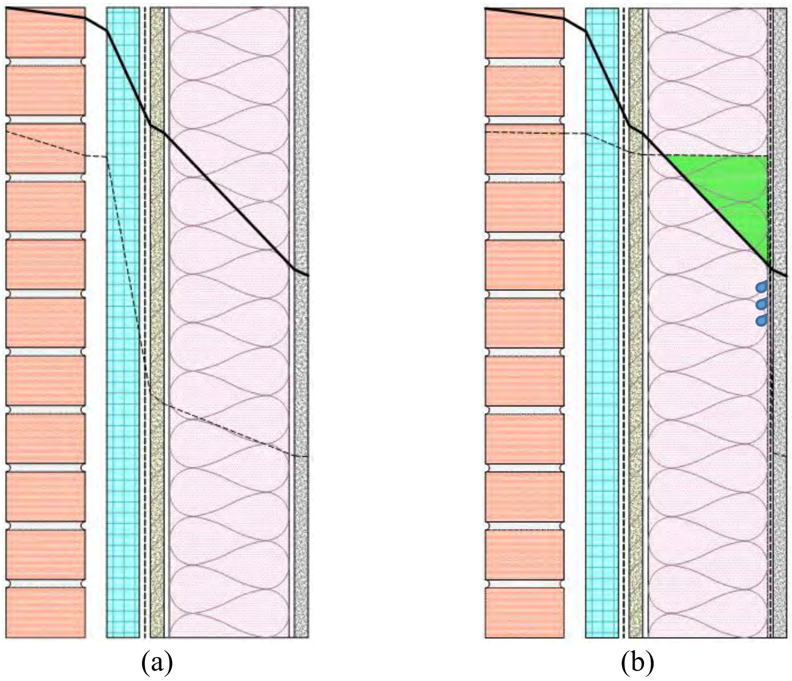


Figure 3: Predicted vapor pressure profile of a typical split insulation system during summer conditions. The dashed line represents the predicted vapor pressure and the solid line represents the saturation vapor pressure. The green shaded region (right) indicates the area where the predicted vapor pressure exceeds the saturation pressure or where the predicted RH exceeds 100 percent. The left graphic shows the pressure profile for the same assembly but without the vapor retarder.

In addition to ambient temperature-induced diffusion, solar radiation can play a role in increasing the rate of moisture transfer through diffusion. After a significant rainfall that wets masonry or other absorptive cladding, solar radiation will heat the cladding material promoting drying through evaporation. As this water evaporates from the cladding into the air space or inboard materials, it greatly increases the moisture content of the air or adjacent material. The higher vapor pressure differential (i.e., higher moisture content of the air), the greater the rate of vapor diffusion. Condensation occurring due to solar radiation and/or summer conditions can wet the interface between the vapor retarder and the batt insulation leading to the development of microbial growth if organic materials are present, such as dust particulates within the batt or paper facers.

In order to reduce the effect of solar radiation-induced vapor diffusion, introducing a ventilated cavity behind reservoir claddings can significantly alleviate these vapor pressures. It should be noted that Class III vapor retarders (e.g., latex or enamel paints) are permitted in Climate Zones 5 through 8 and Marine 4 with ventilated claddings or insulated sheathings.

CONVECTIVE CONDENSATION

As airflow through discontinuities can carry moisture into a wall assembly at a rate orders of magnitude higher than can diffusion through materials, air infiltration or exfiltration is often the primary source of moisture transfer associated with condensation within a wall assembly. Depending on the direction of air flow, ambient air temperatures, and relative humidity of the air and wall system materials, airflow may cause either wetting via condensation or drying through evaporation of the assembly's materials. Airflow occurs when there is an air pressure differential resulting from wind, mechanical pressurization, stack effect, etc. across an assembly and travels from a higher to a lower air pressure.

For example, warm and humid interior air that is able to flow into the exterior wall assembly due to a pressure differential can condense on surfaces of wall components that are below the dew point of the exfiltrating interior air. With air-permeable batt insulation within the stud cavity, it can be expected that some exfiltrating interior air will be able to reach the inboard face of the exterior sheathing, which may have a surface temperature below the dew point temperature to promote condensation. Paths for this type of air flow include discontinuities within the interior gypsum wallboard, commonly found around electrical outlets and other penetrations and along terminal edges at interfaces with floors, ceilings, and fenestration.

In general, there are two primary air leakage paths: direct and circuitous. Direct paths, like the one shown on the left in Figure 4, are typical of a through-wall connection or penetration, where the air flows directly from the inside to the outside or vice-versa. In this case, the air usually carries enough thermal energy to warm up or cool down the component surfaces along the flow path. This typically keeps the surface temperature of the contacted elements within the flow path above the dew point, which means that there will be no condensation along the path. Depending on climatic conditions, liquid condensation or ice may develop on the outboard surface. The primary concern with direct leakage paths is typically thermal shorts ("energy leaks") within the building enclosure.

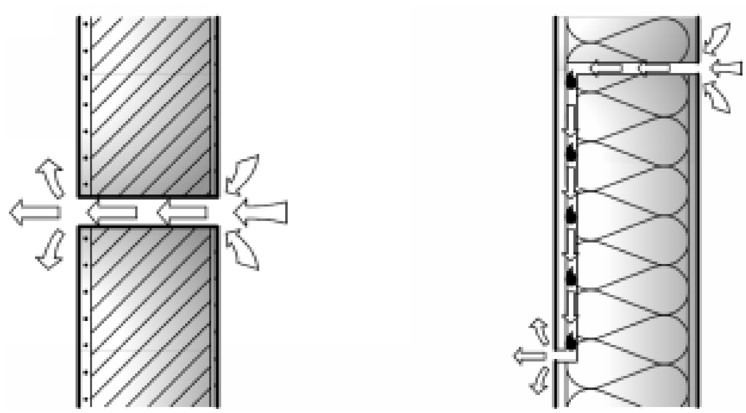


Figure 4: Diagram showing direct air flow paths (left) and circuitous air flow paths (right) from Modelling the Effect of Air Leakage in Hygrothermal Envelope Simulation by Hartwig Künzel.

Conversely, circuitous flow patterns, as shown on the right in Figure 4, do not sufficiently warm or cool the greater area of the traversed surfaces resulting in the potential for moisture-laden air to contact surfaces that are below the dew point temperature of the air. This type of air leakage path can result in the deposition of significant amounts of condensate within the wall system. In order to prevent direct and circuitous air paths, all materials, components, and assemblies should be integrated to provide a continuous air control layer. Even with a "continuous" air control layer, construction practices and general operation and service of the building will allow some air leakage, likely increasing during the service life of the building.

To accommodate reasonably expected imperfections in the air control layer while limiting the development of convective condensation on the inboard face of the exterior sheathing, designers utilizing the split insulation approach can empirically determine the minimum ratio of continuous insulation to total insulation necessary to maintain the inboard surface temperature of the exterior sheathing above the interior dew point. Equation 5 is the simplified method of calculating this ratio considering only the effects of thermal conduction on exterior temperatures. Thermal radiation (e.g., solar heat gain, clear sky cooling), internal thermal convection, and wind washing are disregarded by this formula.

$$IR_{required} = \frac{T_{dp} - T_o}{T_i - T_o}$$

Equation 5: The required minimum Insulation Ratio (IR) to maintain the surface temperature of the sheathing at the dewpoint temperature (T_{dp}), where T_i and T_o are the interior and exterior temperatures, respectively.

Tabulation of calculated minimum insulation ratios for typical interior and exterior climatic conditions are presented in Table 2.

Ratio of Continuous Exterior Insulation to Total Insulation										
	RH		15	20	25	30	35	40	45	50
	T_d, ºF		22	29	34	39	43	46	49	52
Interior Temperature 72 ºF	Exterior Temperature, ºF	40	0	0	0	0	0.09	0.20	0.30	0.39
		35	0	0	0	0.10	0.21	0.31	0.39	0.47
		30	0	0	0.10	0.21	0.31	0.39	0.46	0.53
		25	0	0.08	0.20	0.29	0.38	0.45	0.52	0.58
		20	0.03	0.17	0.27	0.36	0.44	0.51	0.57	0.62
		15	0.12	0.24	0.34	0.42	0.49	0.55	0.61	0.66
		10	0.19	0.30	0.39	0.47	0.53	0.59	0.64	0.68
		5	0.25	0.35	0.44	0.51	0.56	0.62	0.66	0.71
		0	0.30	0.40	0.48	0.54	0.59	0.64	0.69	0.73
		-5	0.35	0.44	0.51	0.57	0.62	0.67	0.71	0.74
		-10	0.39	0.47	0.54	0.60	0.64	0.69	0.73	0.76
		-15	0.42	0.50	0.57	0.62	0.66	0.71	0.74	0.77
		-20	0.45	0.53	0.59	0.64	0.68	0.72	0.76	0.79

Table 2: Minimum Insulation Ratios necessary to maintain the inboard surface temperature of exterior sheathing at the interior ambient dew point temperature for various interior RH and exterior temperature combinations and an interior ambient temperature of 72 degrees Fahrenheit. The orange and blue lines represent the IR for Climate Zones 1 and 2 and Climate Zones 3 and up, respectively. It should be noted that an interior RH between 20 and 30 percent is the ideal range for typical human thermal comfort as published in ASHRAE Standard 55.

The calculated minimum Insulation Ratios corresponding to the various prescribed energy code minimums and distributions are 0.28 for Climate Zones 1 and 2 and 0.37 for Climate Zones 3 and through 8. The ratios are delineated in Table 2 using orange and blue lines, respectively. The exterior temperature and RH combinations below these energy code minimum lines remain at risk for convective condensation on the exterior sheathing. For example, for a 5 degree Fahrenheit exterior temperature and 72 degree Fahrenheit and 35 percent RH interior conditions, a wall constructed in compliance with the Insulation Ratio corresponding to the energy code requirements (0.37 assuming Climate Zone 5) would be at significant risk for convective condensation given the calculated required minimum Insulation Ratio is 0.56.

While the codes require a ***minimum*** of R-13 insulation within the stud cavities, R-19 insulation is typically specified with 2x6 metal studs, which are more commonly used in commercial construction. Since the code provides minimum values, many designers assume more insulation is better; however, this would result in an Insulation Ratio of 0.21 for Climate Zones 1 and 2 and 0.28 for Climate Zones 3 and up. This shifts the colored lines further up in Table 2 resulting in more risk of condensation and/or elevated surface RH at the inboard face of the exterior sheathing.

Since Table 2 only considers thermal conduction, ratios that fall close to the minimum ratio may experience performance problems other than condensation. For example, ratios above the colored lines may result in an elevated surface RH (greater than 80 percent) that can promote microbial growth on certain sheathing facers without the development of liquid condensate. Conversely, slightly above minimum ratios (colored threshold lines in Table 2) may not develop condensation if the actual air leakage rate is low, since this table assumes sufficient air leakage to transport enough moisture from the indoor air to the exterior sheathing.

HYGROTHERMAL MODELING

WUFI Pro 5 (WUFI) is modeling software that can assess the response of a multi-layered system in terms of one-dimensional simultaneous heat and moisture transport. WUFI can model trends in the moisture content and wetting and drying cycles of each component in the system over a period of multiple years using historic climatic conditions for a given geographic location. The effects of air leakage can be modeled by the Fraunhofer IBP air exfiltration model which takes pressure difference due to stack effect and global building air leakage rates, which can be derived by blower door measurements, into account.

WUFI simulations were used to characterize the influence of air leakage rates and elevated surface RH on a prototype wall assembly in an example location (based on Künzel et al., 2012). The framed wall section shown in Figures 2 and 3 with oriented strand board (OSB) as the exterior sheathing was assumed to be oriented north in Chicago, Climate Zone 5. Further, 2x6 studs with R-19 batt insulation was modeled. The combination of the following conditions resulted in nearly 2,000 permutations simulated with WUFI:

- Continuous insulation R-Value from R5 to R20
- Interior RH during winter conditions from 25 to 60 percent
- Air tightness at 75 Pascals from 0 to 1 CFM/ft^2
- Interior vapor retarder: none, Class I, and Class II

The output data was analyzed and is conveyed in terms of ANSI/ASHRAE 160-2016 - *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 160). The main criterion is based on a mold growth model developed by (Viitanen et al., 2010) which has been validated on actual laboratory and field measurements on mold growth and takes the temperature, relative humidity, time, and substrate class into account. The main criterion defines index values of three (3) and above as unacceptable Mold Indexes in Section 6 of the ASHRAE 160 standard are as follows:

Index	Description of Growth
0	No Growth
1	Small amounts of mold on surface (microscope),initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, <10% coverage, or <50% coverage of mold (microscope)
4	Visual findings of mold on surface, 10%-50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 3. Mold Indices from "Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials".

RESULTS

WJE compiled the resulting Mold Growth Index (MGI) in conjunction with the Insulation Ratio to provide a more detailed assessment of the hygrothermal performance of code minimum R-Values in ASHRAE 90.1 and IECC. For example, Tables 4 and 5 illustrate the results, exemplarily for an R 7.5 continuous insulation, which yields an IR equal to 0.28 for the wall system with R19 stud cavity insulation. The tables show the predicted maximum mold growth index after a 10 year simulation on the interior surface of the OSB sheathing depending on the air leakage rate and the indoor winter relative humidity. The table also states the air leakage requirements according to several organizations: Phius (Passive House Institute), DOE NZE (Department of Energy, Net Zero Energy Building, U.S. GSA (General Service Administration) Level Tier 3, and IECC code requirements. Further results can be found in Tables A.1 through A.3 in Appendix A.

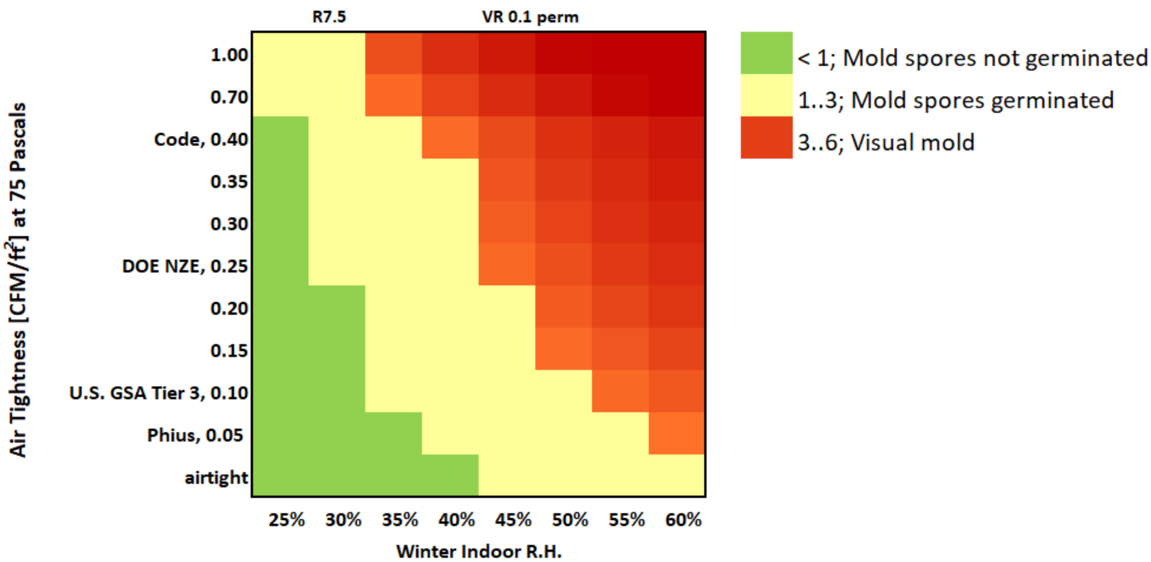


Table 4: Maximum MGI for variable air leakage rates and interior RH with a Class I vapor retarder.

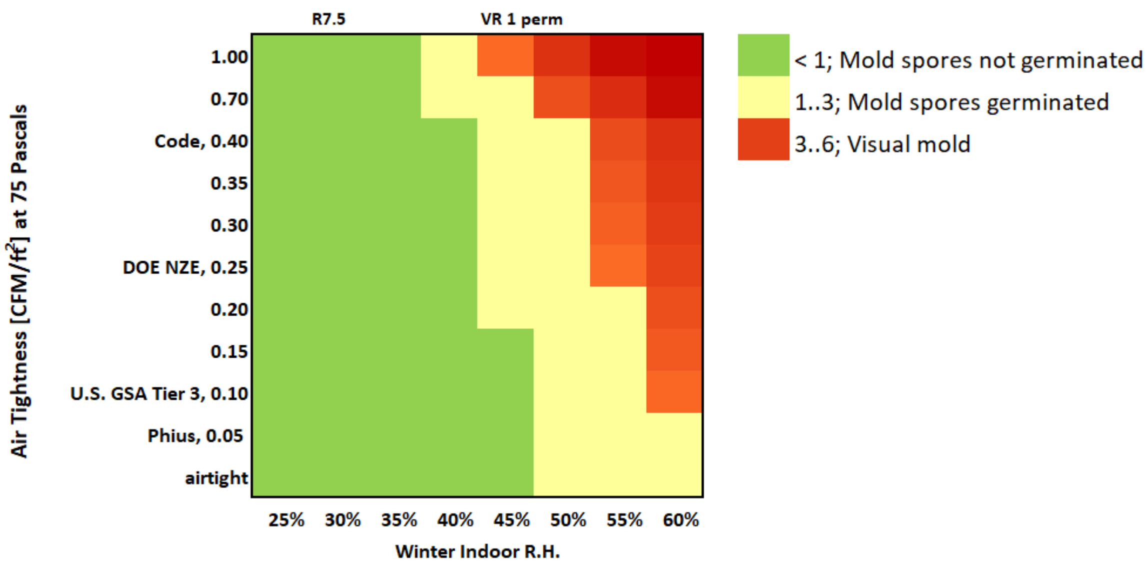


Table 5: Maximum MGI for variable air leakage rates and interior RH with a Class II vapor retarder.

All the diagrams show a similar basic and predictable behavior in that all wall assemblies at higher air tightness and lower indoor relative humidity in winter are at lower risk for development of mold (i.e., green colors in the lower left corner of the diagrams). Altering conditions toward the upper right corner of the diagrams, meaning lower air tightness and higher indoor relative humidity in winter, results in higher risk for development of mold which can be seen by the colors turning from yellow to orange.

It is obvious from the results in the Appendix A that an increasing R-value of the continuous insulation leads to better performing assemblies, which can be explained by the fact that the exterior sheathing will be at a higher temperature, hence a lower risk of condensation of indoor moisture.

Further, a Class II vapor retarder results in overall reduced risk for mold development in all of the permutations compared to no vapor retarder or a Class I vapor retarder. The study suggests that a Class II vapor retarder is the best compromise between vapor control in winter and drying accumulated moisture in the OSB sheathing back to the interior during summer conditions.

Finally, from the results in Appendix A, we can establish the following maximum indoor relative humidity listed in Table 6 for the example wall assembly in Climate Zone 5 assuming code compliant or better air tightness (0.4 CFM/ft^2 at75 Pascals) to achieve acceptable ASHRAE Standard 160 criterion.

Continuous Insulation	Vapor Retarder		
	None	Class II	Class I
R5	40%	45%	30%
R7.5	45%	50%	40%
R10	45%	55%	45%
R12.5	50%	55%	45%
R15	50%	60%	50%
R17.5	55%	60%	55%
R20	55%	60%	55%

Table 6: Recommended maximum indoor relative humidity for the simulated wall assembly with code compliant air tightness or better in Climate Zone 5.

CONCLUSIONS

Tables 4 and 5 show that even if the construction follows code and has even more continuous insulation as required, a hygrothermal safe performance is only predicted for low enough indoor R.H. in winter and low enough air leakage. As the title suggests, compliance with the energy code does not guarantee condensation- or mold-free wall performance.

Hygrothermal performance of wall assemblies is exceptionally complex; a function of numerous variables and assumptions. Thus, simplified empirical design guides may not provide prudent direction.

While this study focused on a single city in Climate Zone 5, additional simulations to include more geographic locations and prototype wall assemblies would provide a more encompassing design guideline for designers to comply with the current energy codes and avoid moisture accumulation and microbial growth due to condensation.

REFERENCES

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APPENDIX A: HYGROTHERMAL MODELING RESULTS

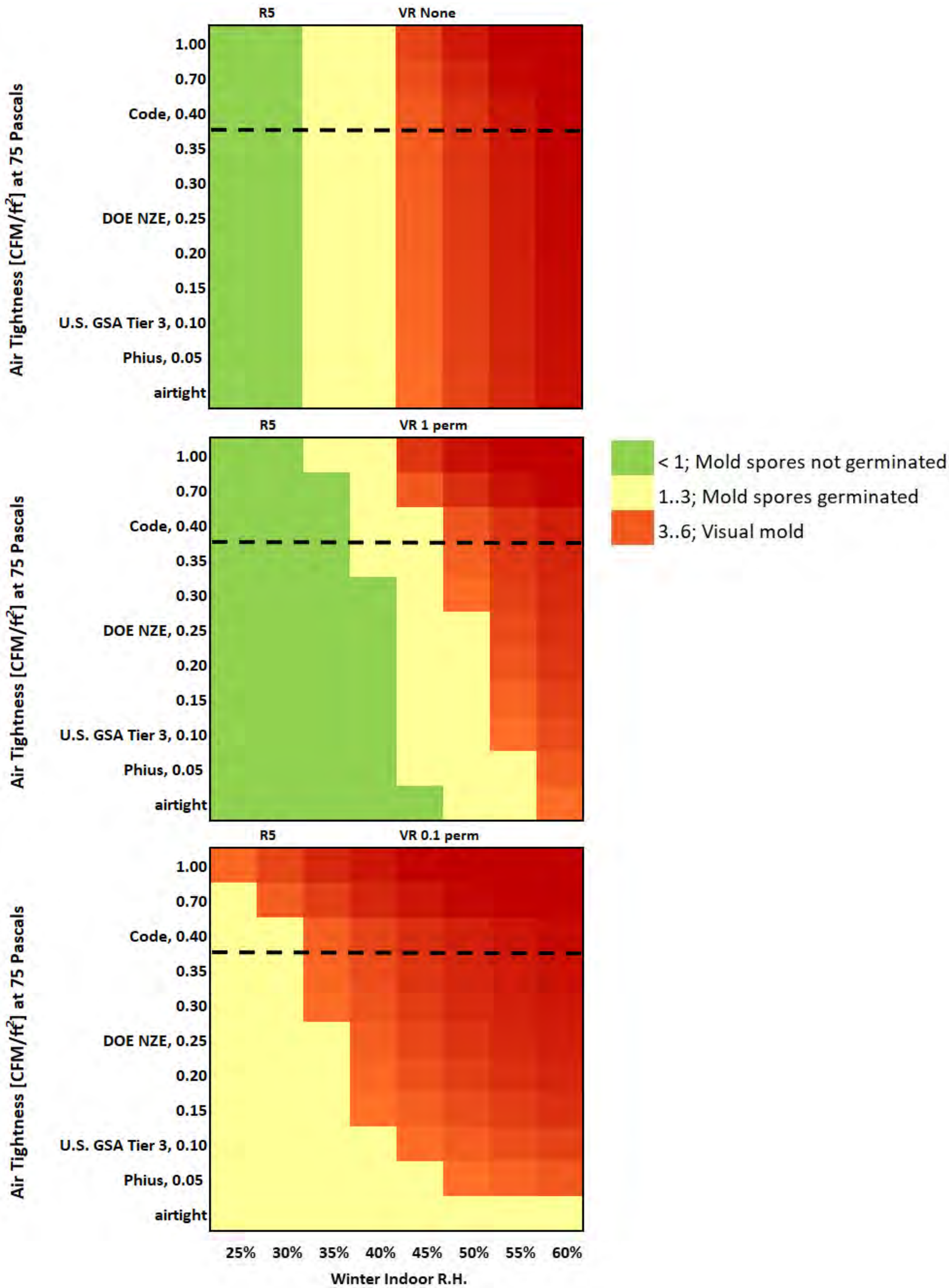

Table A.1: Maximum MGI for R-5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

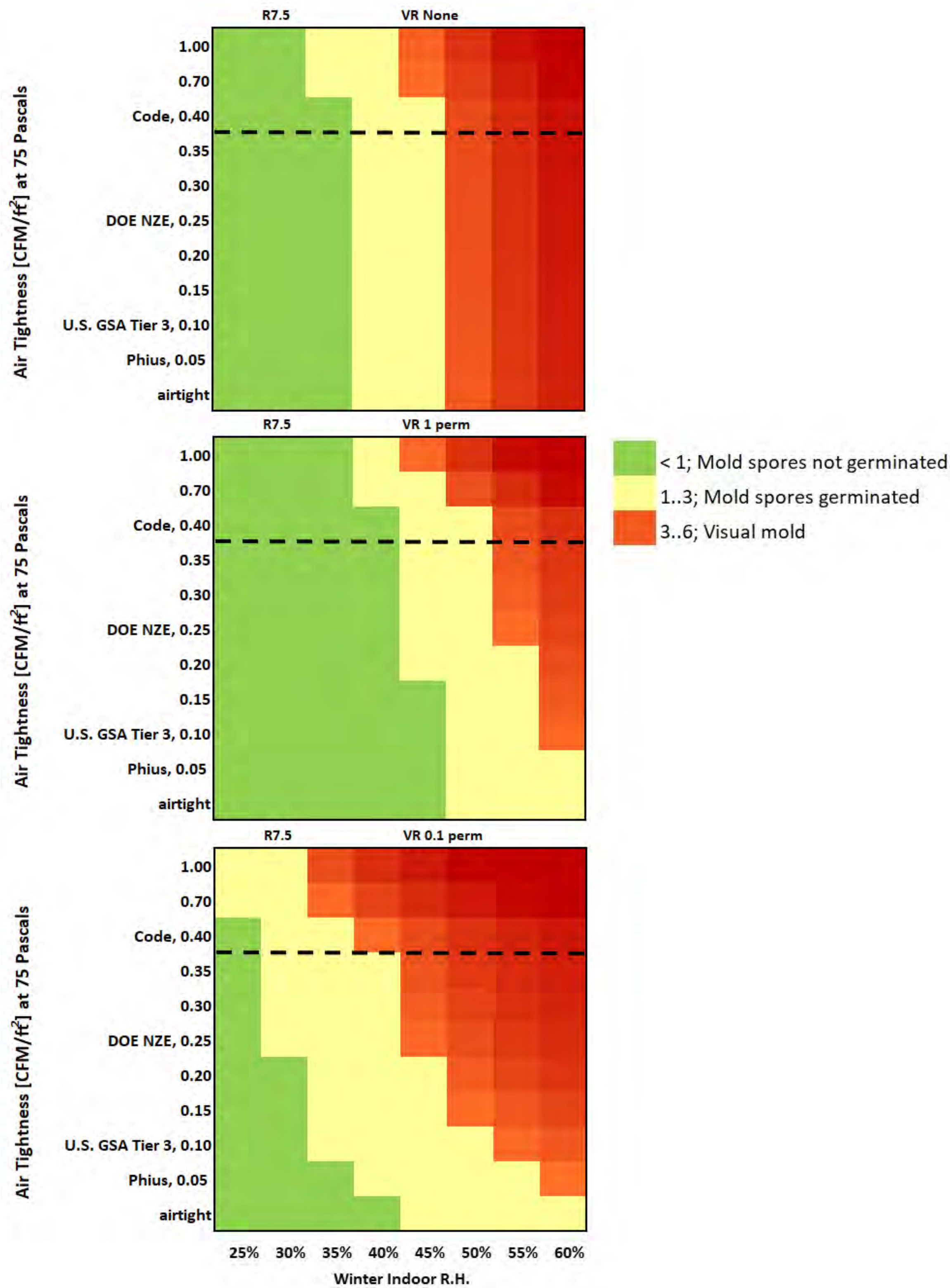

Table A.2: Maximum MGI for R-7.5 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

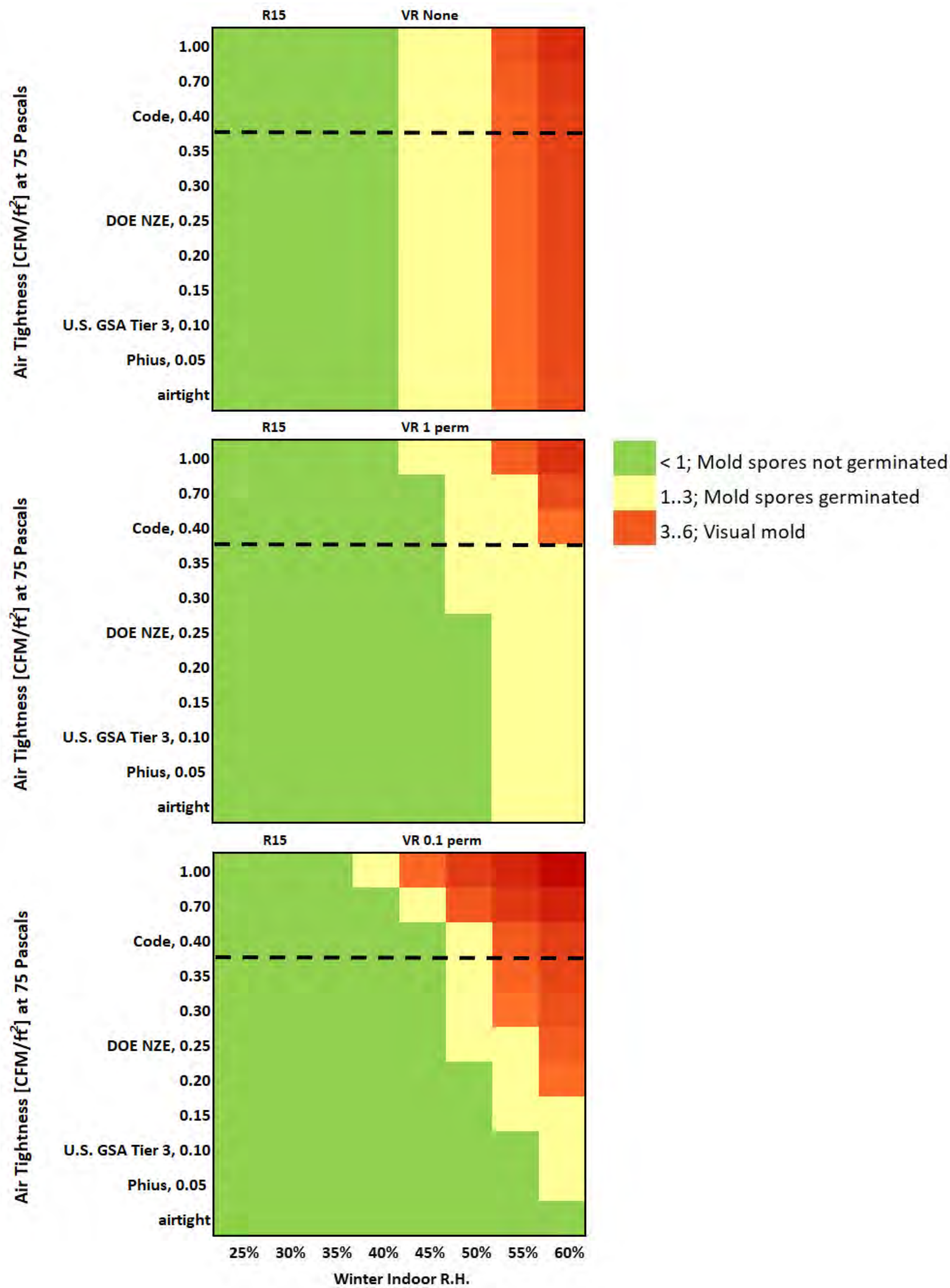

Table A.3: Maximum MGI for R-15 continuous insulation with (top) no vapor retarder, (middle) Class II vapor retarder, and (bottom) Class I vapor retarder.

Wall Upgrades for Deep Energy Savings in Residential Buildings: Interim Results from a Multi-Year Study

C.A. Antonopoulos,[1] C.E Metzger,[2] J.M Zhang,[3] M.C. Baechler,[4] A.O Desjarlais,[5] P. Huelman[6], and G. Mosiman[7]

[1] Senior Analyst, Energy & Environment Directorate, Pacific Northwest National Laboratory, Portland, OR, 97214. (503) 227-9933, chrissi.antonopoulos@pnnl.gov.
[2] Senior Engineer, Energy & Environment Directorate, Pacific Northwest National Laboratory, Portland OR, (503) 227-3099, cheryn.metzger@pnnl.gov.
[3] Senior Engineer, Energy & Environment Directorate, Pacific Northwest National Laboratory, Portland, OR, (503) 417-7573, j.zhang@pnnl.gov.
[4] Senior Project Manager, Energy & Environment Directorate, Pacific Northwest National Laboratory, Portland, OR, (503) 417-7553, michael.baechler@pnnl.gov.
[5] Program Manager, Building Envelope Research Program, Oak Ridge National Laboratory, Oak Ridge, TN (865) 574-0022. desjarlaisa@ornl.gov.
[6] Associate Extension Professor, Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN. (612) 624-1286, huelm001@umn.edu.
7 Research Fellow, Center for Sustainable Building Research, University of Minnesota, Minneapolis, MN. (612) 625-8409, mosi0091@umn.edu.

ABSTRACT

The Pacific Northwest National Laboratory, Oak Ridge National Laboratory and the University of Minnesota are conducting a three-year, multipart study on residential retrofit wall assemblies. The project is funded by the U.S. Department of Energy's Building Technology Office and will identify, test and verify wall assemblies for hygrothermal performance in retrofit applications. The study includes a comprehensive literature review and expert advisory group, which inform wall selection. Selected wall assemblies are then thermally simulated using EnergyPlus and THERM, and hygrothermally simulated using WUFI, to model both thermal and moisture performance of the wall assembly. Eight wall assemblies are then experimentally tested in an in-situ laboratory environment at the University of Minnesota, with a typical residential wall used as a baseline. The in-situ experiment looks at the physical hygrothermal performance of each assembly. The simulation and experimental results will be combined with an economic analysis to produce a techno-economic study of residential wall systems for deep energy retrofits.

This paper presents progress after year one of the study. Wall system modeling and laboratory testing is scheduled to begin in November, 2019. We will discuss the parameters for wall selection and experimental design, which includes approaches to modeling and simulation, along with the physical experiment design. This paper will also outline the parameters for the techno-economic analysis, and criteria used to inform model development.

INTRODUCTION

In the United States, 39% of total energy is consumed by the building sector, and 20% of that total by residential buildings (EIA 2018). New, high-performance homes incorporate a combination of tight building envelopes, mechanical ventilation, and efficient components to ensure comfort, adequate airflow and moisture control. These systems work together to create energy efficient homes that use specific measures to manage moisture and indoor pollutants. Older homes, built before energy code development, represent approximately 68% of the residential building stock in the country (USCB 2017), and often have significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills. Done correctly, deep energy retrofits (DERs) can significantly improve the energy performance of a home's thermal envelope, decreases indoor pollutants and increases homeowner comfort.

The U.S. Department of Energy's (DOE) Building Technology Office collaborates with stakeholders in the building industry to improve energy efficiency in new and existing buildings. The Residential Buildings Integration (RBI) program sponsors this research as part of a larger research portfolio aimed at reducing energy use intensity in residential buildings. This paper provides an overview of thermal and moisture performance of wall systems, summarizes wall system selection for in-situ experimentation, provides an overview of techno-economic approaches to investigate residential wall systems, and discusses thermal and hygrothermal modeling strategies. The Project team includes the Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL) and the University of Minnesota (UMN). The goal of this project is to determine the most optimal wall retrofit system according to the following criteria:

- Cost effective for the energy efficient benefit
- Moisture managed
- Can be applied to a large portion of existing walls in the cold climate

BACKGROUND ON THERMAL AND MOISTURE WALL PERFORMANCE

Hygrothermal building physics refers to the movement of both heat and moisture through building walls, influenced by material characteristics, material placement, climate, and ambient conditions. While the moisture issues and thermal performance of wall assemblies are essentially integrated, the focus of residential construction for decades has been on the thermal performance of building envelopes. Ignoring moisture issues has led to envelope failures in highly insulated homes (Figure 1), primarily caused by faulty construction or a lack of understanding of building science.

Figure 1. Moisture intrusion in the building envelope (Source: DOE Emerging Technologies Roadmap, 2019).

Fundamentally, heat and moisture movement are realized through different transport mechanisms but are not easily separated because they act in unison—moisture carries heat with it, and differences in temperature affect the way moisture moves. Thermal conduction, thermal convection, and thermal radiation are modes of heat transfer. Moisture transport occurs through bulk water movement, convection, or diffusion in a gaseous state, or by capillary transport in a liquid state. Traditional building construction allows moisture movement because natural materials such as stone and wood are permeable and porous. Energy efficient construction, which tightens envelopes using combinations of permeable and non-permeable air and vapor materials, may introduce moisture issues by limiting pathways for moisture transport. Less heat is lost through modern enclosures, which improves energy performance but may introduce moisture risks (Lstiburek 2008). Wall assembly failures almost always involve moisture (Little et al. 2015). Further, the presence of moisture increases the risk of deteriorating indoor air quality (IAQ) associated with increased humidity, which can lead to mold growth (Moon et al. 2014; Simonson et al. 2002; Bornehag et al. 2003). The traditional path to energy efficient envelope construction has been to increase the overall r-value of the wall and tighten the envelope to limit air movement. However, many have noted that this approach could introduce moisture and IAQ concerns (Straube & Smegal 2009; Tsongas 1993; Ueno 2015b). IAQ and moisture issues related to wall systems become a problem when wood framing is exposed to high moisture conditions, leading to fungal growth and potential decay. Mold and dampness in homes has been determined to increase the risks of respiratory illness, especially in children and other sensitive populations (WHO 2009). Mold growth is complicated and depends on both moisture content and temperature. Research has indicated that wood moisture content under 20%, regardless of temperature, will inhibit mold growth (Carll & Highley 1999). Moisture content of around 20–30% with temperatures ranging from 21–32°C is optimal for most decay fungal growth (Carll & Highley 1999). A study in the Pacific Northwest in the 1980s showed that although there was high moisture content and wetting in wood-framed residential wall assemblies, the winter temperatures were low enough to prohibit fungal growth (Tsongas 1985). The American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 160 aims to control moisture content in building design, sets a standard to minimize mold growth on building materials by “30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F)" (ASHRAE 2009). Studies have analyzed wall systems using ASHRAE 160 criteria, and found that simulated walls fail, even though physical monitoring indicated low risk (Arena et al. 2013; Ueno 2015a).

To mitigate moisture issues wall assemblies must be constructed in a manner that allows pathways for moisture transport out of the assembly, allowing the wall to dry to the interior and/or exterior when it gets wet. In terms of moisture performance, exterior drainage cavities and wall ventilation details should be considered in the overall assembly structure (Forest & Walker 1990; Straube et al. 2004; Ueno 2010b). Sometimes this construction detail is called a rainscreen, which refers to the combination of the siding, drainage plane, and moisture/air barrier. The location of ventilation openings and cladding materials both affect the hygrothermal performance of the wall system. One study found that closing the upper ventilation opening in a wall assembly with siding (rather than masonry) reduces the ventilation rate by 30% to 36%; and brick-veneer claddings reduce ventilation rates by up to two orders of magnitude (Langmans et al. 2015). Drainage cavities and wall ventilation details will minimize moisture risk with all cladding types by preventing wetting and providing ventilation to speed drying.

WALL SELECTION

As an initial step in the study, the research team invited experts from industry, academia, the national laboratories, and other research organizations to join an expert advisory committee and participate in an expert meeting to help identify and characterize candidate wall systems. The meeting was held on April 19, 2019, in Arlington Virginia. Thirty-three of the 35 experts invited were able to attend. The objective of this meeting was to bring together leading researchers and innovators to review the research methodology and to encourage suggestions, information sharing, and collaboration. Outcomes informed potential retrofit systems to be developed and tested. Specific topics that were discussed in detail include:

1. Data characterization for proposed wall selection
2. Wall selection for in-situ testing
3. Techno-economic study criteria.

The selection of the wall systems combines physical and techno-economic criteria. For example, some guidance from the expert meeting emphasized the benefits that are achieved by removing cladding before installing an insulation system. Other guidance suggested that it is important for the scalability of the insulation systems that they be easily added to non-energy home improvement projects, especially siding replacement. With this guidance in mind, the project team decided that both under-cladding and over-cladding insulation systems would be included.

Other priorities that came out of the expert meeting were based on a voting exercise where participants put stickers on what they thought was the most important criteria for a wall retrofit solution. The following criteria were voted as the top five, in order of importance to the experts:

- Air infiltration
- Constructability
- Cost
- Ease of control layer installation
- Time to install

After reviewing the input from the expert meeting, the project team held a series of meetings both internally and with DOE. In addition to the priorities that came out of the meeting, the team determined that the wall retrofit options chosen should also:

- be as widely applicable as possible to existing homes in the cold climate, which would make the total energy saving potential as large as possible for the project
- conduct research on wall systems that have not been studied in this way previously.

The last voting exercise of the expert meeting was to get an initial reaction from participants about the walls that they thought might be worth studying according to the criteria they voted on. The top five walls are listed below and were considered in the final wall selection:

- Exterior rigid insulation
- European panels
- InsoFast panels
- Minimally invasive cavity spray foam
- Nail base rips

Taking into consideration all the input from the relevant sources, the eight walls presented in Table 1 were selected for installation the in-situ facility at UMN.

Table 1. Details of selected walls

Baseline	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: empty Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint
Drill-and-fill	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: dense-pack cellulose Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint

Minimally invasive cavity spray foam	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: spray foam Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint
Exterior rigid insulation, existing cladding remains	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: empty Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint 2 or 3" Exterior rigid insulation Vinyl siding
Exterior rigid insulation, existing cladding removed	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: drill-and-fill dense-pack cellulose Sheathing: ¾" x 8" SPF boards Peel and stick air/moisture barrier 2 to 3" Exterior rigid insulation Vinyl siding
Vacuum vinyl siding, cladding removed	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: drill-and-fill dense-pack cellulose Sheathing: ¾" x 8" SPF boards Peel and stick air/moisture barrier Vacuum insulated panel vinyl siding
Mineral fiber on the exterior, existing siding remains	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: spray foam Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint Liquid applied air/moisture barrier 3 inches of rigid stone wool insulation board 1x4 furring strips Cement board siding
"Inspired by EnergieSprong" existing siding remains, (structural panel over the old wall).	Gypsum board with primer and two coats of oil-based paint 2x4 kiln dried SPF 16" o.c. Cavity: spray foam Sheathing: ¾" x 8" SPF boards Asphalt-impregnated building paper Bevel cedar siding with 4" exposure with primer and 2 coats oil-based paint Metal clips (borrowed from commercial building sector) 2x4 24" o.c. frame with EPDM gasket behind the studs with mineral fiber in cavity

	2” foil faced taped polyiso Vinyl siding

The baseline wall aims to represent the most common existing wall in the cold climate. According to ResStock, a national residential database maintained by NREL, this wall system should be wood framed and uninsulated. The other details are developed by the project team. Table 2 shows a common existing wall for the cold climate and how the team plans on transforming those layers into repeatable walls with readily available and consistent materials.

Table 2. Baseline wall

Layer	Typical 1950’s Era Wall	Wall Design for In-situ Testing
Interior coating	several costs of oil-based paint covered by latex paint	primer with 2 coats oil-based paint
Interior finish	lath & plaster	Drywall
Wall structure (2 x 4)	rough sawn DF[1] w/ empty cavity	kiln-dried SPF[2] w/ empty cavity
Sheathing	wide flat sawn 1” DF boards	3/4” x 8’’ SPF boards
Building paper	tar paper	asphalt-impregnated building paper
Siding	beveled redwood/cedar siding w/ 4” exposure	bevel cedar siding w/ 4” exposure
Exterior coating	oil-based lead paint covered by latex paint	primer with 2 coats oil-based (no lead) paint

[1]DF = Douglas fir
[2]SPF = Spruce-pine fir

EXPERIMENTAL PLAN

The experimental plan includes three phases: 1) the energy modeling, 2) moisture modeling, and 3) lab testing. In the first phase, PNNL will conduct energy models on eight wall systems, including a baseline wall. The energy models will include assumptions about all other aspects of the homes, based on data collected from the National Renewable Energy Laboratory’s (NREL’s) ResStock software. These simulations will focus on the energy savings that can be obtained for individual buildings. Large scale estimates of climate-wide or national-level energy savings will be made in the techno-economic analysis, which is a separate part of this study.

In the second phase, ORNL will develop moisture models for the eight wall systems under various indoor and outdoor temperature conditions. These moisture models will use material properties to model each wall system. Some assumptions will have to be made about the air leakage through each wall layer. Care will be taken to provide the model with realistic assumptions. After the field testing is complete, the moisture models will be calibrated using the experimental data.

In the third phase, a physical experiment will take place to test and validate the theoretical models. These experiments will take place over two years in the Cloquet Residential Research Facility (CRRF) owned by the University of Minnesota, located near Cloquet, Minnesota. This experimental plan focuses on the first year of experiments. With lessons learned from the first year, the experimental plan will be updated in about one year from when this is published.

Energy & Moisture Modeling

Laboratory and field evaluations of building envelope performance are expensive, and it is difficult to control environmental conditions, especially for multiple climates. Energy and hygrothermal modeling have been used by many studies for envelope performance evaluations. The research question of the current study specific to the modeling exercise include annual energy consumption and cost savings of the post-retrofit homes. The cost savings will become an input to the techno-economic study to evaluate the cost effectiveness of the retrofits. To capture annual energy cost savings for homes after the deep energy retrofits, whole building energy modeling (BEM) software EnergyPlus 9.0 will be used. They simulate whole building energy consumption using hourly modeling of thermal loads and HVAC systems. BEM tools account for all of the energy interactions between indoor space, outdoor environmental conditions, HVAC, lighting, service water heating, other appliances and equipment, and occupancy behavior. In such analyses, the energy flow through envelope elements such as the walls, roof, and windows, is treated as one-dimensional (1-D) and mass flow of moisture and air and phase changes of moisture are not well captured.

The residential prototypes represent the new construction stock and minimal compliance with the residential prescriptive and mandatory requirements in a few editions of the International Energy Conservation Code. Thus, to use the prototype models for the current study they need to be modified to represent the existing conditions. The inputs for these modifications are taken from the ResStock data published by NREL (Wilson et al. 2017), which is a large-scale housing stock database developed by combining public and private data sources, statistical sampling, and detailed building simulations. Further inputs are used from the Building America House Simulation Protocols (Wilson et al. 2014) to make the prototype models representative of the existing building stock. The Simulation Protocol provides specifications to facilitate accurate and consistent analysis of existing single-family and multifamily buildings. It provides information about the design assumptions, default values for components of existing houses, and a set of standard operating conditions.

A preliminary review of the ResStock Analysis Tool was done through communication with the developers at NREL. More detailed information about the existing building stock will be available to help with assumptions about baseline existing homes. The information on wall type, wall insulation level, and infiltration level will be used to modify the prototype model for baseline performance of existing homes at all representative U.S. climate locations. Other building stock information from ResStock regarding lighting, HVAC systems, and envelope components other than walls will also be used to modify the prototype model, but their inputs will remain the same in the post-retrofit models.

EnergyPlus calculates the building thermal zone loads by developing a heat balance model using different surface heat-transfer algorithms for conduction, convection, and radiation transfers through surfaces, and zone air heat balance algorithms for evaluating outdoor air, zone air, and system air heat transfers over specified timesteps. However, the fundamental assumption of these heat balance models is that air in a thermal zone is distributed with a uniform temperature throughout. EnergyPlus uses a simplified 1-D, parallel-path approach for conduction heat-transfer calculations through the building envelope that ignores the effects of thermal bridging. Thus, this study proposes the use of THERM, a 2-D conduction heat-transfer analysis program based on finite-element method developed by Lawrence Berkeley National Laboratory (LBNL). A THERM model is developed for the wall section selected for simulation and the overall U-value obtained from THERM is used as the equivalent U-value in EnergyPlus by adjusting the modeled insulation inputs. The equivalent U-value thus helps account for the significant thermal bridging effects occurring at the structural components of the wall, which are otherwise neglected in EnergyPlus. Ge and Baba (2015) used a similar approach to compare the energy performance of a low-rise residential building and concluded that this approach helps improve the accuracy of heating and cooling load predictions. Real et al. (2016) used this approach to study the effects of structural lightweight aggregate concrete on the reduction of thermal bridging effects in residential buildings.

EnergyPlus includes several different algorithms for modeling infiltration. The residential prototype models use the “Effective Leakage Area” model, which is based on Sherman and Grimsrud (1980) and is considered appropriate for low-rise residential buildings. In this model, the infiltration is specified by an effective leakage area at a 4 Pa pressure differential, wind and stack coefficients, and is a function of wind speed and temperature difference between the zone and the outside air. In addition to getting the infiltration model right, it is necessary to get the effective leakage area right to represent the conditions in the existing residential stock. These data are available in a tool developed by LBNL called Residential Diagnostics Database, which includes building envelope air leakage data from 147,000 U.S. single-family and multifamily houses (Chan et al. 2013).

The purpose of performing the hygrothermal modeling is to verify that the proposed energy efficiency retrofit measures do not create a durability issue. The use of transient hygrothermal models for moisture control is well established in the building industry in their codes, standards, and building insulation design principles and several building industry hygrothermal models have been developed and are available for commercial use. Building designs naturally shed the liquid water and attempt to minimize entry. They facilitate vapor transport so that moisture doesn’t accumulate within building envelope and prevent mold growth.

WUFI® is one of the commonly used building industry hygrothermal models and is one of the most advanced hygrothermal models for coupled mass and heat transport analysis. WUFI® is an acronym for Wärme Und Feuchte Instationär which, translated, means heat and moisture transiency. It is based on a state-of-the-art understanding of physics regarding sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is also well documented and has been validated by many comparisons between calculated and field performance data.

The transient calculation procedure of the models is as follows. The necessary input data include the composition of the examined component, its orientation and inclination, as well as the initial conditions and the time period of interest. The material parameters and the climatic conditions can be selected from the embedded databases or the actual data can be input if their hygrothermal properties have been measured.

Starting from the initial temperature and water content distributions in the component, the moisture and energy balance equations are solved for all time steps of the calculation period. The moisture balance includes the moisture retention curve, the liquid transport and the vapor diffusion, which are related to gradients in relative humidity and vapor pressure, respectively. The enthalpy of solid and moisture forms the storage of the energy balance. The energy flux consists of the thermal transmittance and the latent heat due to condensation and evaporation of moisture. The coupled transfer equations are solved numerically by an implicit finite volume scheme. The resulting output contains the calculated moisture and temperature distributions and the related fluxes for each time step. The results may be presented as animated moisture and temperature profiles over the cross section of the building component or as plots of the temporal evolution of the variables.

The model accounts for night sky radiation, as this can be an important thermal and moisture load in various climates around the world. This feature allows one to take into account surface wetting during the night. The model also contains algorithms for modeling the effect of wind-driven rain as a function of height. Finally, interior conditions of the can be fixed or can vary depending on time of year.

WUFI® version 6.2 will be employed to evaluate the moisture performance of the selected test walls. Weather data from the test site will be collected and used to create a weather file. Modeling data will then be compared to the measured data collected during the experimental phase for validation and comparison. In addition, typical moisture design year weather files will be used to estimate the durability in other northern climate zones.

Lab Testing

The Cloquet Residential Research Facility (CRRF), owned by the University of Minnesota and located near Cloquet, MN, was designed as a test bed to evaluate the long-term, cold-climate performance of full-scale building envelope components (Figure 2). The CRRF is a single story built on top a full basement. Different building systems and materials were used throughout the facility to allow for testing of various independent sections. The CRRF has a complete set of sensors to measure hygrothermal and energy transport performance of building envelopes including temperature, relative humidity, heat flux, in-situ R-value, barometric, differential and absolute pressure, moisture content, electrical energy and humidifier water consumption. Real time weather data is obtained from the Cloquet Forestry Center.

Development of the experimental plan regarding sensor types, placement, data collection methods and analytical methods are still in development.

Figure 2: Cloquet Residential Research Facility exterior and interior view.

TECHNO-ECONOMIC STUDY

A techno-economic analysis involves the study of a technology from both an engineering and an economic perspective. Many industries use such analyses, but depending on the application, the analytic method can vary significantly. It combines process modeling and engineering design with economic evaluation for a quantitative and qualitative understanding of the financial viability of an investment (Draycott et al. 2018). The techno-economic analysis parameters that will be used to analyze residential wall systems for DER are presented in Figure 2. The analysis is focused on the design, simulation, in situ testing, and economic evaluation of retrofit wall systems that will (1) develop moisture-durable, high-performance retrofit wall systems, and (2) identify and evaluate the economic performance and risk of chosen wall systems.

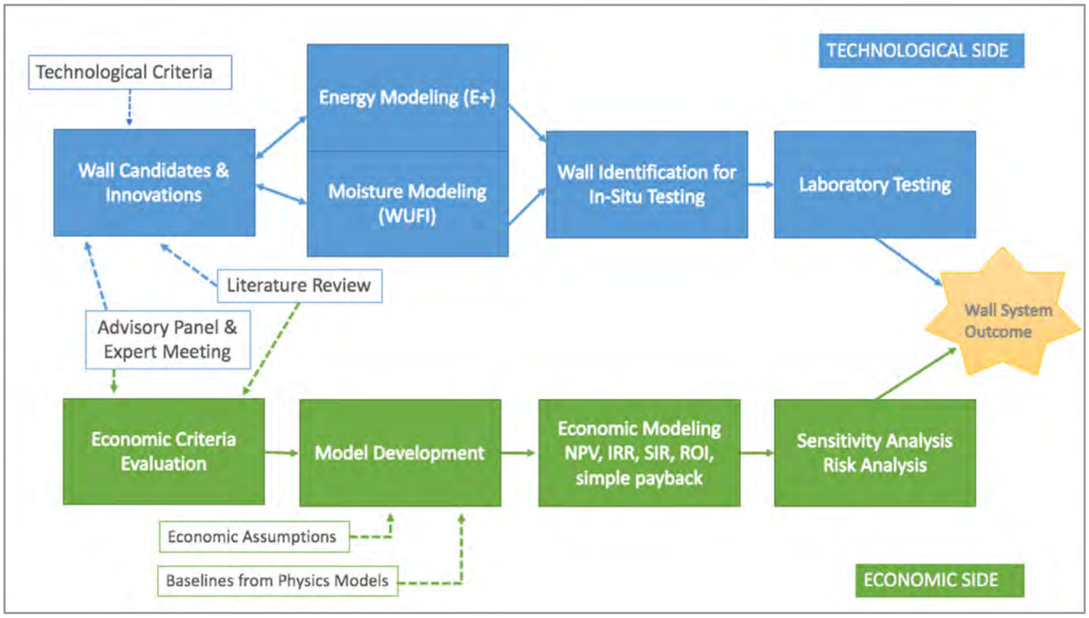

Figure 3. Techno-economic study flowchart.

Experts were asked to identify the most important criteria that should be considered as part of the economic assessment of each wall system to be tested. Each expert was given seven total votes and asked not to put more than one vote on a single category. The outcomes are reported in Table 3 in order of most votes to least. Techno-economic model development includes an activity to weight and rank each criteria; outcomes from the expert meeting will help inform this process.

Table 3. Techno-economic criteria voting outcome

Criteria	Description	Expert Meeting Votes
Air infiltration	Amount of air leakage measured by air changes per hour	23
Constructability	How "fool proof" is this assembly to install?	22
Cost/ ft^2 (Labor)	Labor cost	18
How easy are control layers to install?	Easy, Intermediate, Hard. Are they applied onsite or pre-fab?	16
Time to Install	How long does the assembly take to install?	14
Cost/ ft^2 (Materials)	Material cost	13
Service Life	How long is the expected life of this assembly?	13

Improved Disaster Resilience?	Does this wall system improve resistance to other risks (Includes earthquake, flood, pest, fire and wind.)?	11
Considerations for Roof/Foundations? (Easy, Medium, Hard)	Refers to roof/foundation intersections	10
Embodied Energy Measurement	Does the assembly have a LCA? Is there improved performance from a sustainability perspective?	10
Applicability to Existing Wall Type	Refers to the exterior material of the existing all (e.g. stucco, cedar shake, masonry, etc.).	8
Insulation R-Value (cavity, continuous or both)	Type of insulation and R-Value	8
Must Re-Install windows/doors?	Refers to the difficulty of addressing issues at the openings	7
Climate Adaptable?	Which climate zone would this be cost effective in? Do you see issues with this wall being in multiple climate zones?	5
Impact on Indoor Environment	Are components toxic? Will they have an impact on IAQ?	5
Is the Wall System Assembled on site, or pre manufactured?	Refers to entire wall assembly, including control layers	4
How disruptive is the retrofit approach?	Are there code barriers? Are there homeowner disruptions?	3
Low sound transmission	Does the assembly provide sound protection?	2
Removal of existing cladding required?	Does the cladding typically need to be removed to apply this retrofit?	1
Removal of existing sheathing required?	Does sheathing need to be removed before application?	1
Technical Readiness (TRL)	Early stage R&D, testing/data collection complete, or market ready. Is this a widely available material/technology?	0

CONCLUSION

PNNL, ORNL, and the University of Minnesota have completed the first year of a three-year study on retrofit wall systems in residential buildings. Primary activities during the first year included: engagement of thermal enclosure experts to inform wall selection, identification of the baseline wall, and treatment walls for testing, outline of parameters for hygrothermal modeling, and draft experimental plan have been completed. In year two, simulation and modeling will be complete, and physical experiments will begin. Parameters of the techno-economic analysis have been identified, and model development will also begin in year two. This paper discusses the progress after year one of study.

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Discussing Innovation in Residential Construction at the National Scale

F. E. Paige[1] A. P. McCoy[2], C. Martin[3]

[1]Assistant Professor, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 200 Patton Hall, Blacksburg, VA, 24060. (540) 231-5009, freddyp@vt.edu,

[2] Professor, Department of Building Construction, College of Architecture and Urban Studies/ Virginia Polytechnic Institute and State University, 430C Bishop-Favrao Hall, Blacksburg, VA, 24061. (540) 449-1861, apmccoy@vt.edu.

[3] Senior Fellow, Metropolitan Housing and Communities Policy Center, Urban Institute, 2100 M Street NW, Washington, DC, 20037. (202) 261-5649, cmartin@urban.org.

ABSTRACT

Nationally, energy efficiency goals are changing and to facilitate the execution of improved standards and practices conversations about federal agency's involvement are evolving. This study highlights a national housing workshop sponsored by Housing and Urban Development (HUD) which has begun the process of increasing communication and collaboration between federal and private housing stakeholders. Media, research, industry, and manufacturing stakeholders collaborated to discuss strategies for improving housing innovation in the United States specifically focused on innovation for housing affordability, sustainability, and resiliency. This paper outlines the process of facilitating this discussion and providing an opportunity for housing stakeholders to move beyond words to actions. Key problems and solutions such as data availability and federally moderated databases are presented to describe the plan for the United States towards a sustainable future in the residential building sector. By connecting workshop findings to systematic literature review data, further analysis of suggested solutions is provided in hopes of learning from past events and policies. The workshop discussed in this paper can and should be duplicated for years to come to create a more comprehensive understanding of contemporary issues in the sustainable buildings sector. As climate change impacts become more severe, the frequency of these strategic conversations will need to increase in response to natural disasters, energy scarcity, and affordability. Our technological advancements have outpaced the ability for our current socio-political infrastructure to deliver housing innovations. Through collaboration and strategic investment, the housing industry can catch up to other industries which use big data analytics and public private partnerships to shorten innovation cycles.

INTRODUCTION

For over fifty years, Housing and Urban Development (HUD) has been a federal agency in the United State of America operating to increase citizen home ownership and community development (*Civil Rights Act of 1968* 1968; "HUD Interactive Timeline" n.d.). Housing is a common need of all citizens of a country, but there is no one size fits all solution to meet all consumer housing demands in different contexts (Clapham 2009; Gann 1996). This phenomena creates a difficult situation for a centralized federal agency, such as HUD, who is tasked with distributing limited and fluctuating federal resources. Through policy, research, and strategic partnerships, HUD has been able to position the United States as global innovator in housing and community development.

Collaboration is an integral part of HUD's operation strategy (Martin and Paige 2018; Ross et al. 2016). The home is a hub for society to interface with energy, water, food, communication networks, and more. Federal agencies such as the Department of Energy (DOE), Department of Transportation (DOT), Environmental Protection Agency (EPA), and the Federal Communications Commission (FCC) collaborate with HUD to leverage housing infrastructure to serve society holistically. HUD also works with Community-based non-profits (CBNPs) to act as a decentralized front-line partners to multiply HUD's force in communities (Housing and Urban Development (HUD) n.d.). Managing collaboration requires strategy and resources which need to evolve over time. The internet has allowed for the development of HUD products such as HUD User which allows for HUD to exchange knowledge more efficiently than ever before.

Industry researchers, academics, and policy makers analyze housing data at local, regional, national, and international scales when developing and evaluating innovations. The volume of quantitative data in housing has expanded tremendously in the modern era of "big data"(Batty 2013; Davis et al. 2017; Glaeser et al. 2018; Gyourko and Saiz 2006; Han and Golparvar-Fard 2017) Transferring the data from local levels to the federal level and then back to the local level is a complex task. Data needs to be stored and communicated in an appropriate manner. While many housing stakeholders share a common mission, the goals, objectives, and inventive for housing innovation are split across the industry. To increase innovation in the housing industry, fragmentation cannot continue. The isolation of stakeholders and resources has shown to be counterproductive and new tools for collaboration exist which enable connectivity at lower levels of investment.

Globally, the case study methodology has been a critical tool for communicating local housing innovations (Dias et al. 2016; Hoxha et al. 2017; Lee et al. 2019; Mao et al. 2013). By publishing a case study, housing innovators are connecting a broader community of housing stakeholders to a rich understanding of a specific innovation. With a goal of examining the details of a contemporary phenomena, housing innovation case studies provide additional depth to large scale quantitative datasets (Yin 2017). The qualitative data presented in the context, and in some cases results section, of case studies help innovators better understand lived experiences, stakeholder perceptions, and cultural norms. Modern housing issues are socio-technical problems in which numerical process are not best suited to explore. Dollars and cents can represent a value of damage after a natural disaster, or the minimum income required to shelter a family in a city, but impact of a losing a home to an act of god or an act of economics is more than a number. By adding qualities to quantities, residential construction can fully utilize technological innovations.

Innovation has moved residential construction into a future where high quality homes can be built faster than mortgages can be closed (Lucy Wang 2016). Looking at housing qualitatively provides a deep understanding of many of the most important factors in residential construction, such as, human interactions with housing infrastructure, perceived affordability, and disaster response. The findings of case studies are limited in their ability to be generalized, but when combined, or evaluated by an expert, case studies provide a great value you to housing innovators working in differing contexts. By leveraging data, qualitative and quantitative, an increase in conversation and collaboration must occur to balance out technical and social innovations. Until homelessness, energy poverty, and inadequate housing are no longer issues, every dollar invested in housing innovation must be maximized. To maximize resources, quality conversations must occur where engineers, architects, policy makers, financial institutions, media, and most importantly residents all have the ability to communicate with each other.

Federal agencies like Housing and Urban Development (HUD) are comprised of relatively small and centralized groups of public servants who utilize political mechanisms to support a diverse and geographically spread population (Lutzenhiser 1994). Diversity and distance multiply the resources required for sustaining a national housing stock through economic, environmental, and social shifts. By recording the qualitative responses of housing stakeholders, housing scholars can re-engineer the housing industry to be more adaptable, agile, and effective. Housing needs to catch up to other industries such as manufacturing, computing, and health care which have all leveraged qualitative data to reinvent themselves in recent years.

Humans have always been the focal point of residential construction, but existing methods of connecting housing stakeholders are failing due to their age and capacity. Population growth, demographic diversification, and shifts in communication styles have left the housing industry in dire need for an update to traditional community engagement methods. Social media listening, usability studies, and persona development are a few examples of modern ways to understand housing stakeholders. Before the housing industry invests too heavily into modernizing, the fragmentation of housing stakeholders must be addressed to ensure growth is efficient and socially just. To begin this process, this study brought together a diverse set of 60 housing stakeholders for an in person meeting to begin outlining the blueprint for rebuilding the social and technical components of housing infrastructure.

MEHTODOLOGY

On March 28th, 2018, 62 housing stakeholders representing a variety of housing related professions such as, builders, manufactures, scholars, governmental agencies, service providers, press, and architecture, participated in an invite only discussion hosted by the Virginia Center for Housing Research and the Urban Institute to discuss the role federal agencies can play in improving housing innovation in the United States. The goal of the meeting was to discuss and record insights from varying positions in the housing industry. The invitees were invited to participate in a pre and post survey to allow the research team to capture information beyond the constrains of the workshop time. The pre survey data was used to inform the workshop protocol, and the post survey allowed for participants to add information which they would like to voice after experiencing the workshop. Representatives from HUD participated in the scholars and government agencies breakout section but were moderated carefully to ensure that the conversation in the room was balanced and honest. Moderators were all housing experts with academic and industry experience. Each breakout session had a dedicated note taker who recorded detailed notes on the discussion.

Driving questions:

- Why is innovation so critical for the residential construction industry?
- How are housing professionals impacted by innovation in the residential construction industry?
- What are specific enablers to innovation in the residential construction industry?
- What are the most important areas of innovation? How can HUD and other public agencies help expand the industrial capacity for innovation in residential construction?
- Which operational criteria are appropriate strategies for intervention in the housing industry's innovation pipeline?
- Is HUD the appropriate stakeholder to increase operational areas?

The notes from the breakout session were coded in NVivo. A first cycle of descriptive codes were generated, then in a second cycle of coding, patterns were developed across breakout sessions. The data is currently be recoded at the first cycle level using a versus coding process to evaluate the differences among participant groups to inform our policy analysis. In the results section which follows only the descriptive codes and pattern codes will be discussed. Over 197 statements were coded during the coding process for this study. 197 represents the current number of references in the dataset but the number fluctuates as the research team evaluates the findings. The length of qualitative codes varies by coder style and technique used. Given the variety of questions asked and respondents, the codes in this study were "chunked" highlighting a complete statement to provide context when looking at references code by code.

RESULTS & DISCUSSION

This paper highlights patterns found which focus on enablers and barriers for improving housing innovation which have the potential to transfer globally. Federal agencies, specifically HUD was the focus on participant's responses but the findings below transfer to contexts outside of HUD and the United States of America. Table 1. Provides an overview of the pattern codes and provides representative participant quotes. The following discussion provides insights on how stakeholders from a variety of background believe federal agencies should play a role in housing innovation.

Table 1. Selected Pattern Codes from Second Cycle Coding

Pattern Code	Example Participant Response
Regulations	*You have all these disaster funds coming in from different channels and dynamic situations with FEMA changing standards, it's almost changing on a daily basis.*
Consumer Demand	*We miss opportunities to really influence communities through portals that are already there [churches, schools, jobs].*
Return on Investment	*No metrics for writing green mortgages makes green mortgages too risky.*
Unintended Consequences	*Improving energy performance of building shell, increase 1" or 2" of foam, foam builder and window installer do not communicate how proper installation should look, no one takes responsibility.*

REGULATIONS

Regulations were discussed as both enablers and barriers to housing innovation. Federal agencies were considered by participants to be critical role players in the creation and execution of regulations. While many types of policies play a role in housing innovation (Lowe and Oreszczyn 2008; Martin 2015), regulations were described to be both general policies and specific building codes. HUD was specifically highlighted in its administration and control over the building codes related to premanufactured housing in the United States. Premanufactured housing and modular housing is gaining traction in the U.S. and in global markets, specifically with the purpose of developing affordable energy efficient housing (Steinhardt and Manley 2016). Premanufactured housing is also being considered for temporary or rapid response housing after natural disasters. Building codes focused on premanufactured housing must evolve to encourage the best housing product and not only the most affordable product. Workshop participants suggested for HUD and other federal agencies to look at the codes and regulations of other countries which have already faced the affordability and energy scarcity issues the United States is heading towards.

CONSUMER DEMANDS

Housing consumers need a basic standard of housing but also have strong “wants” in relation to their housing demands. The housing industry has a difficult time getting consumers to demand what is in their best interest. The fragmentation of the housing industry intensifies this barrier by stakeholders on the supply chain lacking coordination and integration. Education was suggested by workshop participants and HUD and other federal agencies play a large role in providing objective education and information to consumers. To improve the marketing of knowledge to consumers, workshop participants suggested for HUD and other federal partners to leverage churches, schools and jobs. One participant in particular provided insights from the telecom industry which connected to consumers by focusing on friends and family. Ensuring that consumers clearly understand the benefits and costs of technologies and housing innovations is very important for federal agencies.

RETURN ON INVESTMENT

Return on investment was considered to be a major barrier in which federal agencies must improve for housing stakeholders to continue to innovate. Specifically in the United States where electricity is not relatively expensive, the return on investment can difficult to justify for some high cost innovations (McCoy et al. 2015). Secondly, when builders or housing developers are investing, energy efficiency and resiliency outputs are difficult to evaluate. Traditional financial mechanisms do not appropriately incentivize investment in housing innovations. Currently, there have been recent changes to policies which are enabling early adopters to develop and deliver designs with competitive returns on investment. Globally, federal agencies need to update policies and processes to incentivize builders to build housing infrastructure that is affordable, energy efficient, and resilient. Risk is a major factor in residential housing innovation and until the return on investment is large enough, most housing stake holders will not gamble on housing innovations.

UNINTENDED CONSEQUENCES

Housing innovations are at mercy to the system they are created in. The fragmentation of the housing industry has established processes where housing innovations are created by specific stakeholders for specific contexts. While a product or strategy is designed with a specific goal in mind, many times a housing innovation is adapted and used in a variety of contexts with limited data and capacity for housing stakeholders to predict unintended consequences. Energy efficiency innovations were highlighted by workshop participants who discussed improper installations and incomparable innovations. Furthermore, placing responsibility and blame on specific stakeholders for unintended consequences is a difficult task in the United States housing industry. Many times unintended consequences do not present themselves as a major issue until well after construction. By the time an unintended consequence is identified, builders warranties have expired, specific stakeholders may have left the industry, and policies have changed. Federal agencies have the longitudinal stability to address these issues systematically. Where federal agencies lack capacity is in regards to the resources required to deal with unintended consequences. Especially in the realm of low-income housing where insurance companies and other financial partners provide limited help.

CONCLUSION

Federal agencies across the globe will have to adjust housing protocols to keep up with modern consumers and global issues. Climate change, energy scarcity, and the internet have forced many other industries to reinvent themselves and housing must adjust as well. In the United States, global examples of housing innovations must be considered and translated to meet the needs of American consumers who can now instantly access information about global housing offerings. Furthermore, population increases globally, and the urbanization of society will make current housing and public infrastructure systems obsolete. Communities are diversifying and cultural norms are no longer bound geographically. Builders and other housing stakeholders will be required to diversify their offerings all while dealing with housing affordability and ownership issues that are arising in current global economic conditions.

The participants of the workshop discussed in this study provide useful insights on some of the most critical enablers and barriers to innovation. While the discussion points, or pattern codes in this study are not new, the specific suggestions for federal agencies. The processes and operational capacity of federal agencies are currently under investigation by the research team but at this point it is clear that federal agencies must continue to collaborate and also improve their digital infrastructure. Objective, easy to access and understand information about housing innovations must be hosted by federal agencies to allow fragmented stakeholders to work together. Federal agencies in the United States have access to resources which uniquely position them with an advantage over local level agencies and even global housing companies to be data distributors. When an issue occurs in one sector of residential construction, the rest of the industry should be alerted and empowered to avoid the same issue. Furthermore, when an innovative product or strategy is developed, housing stakeholders, especially consumers, should be alerted and empowered to take full advantage of our industries success.

Fragmentation, scale, and competing interests have existed in housing and many other industries for decades but now is the time where housing must evolve to meet a societal need. The conversation discussed in this paper was considered to be a success by HUD and further conversations are occurring. HUD is leveraging its positioning to bring stakeholders together face to face and digitally using their HUD User platform. While existing communication channels have existed for the housing industry, they are being adapted and evolved to focus on how to improve housing innovation holistically. Previous attempts at collaboration clearly show our industries fragmentation and competitiveness which will continue to exist but must be moderated by powerful objective parties like HUD and other federal agencies who can force and incentivize collaboration.

Future conversations will replicate and improve the protocol used in this study. A limitation of this study was its scale. A larger group of housing stakeholders must be analyzed to understand the full picture of housing in a nation as large as the United States of America. Also, international perspectives were not included in the scope of this project. International thoughts were brought in by workshop participants with international experience, but the focus of this study was on domestic stakeholders who currently work in the United States. As stated previously, housing is a global issue in which global perspectives much be leveraged. When considering international perspectives, the protocols for this study will need to evolve to ensure that the context of participant contributions are fully understood. The structure of housing infrastructure delivery systems varies drastically from country to country.

The findings reported in this study were specifically selected for their ability to be transferred from country to country. Future reports from this workshop will report out specifics which can be evaluated by global experts on their applicability for their context. Suggestions for how HUD and other federal agencies in the United States can improve housing innovation to deal with disaster response, healthy housing, affordable housing, and energy efficiency were all discovered as a part of this study further providing evidence for the replication of this study in other countries who seek to develop suggestions for their federal agencies.

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Building Industry: Trends in Sustainability and Building Science Applications

D. J. Gerring[1] and R. A. Wozniak[2]

[1]Associate Professor, Architecture, Pennsylvania College of Technology, One College Avenue, Williamsport, PA 17754. 570-320-2400x7015, dgerring@pct.edu.
[2]Associate Professor, Architecture, Pennsylvania College of Technology, One College Avenue, Williamsport, PA 17754. 570-320-2400x7131, rwozniak@pct.edu.

ABSTRACT

This study was done to help identify how the building industry is learning about issues related to sustainability and building science. Interviews were completed in the fall of 2019 by students enrolled at Pennsylvania College of Technology of 23 alumni concerning where they are currently working. The firms were diverse, representing a broad sector of the design and construction industry, many located in Pennsylvania. The major findings were that firms rely heavily on industry publications and material suppliers to stay up-to-date. Firms are working to improve standard details for performance but 26% are not addressing achieving a continuous thermal envelope. Firms that are doing energy modeling are hiring consultants for this work (87%). The greatest challenges for the future were identified as costs and sustainability. The study shows that there is still a gap in the industry for application of building science performance issues and in fully understanding sustainability issues in a way that proves their value.

INTRODUCTION

This study was done to get an idea of how architectural and building industry firms are adapting to increases in required base code performance as well as the increased use of voluntary rating standards such as 2030 Challenge (2030 Challenge - Architecture 2030, n.d.) and US Green Building Council's Leadership in Energy and Environmental Design (LEED) (United States Green Building Council, n.d.). Designing these high-performance buildings requires a change in detailing and possibly materials. We wanted to know how firms are adapting to these standards, how they are learning about industry changes, and what they are doing to apply practices for integrated design, building performance simulation, and updating detailing.

METHODS

This study was completed by calling and interviewing past graduates from the Pennsylvania College of Technology Architecture program and asking them questions about the practices of the current firm they working for. Graduates were selected from the list of alumni that was provided by the institution. The alumni list includes graduates from 1966-2019. There was an initial email sent to all alumni with email addresses asking them basic questions about their firm and if they were

interested in participating in the study. These respondents were included in the study as were additional graduates who were called using the alumni list.
Interviews were conducted by 7th semester students enrolled in BSD432, Architectural Design Studio VI. Each student was supposed to complete 2 interviews. There were 27 survey questions and interviews lasted between 45-60 minutes. The 27 questions focused on how firms are adapting to changing requirements in building codes, and application of building science performance and sustainable practices.

23 interviews were completed by phone between August 19 and September 13, 2019. Students recorded notes from their interviews and then split up the responses by question for analysis. Students each analyzed 2 of the question responses.

Responses from each question were correlated and analyzed for trends. Students made charts and graphs to summarize the data. If an individual's response was particularly interesting or different from others then those statements were included with the question results.

RESULTS

What did you find

- Report on data collection and/or recruitment
- Participants (demographic, clinical condition, etc.)
- Present key findings with respect to the central research question
- Secondary findings (secondary outcomes, subgroup analyses, etc.)

The first set of data results describes the major attributes of the firm whom the respondent worked for. This covers the size and location of the firm, the kinds of services and projects the firm specializes in, and general project costs and locations.

The makeup of the 23 firms surveyed was diverse (see Figure 1). 10 (43%) had fewer than 25 employees and 13 (57%) had more than 25 employees. 10 of the firms had multiple locations. Most of these firms were located in Pennsylvania but included large firms with offices worldwide. There is a variety in size and cost of the projects these firms do. These projects can range anywhere from about $5,000 to $100,000,000 and 750 square feet to 300,000,000 square feet.

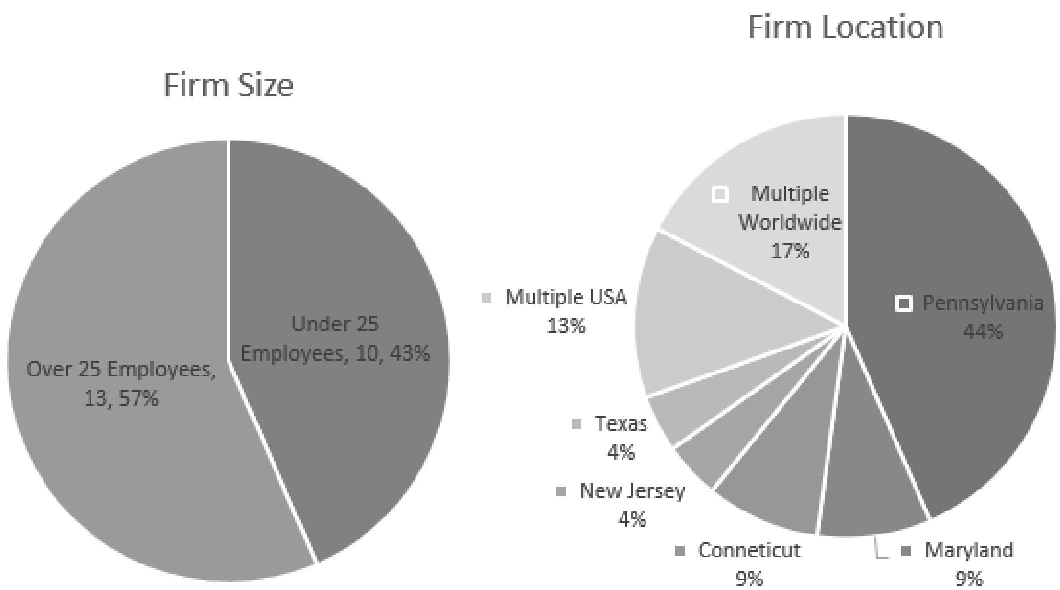

Figure 1. Demographics about the firms participating in the survey

Many of the firms provided multiple services which included general architectural practice, engineering, urban planning, space planning, building commissioning and sustainability consulting. The services graph (Figure 2) contains more than 23 responses due to interviewees identifying more than one service.

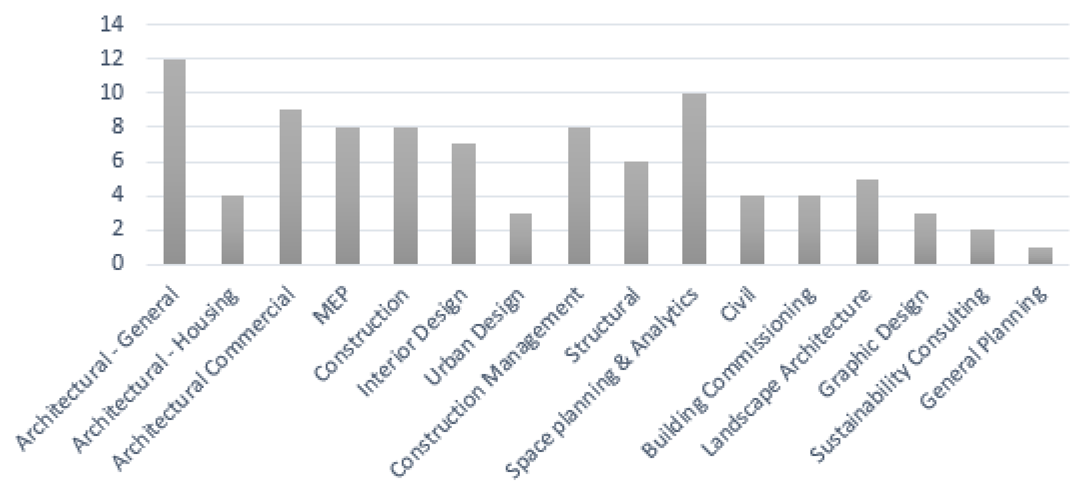

Figure 2. A summary of the types of services offered by the firms in the survey.

The firms worked on a variety of project types (Figure 3). If a firm indicated more than one project type then that response was counted as mixed. This figure also shows the percentages of new construction vs. existing building shell fit-out and renovation done in each firm.

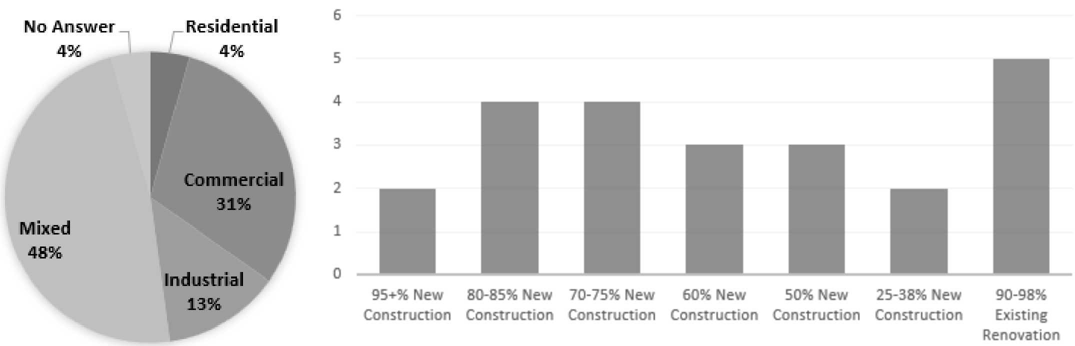

Figure 3. Types of projects and their mix of new/existing construction.

The projects done by these firms are located in a variety of climate zones (Figure 4). 15 (63%) of the firms interviewed work on projects in temperate zones, with most locations in Pennsylvania. 6 (25%) have projects located in all types of climate zones, ranging from the Unites States to parts of Europe and Asia. 3 (13%) have buildings in cold climates, and another 3 (13%) have buildings in hot/humid climates. 2 (8%) of the firms just have projects in a hot/arid climate. Most of these projects have been completed in usual jurisdictions for those areas: only 11 (46%) of the firms had worked on historical buildings or in a historical district.

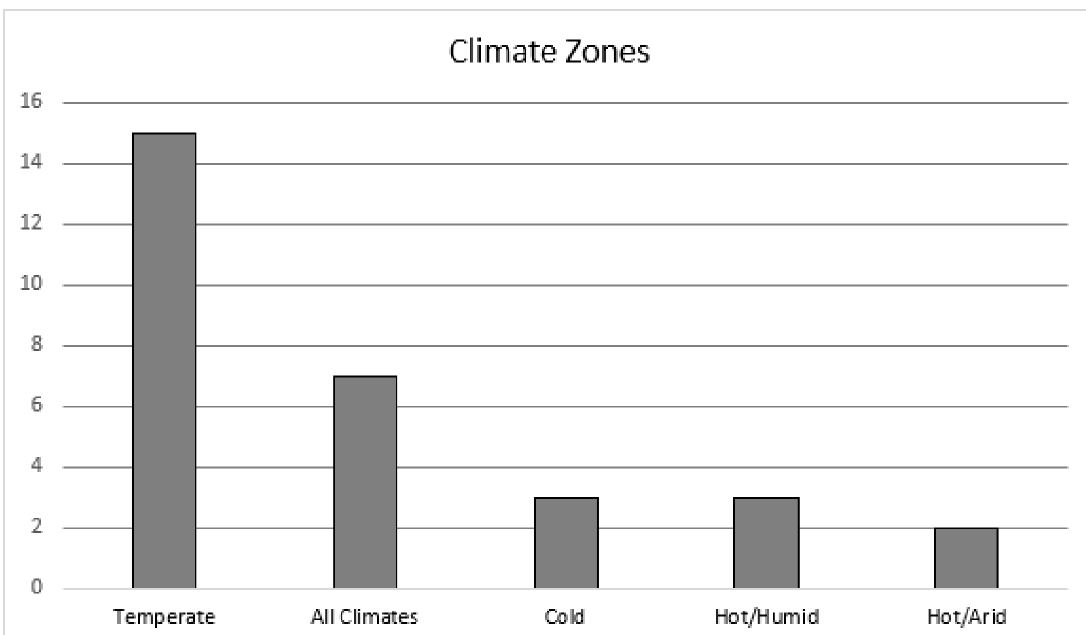

Figure 4. Firm identification of the climates their projects are built in.

This completes the summary of questions based on general firm information. The next questions are about how the firm keeps abreast of changes and how those get updated into standard details and specifications.

The question of "How does your firm approach learning about changes in the building industry?" shows that firms rely heavily on newsletters and industry publications as well as internal information sharing (Figure 5). The majority of the firms are actively working to find out what is changing. Surprisingly 3 firms said they didn't do any research. The other 20 firms used a variety of methods so there are more than 23 answers in the chart. It is interesting that 11 (46%) of the firms had regular presentations done in-house sharing staff research and projects. Interesting comments included: "we hire a lot of younger people", "we have people seeking Passive House certification", "we have our own university to focus on education—goal courses and internal education with our own trainers".

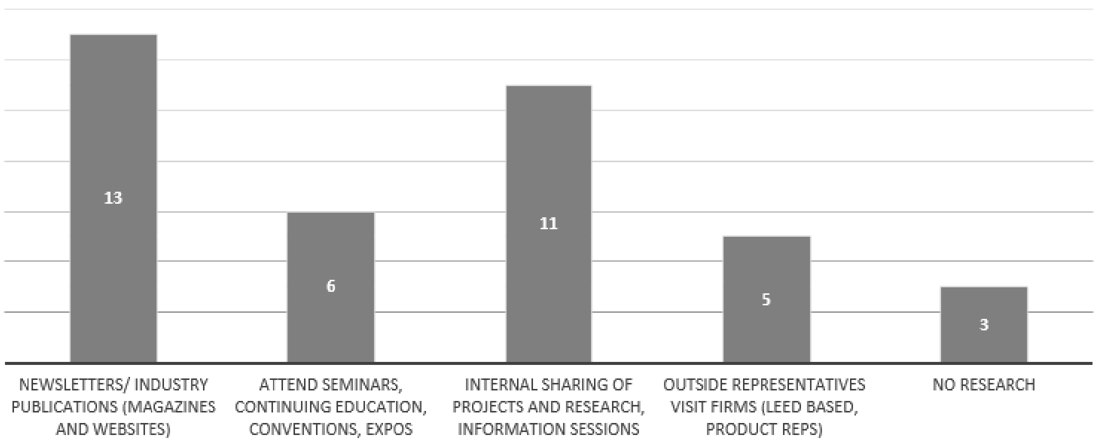

Figure 5. How firms are learning about changes in the building industry.

The follow-up question to how firms are learning about changes was "How does the firm keep employees abreast of industry changes?" (Figure 6). These responses correlate with those from Figure 5, showing a reliance on product representatives (16) to update employees about materials. The second most important method is the use of conferences, workshops, seminars and on-line training (10). Note that most respondents listed more than one method so the overall numbers add up to more than 23. Interesting comments included: "I don't know that there are any things other than being told we are doing something differently", "courses offered at local community colleges", "we have internal educational programs and are highly encouraged to sign up for educational seminars", "company newsletters", "must take vacation days to attend conferences", "we require employees to attend education for basic technologies". Conferences and groups listed included: AIA (American Institute of Architects, n.d.), CSI (Construction Specifications Institute, n.d.), Masonry Seminars, Code Seminars, ICSC (International Council of Shopping Centers, n.d.), Autodesk University (Autodesk University, n.d.), USGBC (United States Green Building Council, n.d.), Passive House (Passive House Institute US, n.d.), The Society for College and University Planners (The Society for Colleges and University Planners, n.d.), American Society of Landscape Architects (American Society of Landscape Architects, n.d.), NCARB (National Council of Architectural Registration Boards, n.d.), Southeastern Association of Housing Officers (Southeastern Association of Housing Officers, n.d.), Emerging Leaders United (Emerging Leaders United, n.d.).

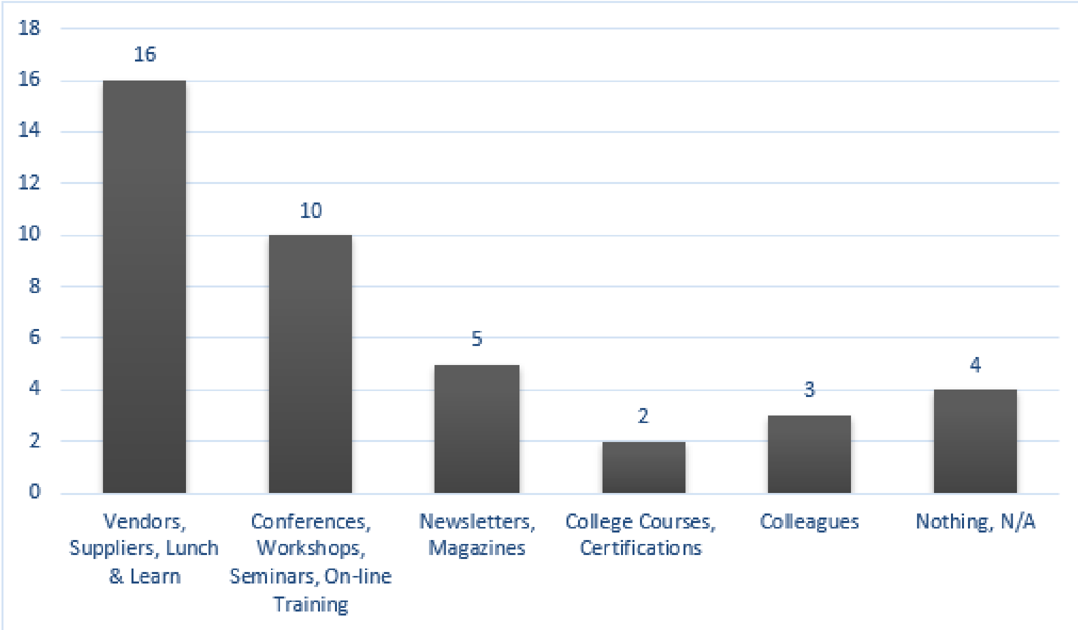

Figure 6. Methods used to keep employees abreast of industry changes.

The results of "How does your firm update standard details and specifications as building performance increases?" shows a wide variation. 5 (21%) of respondents were not sure or didn't answer the question. Several firms make changes as required per codes or city standards. Several mention that they consult manufacturers to update details and specifications. Several maintain reference libraries of details and standard templates. Several mention that designated specification writers and teams keep standards up to date. Several mentioned that they go to seminars and lectures, research, rely on individual experience, and follow building checklists. Interesting comments include: "Our company has always been ahead of the game for the past 12 years. Our company has set our own bar higher than the standard that is just now catching up to us.", "Most of our projects now try to aim to meet LEED certification or if we don't plan on using LEED we still are required to track our waste and electrical in a program called Footprint.", "They do not do that (Laughs Hysterically)", "Dependent on the new building material. Depends on the client wants to use. Adapts as needed.", "Studying prints from local architects and mechanical engineers to see what trends and new technology are being used.". Professional software mentioned include Vertex, Revit, MasterSpec, and Footprint.

This completes the group of questions addressing how firms are staying up-to-date with training, industry trends, and how they update their standard details and specifications. The next set of questions addresses the use of performance and rating standards.

Figure 7 shows the target for firms to meet or exceed the base energy code. 12 (52%) exceed base energy code requirements followed by 7 (31%) not exceeding base energy code. Interesting comments include: "Will mostly design to code and nothing more. Clients come for architecture not efficiency. Company is trying to incorporate efficient design but is having trouble."; "We always keep sustainability in mind when designing, however, since we work for public funded companies, the funds are not always available for them to take our suggestions into consideration."; "We have been doing sustainable design since the 80's, implementing passive systems, orientation, building envelope, energy modeling, type/density of insulation, try to get the best value without overdesigning, basic concepts that make a building more efficient."; "We strive to achieved LEED silver standards on all projects, even if the client chooses to not get the certifications."

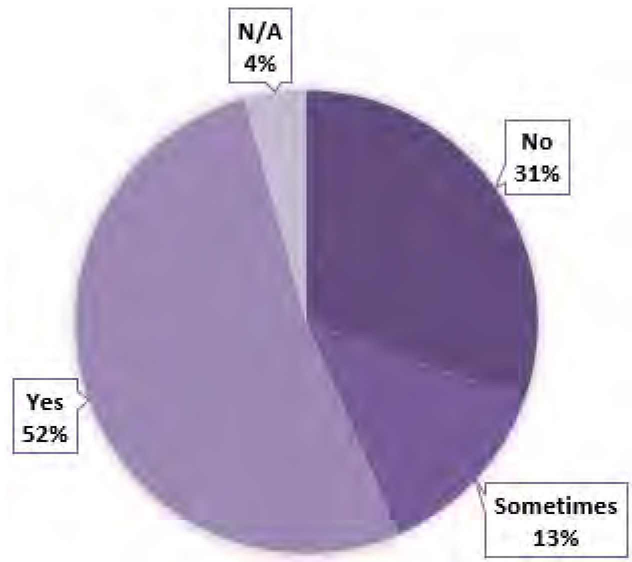

Figure 7. Firm Target for Energy Code.

Of the 23 firms only 5 (22%) are committed to regularly using a performance or rating standard such as the 2030 Challenge (Figure 8). 2030 Challenge (2030 Challenge - Architecture 2030, n.d.), Passive House (Passive House Institute US, n.d.), Hyatt Thrive (Hyatt Thrive, n.d.), JUST (JUST Architecture, n.d.), Well Building (International WELL Building Institute, n.d.), and Living Building Challenge (Living Building Challenge, n.d.) were each mentioned once. LEED was mentioned 3 times. Interesting comments include: "We had discussed this option multiple times and have concluded that we have no commitment to the 2030 challenge."; "we ourselves cannot fully commit. It depends on the client, but we always try to give a design option with sustainability involved to try and 'sway' the client."

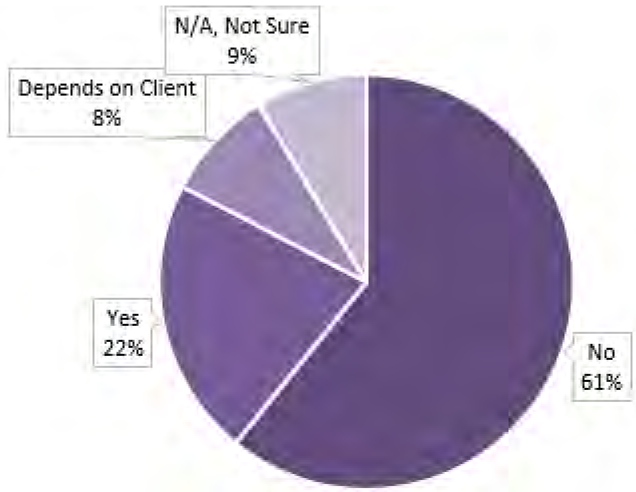

Figure 8. Firm is Committed to using a Rating System.

This concludes the section on performance and rating systems. The last set of questions are concerning how firms are updating their projects to meet or exceed code and their use of detailing for thermal barrier, air barrier, moisture migration and energy modeling.

The question concerning how firms have changed their detailing and specification of materials due to increased thermal air barrier requirements had similarities in responses based around approaches (Figure 9). 13 firms (56%) indicated that they were using more insulated building materials, had updated and changed their details, and generally were attempting to achieve continuous insulation and better taped barriers. 3 firms (13%) based details on climate issues, project concerns and client needs. The remainder meet compliance, were unsure/unknown, or not applicable to their firm. People mentioned the use of structural insulated panels (SIPS) construction, fluid applied water restive barrier (WRB), taped joints on exterior substrates, and tighter seals around windows and other openings. Interesting statements: “Our details are more advanced than they used to be.”, “We are hyper focused on these systems.”, “Buildings today are more sophisticated, take more care when designing envelopes, have to pay more attention to their detail so they update their details constantly, but these components specifically have changed quite a bit as energy codes have become more strict.”, “We have designated employees who deal with specification of materials”.

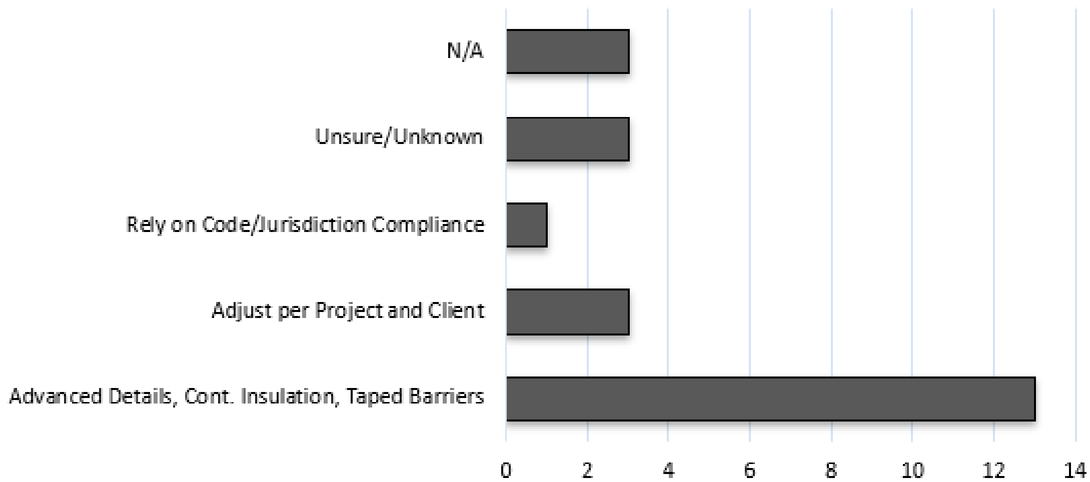

Figure 9. How firms have changed detailing/specification of materials due to increased thermal and air barrier requirements.

Another question asked about different detailing in the firm's detail library based on climate zone the project is located in. 7 firms said yes and another 3 said the library was lacking so individuals had to take the base detail and change it to meet the climate. 5 firms build in the same climate and don't need to adjust details. Another 5 provided just a no answer. 1 was unknown and 1 outsourced their details.

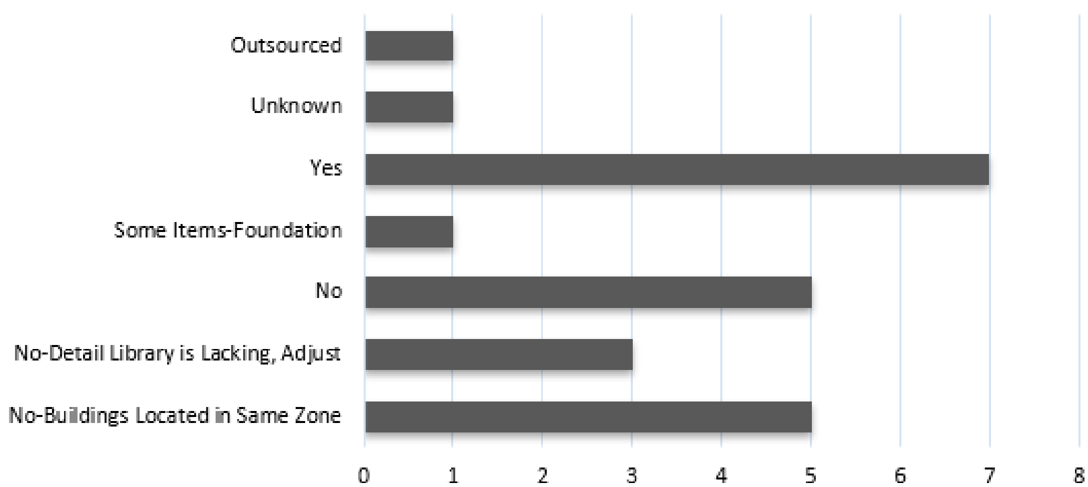

Figure 10. If the firm's detail library includes different detailing depending on climate zone.

Figure 11 summarizes the responses to the question about is the firm providing a consistent thermal envelope with minimal thermal bridging. 13 (57%) firms stated they did. 6 (26%) firms said they did in particular circumstances such as in floor heating with slab on grade, when obtaining LEED certification, or when have particular building features such as a walkout basement. 1 response each for no and unknown as well as 2 for N/A due to the types of projects the firm completes. Interesting comments: "Sometimes, if clients ask for it.", "Not as much as they'd like to. Still not standard in every design. Actively working to improve.", "Yes, but depends on the project. Work with consultants about details."

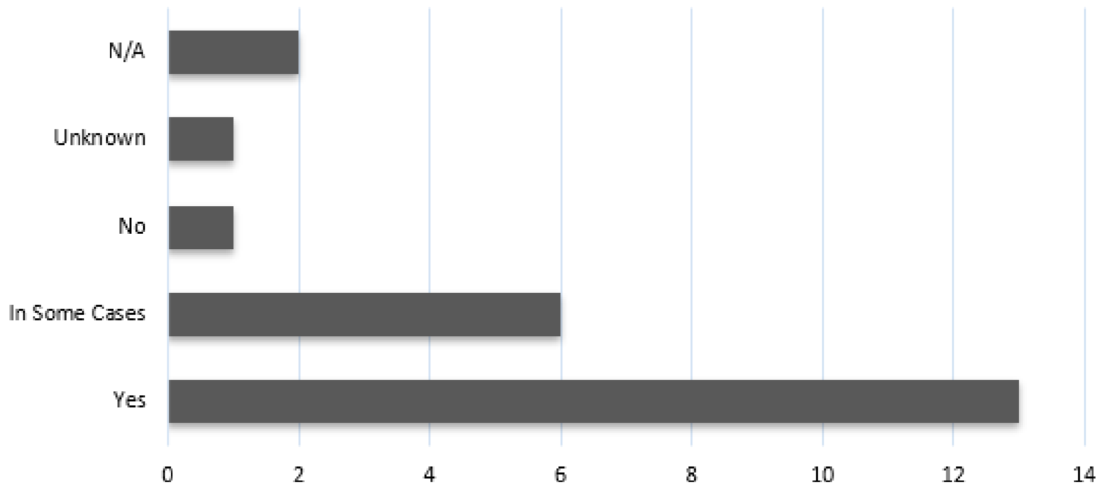

Figure 11. Is firm providing a consistent thermal envelope (including under slab insulation) with minimal thermal bridging?

Only 1 respondent described that their firm was using a combination of details and specification language to achieve air tightness. 1 respondent said they were using air barrier tapes to achieve air tightness.

The responses for "Do you work with a consultant to provide energy modeling/testing?" are shown in Figure 12. There were a total of 13 (57%) that use consultants for modeling and testing. Of those, 11 (48%) hire out consultants while 2 have these services in-house. Consultants and methods mentioned: HERS rater = 1, blower door testing = 3, HVAC = 1, LEED = 1, 3rd party commissioning agent = 2, thermal imaging = 1. There were 2 responses that said they only used modeling if there was a budget for it or it was necessary for project certification.

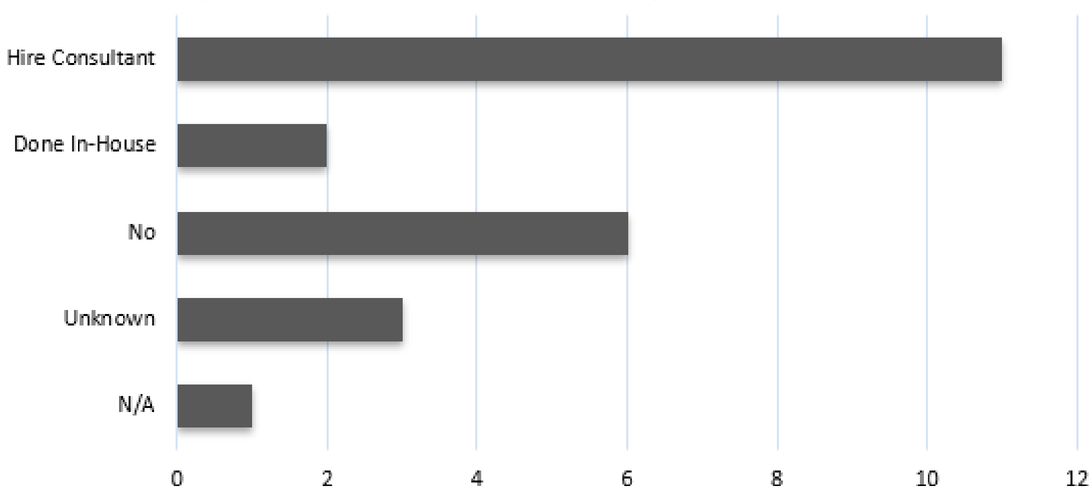

Figure 12. Does firm work with a consultant to provide energy modeling/testing?

Responses for "How are you detailing to allow wall assembly to dry out?" were widely varied (Figure 13). 7 were either N/A or Unknown. 2 hired consultants, 2 followed best industry practices, 4 use an air cavity with weep holes, and 3 use rainscreens (air space and water/vapor barrier). There were 5 other responses which included: "Because our medical buildings experience moisture from both sides of the wall, we use 'blue skin'." (a self-adhering vapor permeable air barrier), "Detail library is used. Representative will supply appropriate detail based on manufacturer."; "We study and implement strategies to allow the assemblies to breathe.", "We design to the 'warm in winter' side of the wall.", "There's no one typical way to detail anymore, really depends on the project and specific site conditions, do a lot of mock ups for contractors, do third party testing, run simulations, do site visits to test."

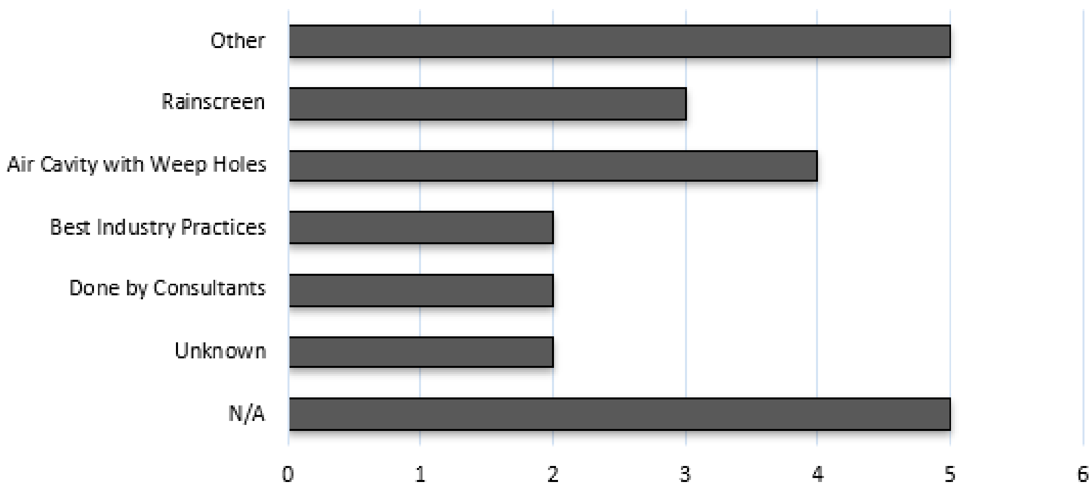

Figure 13. How is firm detailing to allow wall assembly to dry out?

This concludes the questions on how firms are working with energy modeling and envelope performance issues. The last section is looking at what challenges face the building industry.

The last question was "What is the biggest challenge the building industry faces today?" (Figure 14). Some respondents listed more than one, so the total count is above 23. Interesting comments: "our dependency on fossil fuels in order to generate power", "Most customers want 'Value Engineering' and it's tough to sell them on these new sustainable measures, when there are cheaper, more cost-effective measures now rather than later.", "how expensive it is to make a building LEED certified", "technology is not leveraged in our industry like it has been for other industries", "clients don't realize that aggressive schedules can weigh on a project".

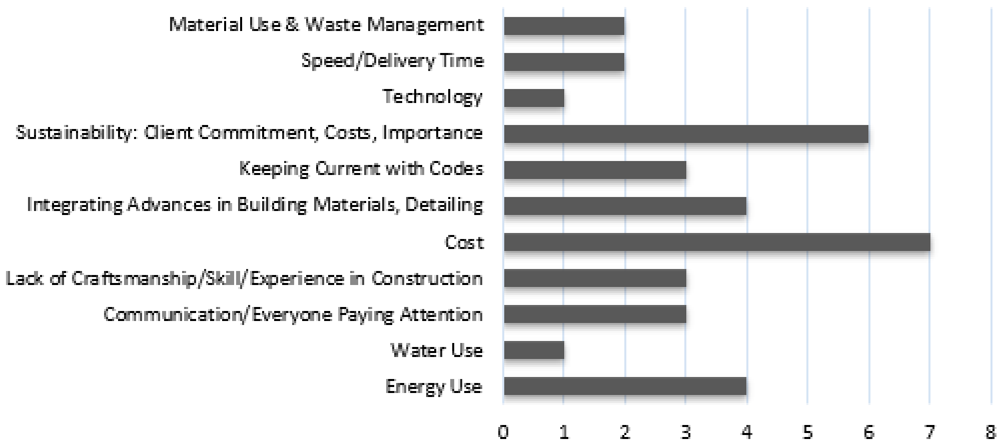

Figure 14. Summary of what respondents thought was the biggest challenge facing the building industry today.

This concludes the summary of the research data results.

DISCUSSION

The data shows that the firms interviewed represent a broad sector of the building industry working on a wide variety of projects located mostly in Pennsylvania but also in all different climate conditions around the world. This diversity is helpful because it appears that interviews were conducted with people working from very small to very large projects providing a range of services. This means that the data reflects a wide view rather than a cluster around the same kind of firm size, projects, and offerings.

One limitation of the study was the small sample size, so even though there was a variety of firms, there were only 23 of them and there was no correlation made between the defining features of the firms to the industry at large (i.e. firm size, focus, location). There were 5 firms that focused on build-outs of existing spaces. These firms generally didn't have any control over the detailing of the building shell. This accounts for the large number of not applicable type answers for some of the survey questions.

It was interesting that there were so many firms who had regular presentations in house to share the research and work being done within their firm. This seems like a great way to take advantage of what people have learned on a project and bring everyone in the firm up to speed on new products and applications for the firm. There is a heavy reliance on industry publications and material suppliers to keep both firms and employees up-to-date with changes. This is interesting because it raises concerns about the overall scope and focus of the information that is being promoted by the particular publications and vendors. It is concerning that 3 (13%) of the firms do not do research. This points to a gap between 'business as usual' and really understanding what is changing in the industry.

There were a wide variety of responses on how firms are keeping their details updated, it was clear that some had very organized libraries that were regularly checked and monitored by specific people while others were not. When these responses are compared to the detailing questions it is clear that there is a reliance on the employee's experience, consultants, and product representatives to adjust standard details to the particular project. This is a traditional focus because while a person is working on a specific project it is billable time to develop the details. Time just updating the detail library is not billable to a specific client.

Although 51% of the firms were exceeding energy code requirements for building performance, it is interesting to note that 44% do not (13% of those indicating that sometimes they did, but only if the client wanted it). It is a bit surprising that 61% of the firms were not committed to a particular standard or rating system and yet they still were creating buildings above code.

It appears that many firms have worked to substantially improve their standard details. 56% stated that they were actively working to have better thermal and air barriers. Adding in the 13% that worked with clients and the project to achieve appropriate solutions, that would indicate that 69% are considering the design of their thermal and air barriers. It would appear that the same firms that are actively creating barriers are committed to providing consistent thermal envelope with minimal thermal bridging (57%). This is interesting to compare to 52% that state that they have standard details that relate to the climate they are building in. However, there are still 6 (26%) that said they were not ever addressing achieving a continuous thermal envelope.

Of the 15 firms (65% of the firms interviewed) that do energy modeling, 87% of them are hiring consultants for this work. Some of this was required for 3rd party verification and for certifications.

Responses for how designing the wall to dry out show that on the whole firms are aware of water flow issues, but not necessarily vapor transportation. It is unclear from these responses what percentage of the firms are appropriately addressing this issue. Out of the recorded information only 3 (13%) specifically explained what they were doing in a way that showed they understood the issue. It is interesting that 2 responses are for following best industry practices and 2 are hiring consultants. It is a limitation of this data set that one cannot be sure how the firms are detailing for vapor transportation.

In the section about the challenges facing the industry it is not surprising that general building and development costs topped the chart at 7 responses. It is interesting that there are 6 responses for sustainability—including how to get clients on board. Tied with 4 responses each are a concern for the intense energy usage in buildings and staying abreast of building material advances.

CONCLUSIONS

The study shows that there is still a gap in the industry for application of building science performance issues. Detailing in most of the firms ends up being the responsibility of the technician working on the project—or outsourced to a consultant. This points to a potential communication breakdown and building failure. Having the one response that said they hired young people to keep abreast of changing issues is a problem because these same young people don't have the experience to recognize where a detail could fail or to ask for help in fixing an outdated detail in the standard library. It could be very helpful for research to be done on how to make detailing and updating standard library details valuable as a balance between accuracy, time, billables and actual cost.

It is both valuable and a concern that firms are relying so heavily on manufacturers for information about building. The value of having an expert assist in getting your detailing (using their product) is high. However, the firm may not be getting a full picture of what the issues are and how well that particular product is meeting those demands. It could be interesting to know what the industry publications and the lunch-n-learns cover as a broad scope for keeping people informed about industry changes.

It is definitely a concern that sustainability, energy modeling, and efficiency are not well enough understood by the firms and clients to be able to really achieve high performance without it appearing to cost more. It would definitely be helpful to get more information to those doing base code design (44%) about the benefits of sustainable practices and how integrating modeling can improve efficiency and create better designs. It was surprising that not one of the firms had signed onto the 2030 challenge. There is a breakdown when there is one response that said that they were 'designing for architecture and not efficiency' indicates complete ignorance of the impact and responsibility that an architect has for the built environment and the long-term impact of unsustainable choices.

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A Path to Zero Energy Ready Home Construction

T.L. Gilbride[1] and M.C. Baechler[2]

[1]Scientist, Energy and Environment Directorate, Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA, 99352, 509-371-6047, Theresa.gilbride@pnnl.gov
[2]Senior Program Manager, Energy and Environment Directorate, Pacific Northwest National Laboratory, 620 SW 5th Ave., Suite 810, Portland, OR 97204, 503-417-7553, michael.baechler@pnnl.gov

ABSTRACT

While the number of zero energy homes constructed in the U.S. has grown dramatically, increasing nearly 400% since 2015, zero energy homes still accounted for less than 1% of all U.S. homes constructed as of December 2018. Concerns about high costs or implementation challenges have kept many builders from attempting zero energy home construction. However, builders participating in the U.S. Department of Energy's Zero Energy Ready Home Program are showing that zero energy ready home construction can be achieved simply and cost effectively with off-the-shelf equipment and materials and common construction techniques. Construction methods used by builders in the DOE program are compared with those used in just-to-code new homes and existing homes for several key components, including wall assemblies and HVAC systems. Examples of cost-effective assemblies used in the Mid Atlantic states are provided.

INTRODUCTION

Government and university-sponsored research has investigated the possibility of constructing zero energy homes, homes that make as much energy as they use, over the past several decades, starting with the development of residential solar photovoltaic (PV) systems, which saw a big rise in interest after the the energy crises of the 1970s, following earlier public and private funding in PV development. This interest stalled somewhat in the 1980s due to falling fossil fuel prices then revived in the 1990s and again around 2007 as PV panel production picked up (Jones and Bouamane 2012). Government- and industry-sponsored research efforts, which have included laboratory investigations of building envelope assemblies, increasingly advanced building energy models, and the development of improved materials, have all helped to advance zero energy home research. The feasibility of constructing net zero energy homes has been verified by numerous proof-of-concept projects in the early 2000s supported by the U.S. Department of Energy (DOE)'s Building America program and other regional programs as well as by innovative builders (Oliver 2006, DOE 2004, NYSERDA 2011, FSEC 1999, DOE 2003a, DOE 2003b Aldrich et al. 2006, Sherwin et al. 2010, Hartweg 2007). In recent years, the interest in zero energy construction has really taken off.

Team Zero (formerly known as the Net-Zero Energy Coalition) reports that, as of December 2018, there were over 22,146 new zero-energy single-family and multi-family homes built or underway in the United States and Canada since the team started tracking zero energy homes in 2015 (Team Zero 2019). As seen in Figure 1, the number of units reported in 2018 represented a 59% increase over 2017, which had seen a 70% increase over 2016; all together this represents a four-fold increase in zero energy units since 2015, the first year of the inventory. Team Zero notes actual numbers may be higher; the team relies on builders to self-report. A 2017 report by Dodge Data & Analytics and the National Association of Home Builders shows that, among builders with an interest in green, 29% had already built a net zero, near zero, or zero energy ready home in the past two years and 44% expected to build one in the next two years (Dodge 2017). California became the first state to *require* that all new homes built in its domain will be zero energy ready starting in 2020 (CEC 2018). Oregon's governor issued an executive order in November 2016 requiring all new homes in that state to be zero energy ready starting in 2023. Many municipalities have followed suit: in August 2018, 19 mayors from around the world, including seven U.S. cities, pledged to make all new buildings in their municipalities net zero by 2030 (Walker 2018). This growth, while rapid, still represents less than 1% of the 1,499,500 new homes started in the United States in 2018 (FRED 2019).

A PATHWAY TO ZERO ENERGY HOME CONSTRUCTION THROUGH DOE'S ZERO ENERGY READY HOME PROGRAM

Helping to make zero energy construction achievable for ordinary home builders is an important goal of DOE's Building America program. For over a decade, DOE has been encouraging incremental change in the building industry by sponsoring research and recognizing builders who go beyond code through its voluntary home labeling programs. From 2008 to 2013, over 14,000 homes were certified through DOE's Builders Challenge program, which pushed builders to achieve Home Energy Rating System (HERS) scores of 70 or lower; in comparison, an ENERGY STAR Certified Home at that time would have scored an 85 or lower on the HERS index. In 2013, DOE launched the Zero Energy Ready Home (ZERH) program. As of October 2019, 4,545 DOE ZERH homes have been certified. While there was a modest increase of 28% in 2019, the number of homes certified in fiscal year 2018 represents a 66% increase over 2017, which represents a 104% increase over 2016 (see Figure 2). The number of DOE program partners has grown too, from 187 in 2013 to 1,086 builders, raters, trainers, designers, lenders, and manufacturers as of September 2019.

The DOE program criteria are summarized in Figure 3. To achieve a DOE ZERH certification, the builder must meet seven mandatory requirements, then follow either a prescriptive path with a specific list of requirement or a performance path that allows tradeoffs to meet a target HERS score. The first mandatory requirement is to certify the home to ENERGY STAR Certified Homes Version 3.0. Version 3.0 requires that insulation levels meet or exceed those specified in the 2009 International

Energy Conservation Code (IECC). In states that have already adopted insulation requirements equivalent to the 2012 or 2015 IECC, the builder must meet ENERGY STAR Version 3.1 or 3.2.

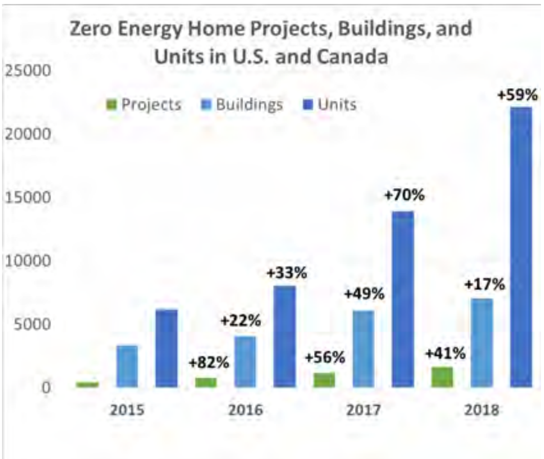

Figure 1. From 2015 to 2019, the number of zero energy homes completed or underway in the U.S. and Canada has increased 400%.

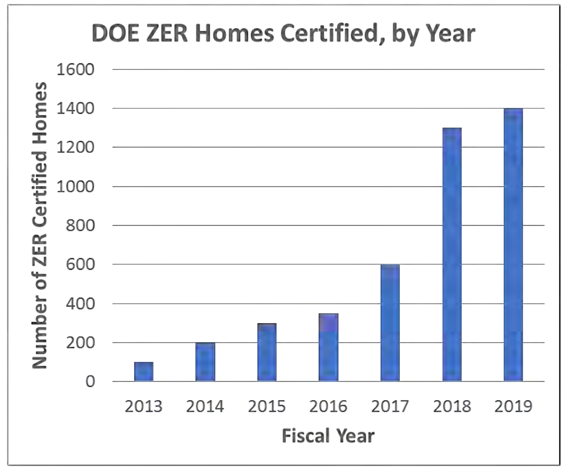

Figure 2. Since 2014, the number of homes certified through the DOE Zero Energy Ready Homes program has grown 700%.

Figure 3. To earn the DOE ZERH label, builders meet these requirements and a target HERS score based on size and climate-specific criteria (DOE 2019).

Second, the home must be certified to the U.S. Environmental Protection Agency's (EPA's) Indoor airPLUS program. In addition, homes must meet the hot water distribution requirements of the EPA's WaterSense program, have ducts (if any) in conditioned space, and have a solar electric system installed or be ready for it with the conduit and electrical panel space in place. In addition, DOE has a prescriptive list of criteria for space heating and cooling, water heating, air sealing, and windows, based on climate zone. Builders can meet the prescriptive list or take a performance path that allows tradeoffs to achieve a target HERS score based on the home's size and design using a RESNET-accredited software (DOE 2019). The performance of each home must be verified by a third-party energy rater who will inspect the house to see that it meets the requirements, conduct blower door testing and duct blaster testing (if needed), and determine a HERS score using a HERS rating software such as RemRate, Ekotrope, or Energy Gauge.

The target HERS score is determined by creating a model of a target home based on the builder's intended home design, if that design were built to the prescriptive requirements, with a size adjustment calculation factored in. So, unlike the previous Builders Challenge, the Zero Energy Ready Home program does not set one program-wide HERS score. Target HERS scores for ZER homes with no photovoltaic (PV) panels installed typically fall in the HERS 40 to 60 range. The program-wide average is HERS 47 for homes without PV, although builders have gotten as low as HERS 25 without PV. When PV is included, many homes fall below a HERS 10, with several achieving at or below HERS 0 (generally a HERS score of less than 0 is considered a net zero home). Builders with these exceptionally low (< 0) HERS scores point out that their homes are producing enough electricity to power not only the home but often one or two electric cars as well.

DOE honors exemplary participants in the ZERH program through its annual Housing Innovation Awards (HIA). Since 2013, DOE has recognized 225 projects in all U.S. climate zones and in five housing categories: 16% production, 43% custom for buyer, 18% custom spec, 16% affordable, and 6% multi-family. DOE has gathered extensive data on these homes; findings in this paper are based on these data.

A COMPARISON OF DOE ZERH HOMES WITH NEW CODE-BUILT HOMES AND EXISTING HOMES

Two areas that significantly impact energy usage in a home are the building envelope and the heating, ventilation, and air-conditioning (HVAC) equipment. Figure 4 shows a comparison of choices in wall type made by builders in the DOE ZERH program and by builders of new to-code homes. The data for new code-built homes built in 2018 (shown in yellow) were obtained from Home Innovation Research Labs (HI) from their 2018 Builder Practices Survey (HI 2018). The DOE data (shown in blue) are compiled from the 225 projects that have participated in the DOE ZERH Housing Innovation Awards.

While in both sets the most common wall type is site-built light-frame construction, it constitutes a greater percent of homes from the HI to-code builder survey data set than from the DOE ZERH data set. The data includes a further breakout by 2x4 versus 2x6 wall studs. For the to-code builders, 2x4 16-inch on center (o.c.) framing was clearly the most popular wall type. In contrast, among ZERH single-family home builders, 2x6 was the most popular. Most of the ZERH builders who reported using 2x6 wall construction said they used 24-inch o.c. stud spacing, an advanced framing feature that allows more room in the wall for insulation than does 16 inch o.c. spacing. These builders also typically employed other advanced framing techniques like turning or eliminating a stud at the corners and using ladder blocking rather than a set of three studs where interior walls intersect exterior walls, minimizing studs around windows, and using open or insulated headers rather than solid lumber headers above doors and windows. These steps reduce lumber costs and allow more space for insulation.

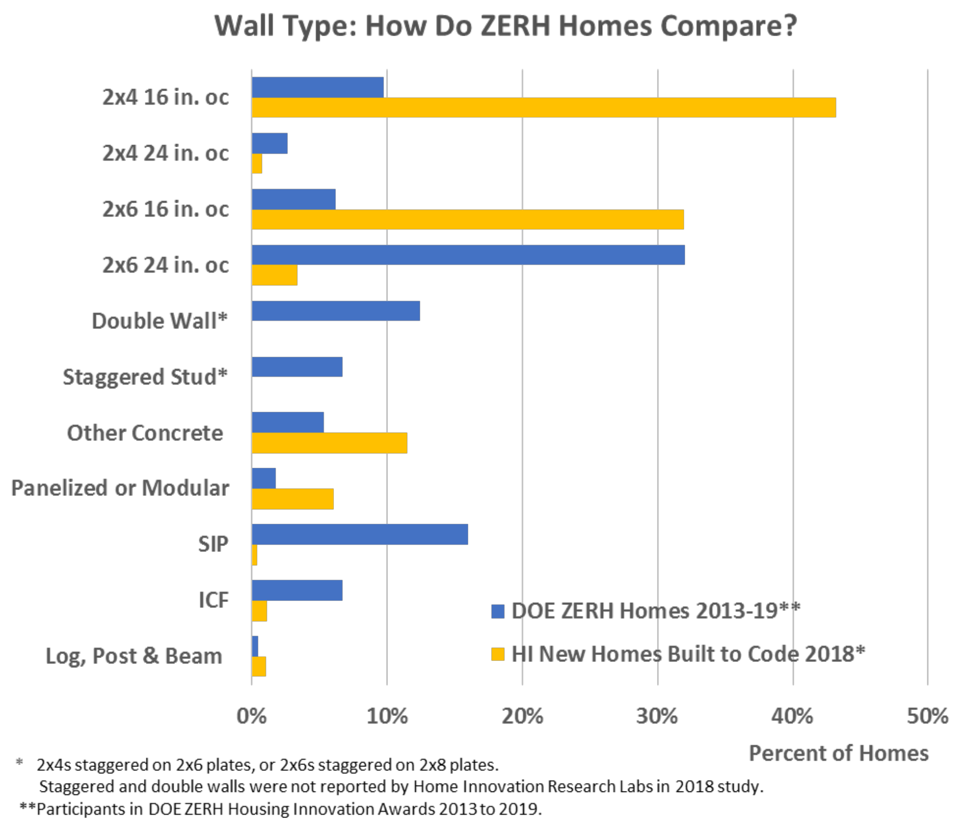

Figure 4 Wall Types in DOE ZERH Homes versus Just to Code Homes

The DOE ZERH data also indicates double walls and staggered studs, two innovative techniques used by builders to stop thermal bridging or the transfer of heat through typical framed walls through the studs which touch both the interior and exterior surface of the wall. Double walls consist of two framed 2x4 or 2x6 walls typically set 1 to 4 inches apart to form an 8- to 12-inch deep wall cavity that is filled with any combination of batt, blown, or spray foam insulation. Because solid lumber doesn't extend through the cavity from one side to the other, there is no thermal bridging.

Staggered stud walls also stop thermal bridging by placing 2x4s on 2x6 plates or 2x6s on 2x8 plates with the studs positioned to alternately align with either the inside or outside edge of the plate, allowing space to wrap insulation around the inside edge of every plate. These wall types illustrate the types of innovations ZERH builders incorporated into their homes.

The ZERH winners were also more likely to use structural insulated panels (SIPs) or insulated concrete forms (ICFs). Not counting ICFs, other concrete wall types make up about 8.5% of the HI homes and about 6% of the ZERH homes. The ZERH concrete homes use higher performance foam-core blocks or precast insulated concrete panels. ICF and SIP homes tend to be much more air-tight than conventional stick built homes. Although not addressed in these figures, ZERH builders often go well beyond the code-required airtightness levels by employing copious and redundant air sealing materials, including caulk, tape, and spray foam to seal all potential areas of air leakage around plumbing, wiring, doors, and windows and at wood and sheet good seams.

Figure 5 shows heating system choices using data from three sources: the HI survey of just-to-code builders, the DOE ZERH HIA winners, and the U.S. Energy Information Administration's 2015 Residential Energy Consumption Survey (RECS) representing the 118.2 million existing U.S. primary residences (EIA 2017).

Central, forced-air ducted systems are by far the most common heating type for all three data sets; however, the fuel type varies. Gas furnaces are the most common type of forced-air systems in existing and new homes while, for the ZERH homes, heat pumps are the primary forced air system. While the RECS existing homes and ZERH data sets showed similar numbers of homes with hydronic heating, in the RECS homes the heat source is likely to be oil or gas boilers (5% had oil boilers or furnaces, 5% used gas for hot water or steam heating) while in the ZERH data set, the heat for the hot water system could come from a variety of sources, including air-to-water heat pumps, ground-source heat pumps, tankless gas boilers, solar thermal systems, or some combination of these. Electric furnaces, baseboard, or radiant heaters were much more common in the existing homes than in the newer homes (26% in the RECS data, versus 8.8% in the code-built data and only 1.25% in the ZERH data). Many ZERH builders are turning to ductless mini-split heat pumps to match their low heating loads; 25% of ZERH builders had installed ductless or ducted mini-split heat pumps, while only 2.8% of HI to-code home builders installed mini-split heat pumps. (The RECS data did not offer a breakout for mini-split heat pumps.)

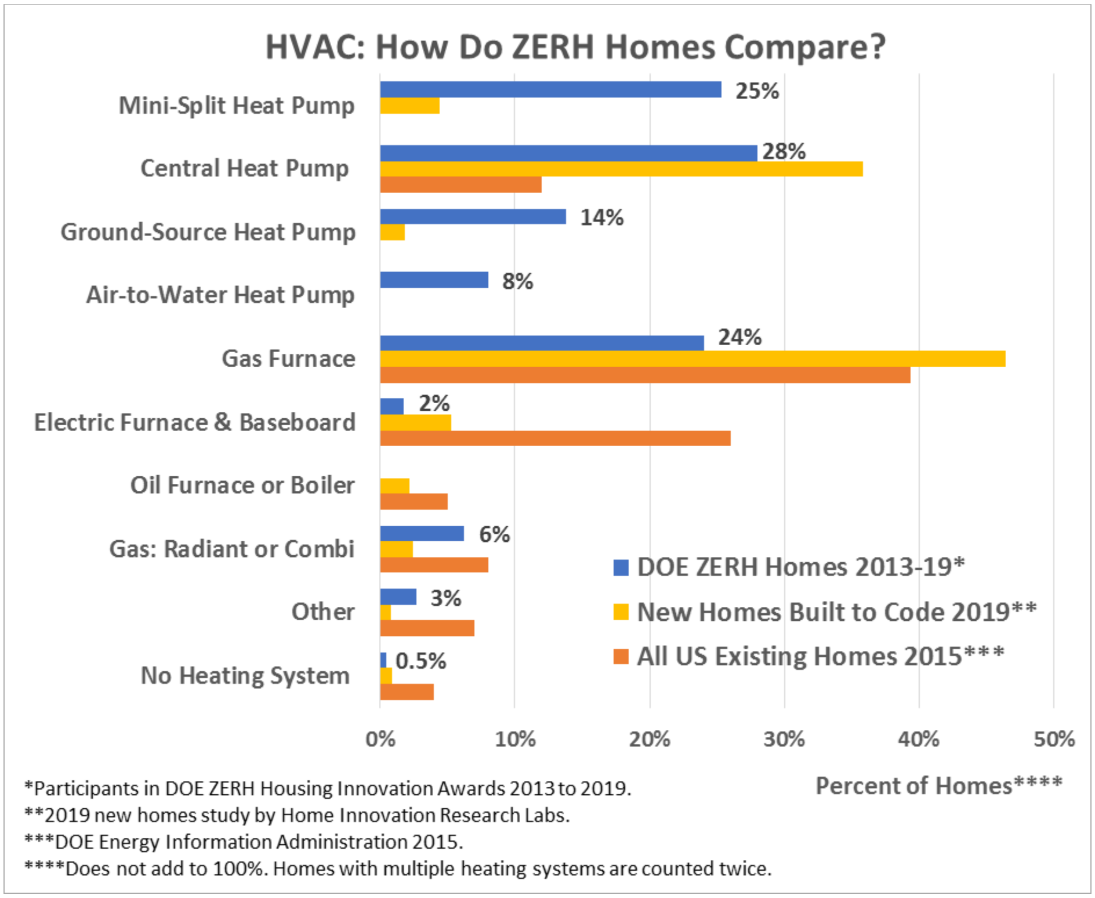

Figure 5. Heating Systems in DOE ZERH Program versus 2016 New Homes and Existing U.S. Homes.

While not shown in Figure 5, information gathered from DOE builders reflected another ZERH trend – passive solar for home space heating, with builders on nearly 20% of the projects reporting they incorporated passive design as a secondary heat source. Although no ZERH builder relied on it entirely, some who used passive solar design features along with highly efficient building shells mentioned that the mechanical heating systems they installed rarely came on.

Figure 6 shows equipment selections by DOE ZER builders for several other building components. In regard to HVAC, heat pumps dominate as is indicated by all of the blue pie slices. More than three-fourths of the DOE builders chose some type of balanced ventilation, either an energy recovery ventilator (ERV), heat recovery ventilator (HRV), or a balanced system using controlled dampers on a central air handler with a fresh air intake to bring in outside ventilating supply air while timered exhaust fans pull stale air out of the home. While triple-pane windows are installed in less than 2% of homes nationwide, over 40% of DOE ZERH builders have chosen triple pane. While gas tank water heaters are the predominant water heating type in

U.S. homes, they constitute only 2% of the water heaters installed in DOE ZERH homes. Heat pump-based systems comprise nearly half of all water heating systems with stand-alone air-source heat pumps accounting for over one-fourth of systems and ground-source and air-to-water heat pumps providing both space and domestic hot water heating in nearly 20% of homes. Over the past six years of the program, LEDs have taken an increasingly larger portion of the lighting systems, starting at 25% of homes in 2013 and reaching 100% of the ZERH homes in 2018. Although builders are not required to install solar photovoltaics, 64% have chosen to install PV panels.

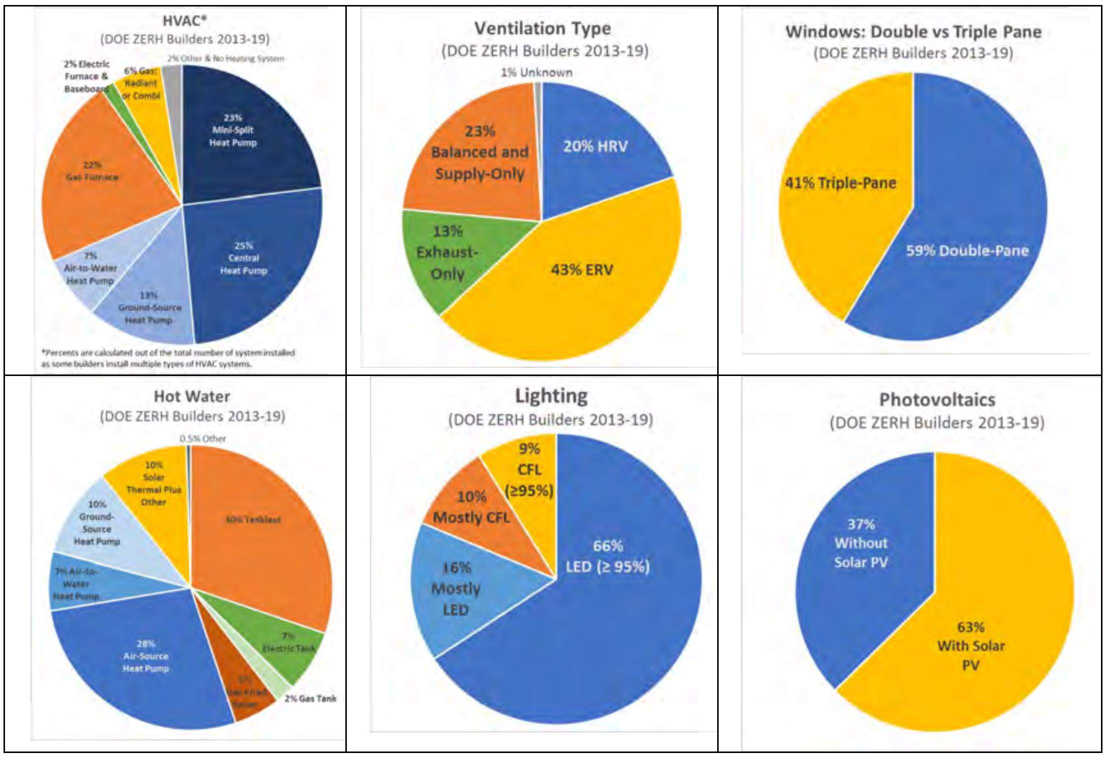

Figure 6. DOE ZERH Builder Equipment Choices, 2013-2019

DOE ZERH PROJECTS FROM THE MID ATLANTIC STATES

Of the 225 projects that participated in the DOE ZERH program, 43 were from the Mid-Atlantic states (DE, MD, NJ, NY, OH, PA, VA). These projects were fairly evenly distributed among three climate zones: 16 projects were located in IECC 4A mixed-humid, 16 projects were IECC 5A cold, and 11 projects were 6A very cold.

Table 1 provides a look at several representative Mid-Atlantic ZERH projects. Key envelope and mechanical features are listed. The third column shows annual energy costs and savings, and added first cost to get the home beyond code to the DOE ZERH level. If the builder installed PV panels on the home, costs and savings

Table 1. Sample DOE ZERH Projects from the Mid-Atlantic States

Project	Energy Measures	Costs & Savings without PV	with PV
ICF			
 Charis Homes, ICF Home, North Canton, OH 2016	Envelope: ICF walls, vented attic with R-50 cellulose, ICF basement, double-pane windows, 1.65 ACH 50. Mechanicals: ground-source heat pump for hydronic forced-air heating and desuperheater for hot water with backup tankless gas. ERV. No PV.	HERS 31 Ann. Energy Costs: $2,322 Annual Savings: $4,144 Added 1st cost: $22,000 Net Mon. cash flow: $233	
 Greenhill Contracting, Newburgh Custom, Newburgh, NY, 2019	Envelope: ICF walls R-22, un vented attic with R-65 10-=.5” open-cell + 2.5” closed-cell spray foam under roof deck; R-22 ICF basement; triple-pane windows, 0.18 ACH 50. Mechanicals: ducted mini-split heat pump 9.8 HSPF, 16 SEER; heat pump water heater; ERV. 10.2-kW PV.	HERS 39 Ann. Energy Costs: $1,800 Ann. Savings: $2,200 Added 1st cost: $10,000 Net Mon. cash flow: $133	-5 $1,000 $3,950 $37,000 $140
SIPs			
 High Performance Homes, Danielle, Gettysburg, PA, 2017	Envelope: R-23 SIPs; vented attic with 1” closed-cell spray foam + R-49 cellulose on ceiling deck; precast concrete basement with R-21.3 walls, R-10 under slab; double-pane windows, 1.1 ACH 50. Mechanicals: ground-source heat pump 5.6 COP, 20.3 EER; desuper-heater + electric tank water heater; exhaust fans. 4.9-kW PV.	HERS 35 Ann. En. Costs: $1,300 Ann. Savings: $2,400 Added 1st cost: $26,500 Net Mon. cash flow: $-2	16 $700 $3,000 $49,500 $65
2x6 24 in. o.c.			
 Charis Homes, The Aspen, Uniontown, OH 2017	Envelope: 2x6 24 in. oc walls with R-23 mineral wool; vented attic with R-50 cellulose, ICF basement, triple-pane windows, 1.50 ACH 50. Mechanicals: gas furnace 97.4 AFUE, 19 SEER AC, tankless gas water heater, exhaust fans. No PV.	HERS 36. Ann. Energy Costs: $2,050 Annual Savings: $1,150 Added 1st cost: $2,800 Net Mon. cash flow: $84	
 Garden State Modular, Coastal ZERH, Lavallette, NJ, 2017	Envelope: 2x6 24 in. oc walls, R-21 fiberglass batt + 1” rigid foam = R-23; vented attic, R-49 cellulose; pier foundation, R-24 closed-cell spray foam in joists; double-pane windows, 1.50 ACH 50. Mechanicals: gas furnace 97.4 AFUE, 19 SEER AC, tankless gas water heater, exhaust fans. No PV.	HERS 40 Ann. Energy Costs: $1,700 Annual Savings: $1,200 Added 1st cost: $7,000 Net Mon. cash flow: $63	

 Health-E Community Enterprises of Virginia Noah's Ark, Hampton, VA, 2019	Envelope: 2x6 24 in. oc walls with 2" closed-cell spray foam + 3.5" fiberglass+R-3.6 coated OSB for R-31 total; unvented attic with R-19.5 closed cells + R-25.2 open-cell spray foam. Pier foundation; double-pane windows; 1.6 ACH 50. Mechanicals: heat pump 10 HSPF, 19.75 SEER AC; heat pump water heater, ERV. 13.1-kW PV.	HERS 47 Ann. Energy Costs: $2,000 Ann. Savings: $1,800 Added 1st cost: $3,500 Net Mon. cash flow: $131	-16 $-250 $3,900 $31,000 $158
 Insight Homes, Whatley, Millsboro, DE, 2018	Envelope: 2x6 24 in. oc walls with R-33 blown fiberglass; vented attic with R-49 blown fiberglass; unvented conditioned crawl R-10 XPS on interior; double-pane windows, 1.9 ACH 50. Mechanicals: heat pump 18 SEER, 9.6 HSPF, 97.7 AFUE propane furnace backup; tankless water heater; exhaust fans. No PV.	HERS 52 Ann. En. Costs: $2,700 Ann. Savings: $3,250 Added 1st cost: $11,300 Net Mon. cash flow: $173	
 United Way of Long Island, United Veterans Beacon House, Huntington Station, NY, 2017	Envelope: 2x6 24 in. oc walls with R-20 cellulose + 1.5" Rigid foam, for R-30 total; vented attic with R-50 cellulose; basement with R-12 polysio rigid foam on interior; triple-pane windows, 2.06 ACH 50. Mechanicals: 95 AFUE wall-hung boiler with hydrocoil, 13 SEER AC; solar water heater + boiler backup. ERV. 8.5-kW PV.	HERS 31 Ann. En. Costs: $1,750 Ann. Savings: $3,900 Added 1st cost: $7,350 Net Mon. cash flow: $287	-5 $-200 $5,850 $57,350 $195
 United Way of Long Island, Suffolk County LandBank Attainable Housing, East Patchogue, NY, 2019	Envelope: 2x6 24 in. oc walls with blown fiberglass + 2" rigid foam for R-31 total; vented attic with R-50 blown fiberglass; basement with R-10 XPS on exterior; triple-pane windows, 1.15 ACH 50. Mechanicals: ducted mini-split heat pump, 9.8 HSPF 16.2 SEER; heat pump water heater; ERV. 9.8-kW PV.	HERS 51 Ann. En. Costs: $1,700 Ann. Savings: $1,600 Added 1st cost: $9,000 Net Mon. cash flow: $88	-15 $50 $3,200 $23,000 $151

with PV are shown in the fourth column. It should be noted that the costs were self-reported by the builders and vary widely. Although the builders were instructed to include only those costs incurred to bring the home from code up to the program criteria, some builders may have included all upgrade costs. The third and fourth columns also show net monthly cash flow without and with PV. Green indicates instances where the home owner will make more money in a month in energy savings than the additional measures to meet DOE ZERH requirements will add in cost to the monthly mortgage.

Figures 6, 7, and 8 compare the 43 Mid-Atlantic builders to all ZERH builders in terms of choices in wall type, HVAC, and ventilation. None of the Mid-Atlantic builders used 2x4 studs but 2x6 24 in. o.c. were a popular wall type as were ICFs. Mid Atlantic builders were less likely to use air source heat pumps than ZERH builders in general but ground source heat pumps were surprisingly popular. Mid Atlantic builders were almost twice as likely to use ERVs as all ZERH builders.

Figure 9 compares all of the wall assembly and HVAC combinations found in the 43 Mid-Atlantic projects in terms of annual energy savings, not including PV. Projects with similar wall-HVAC combinations were combined and their energy savings were averaged. This graph includes only those of the 43 projects where energy savings were reported in comparison to the IECC 2012 or 2015 (which have nearly identical insulation requirements). The 20 Mid-Atlantic DOE ZERH projects that were built to the 2009 IECC are not included in this data set because there were significant increases in insulation requirements between the 2009 IECC and 2012 IECC.

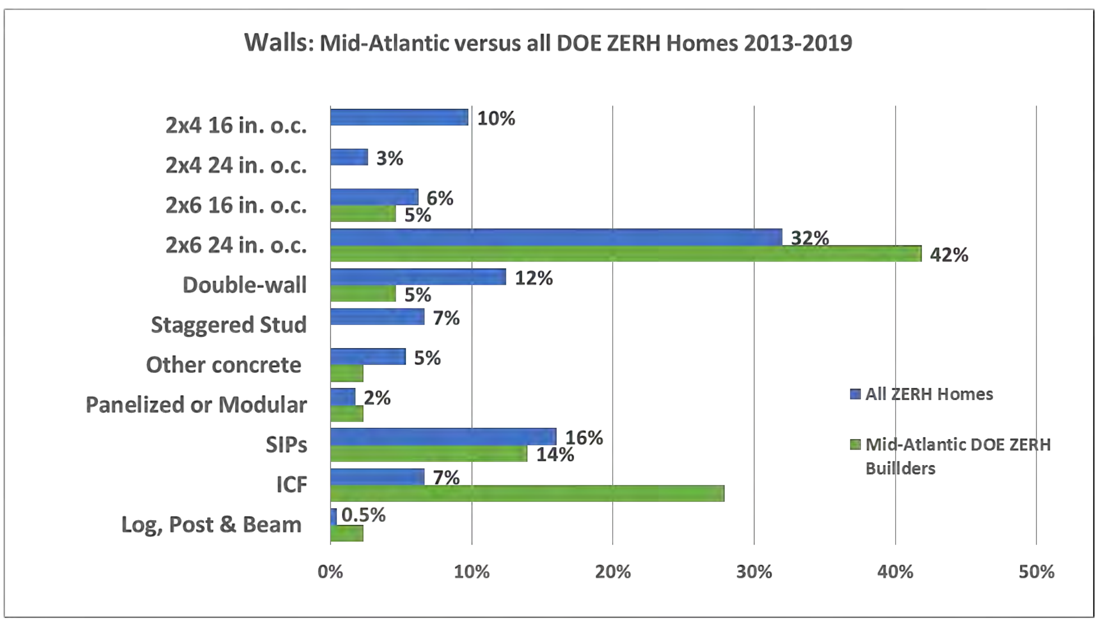

Figure 6. Wall Choices Mid-Atlantic versus All DOE ZERH Projects, 2013-2019.

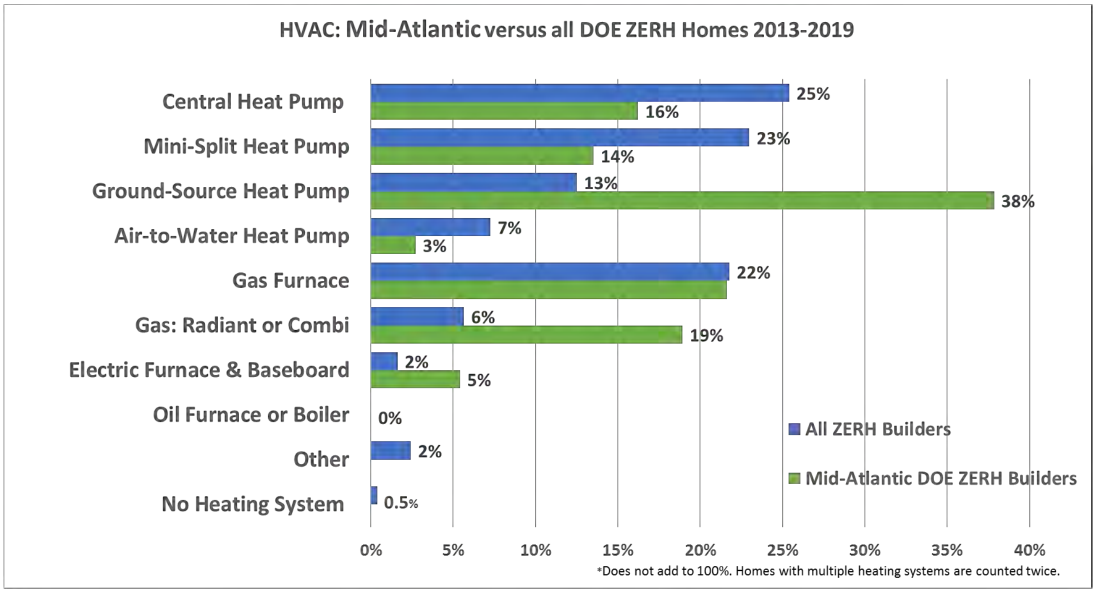

Figure 7. HVAC Choices Mid-Atlantic versus All DOE ZERH Projects, 2013-2019.

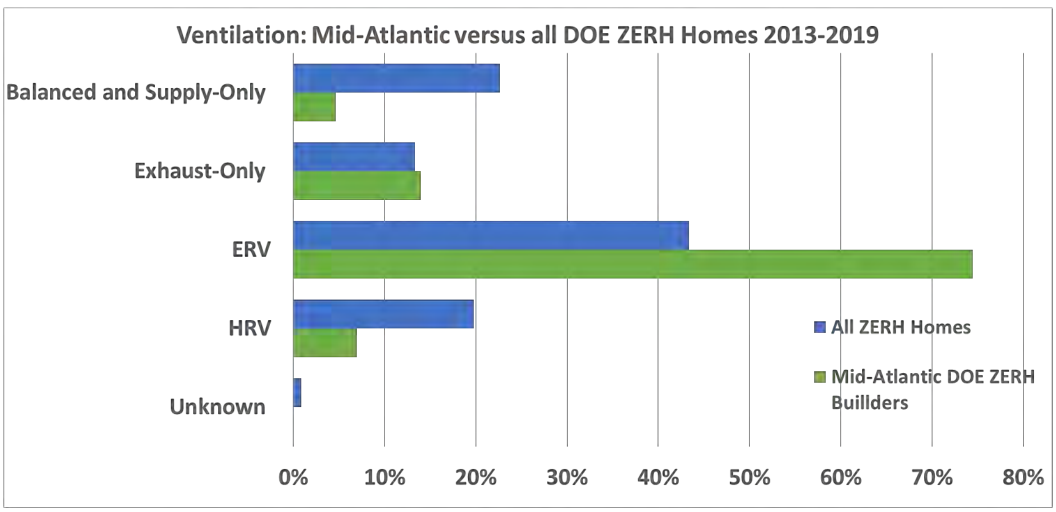

Figure 8. Ventilation - Mid-Atlantic versus All DOE ZERH Projects, 2013-2019.

As can be seen from Figure 9, homes constructed with SIP and ground source heat pumps saved the most energy in the Mid-Atlantic region. ICF homes with ground source heat pumps saved the second most. However 2x6 24 in. o.c. walls with 1 inch of rigid foam and a high efficiency heat pump also performed very well. As seen in Table 1, costs varied considerably and did not necessarily correlate with the wall-HVAC combinations.

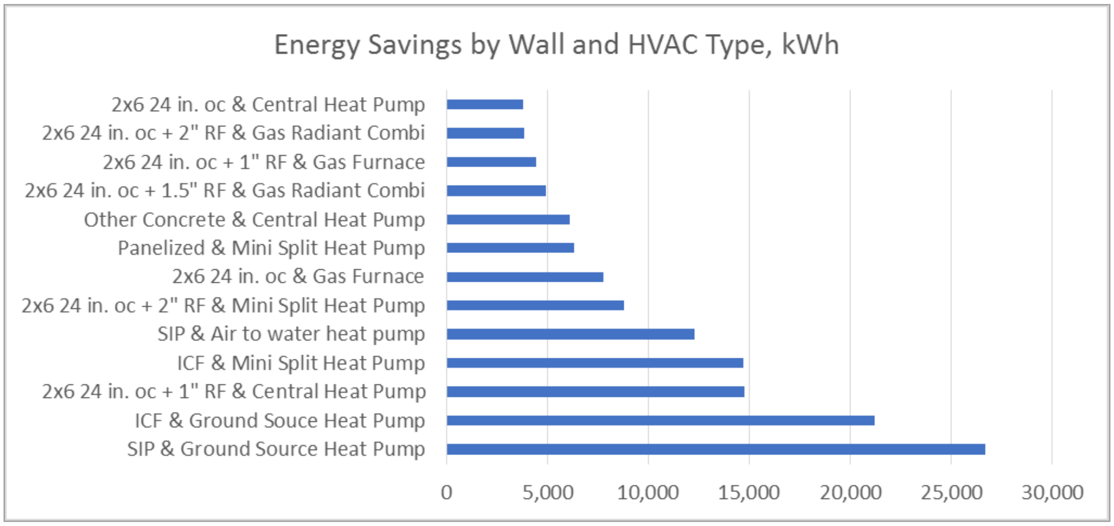

Figure 9. Annual kWh Energy Savings for DOE ZERH Projects in the Mid-Atlantic States compared to the 2012 IECC.

CONCLUSIONS

DOE's Zero Energy Ready Home program maps out a clear path that builders can follow to achieve zero energy homes. The ZERH program's performance path allows builders to make tradeoffs in energy-efficiency measure choices as they seek to achieve a target HERS score for their home design. Data presented show the choices builders are making in several key areas to achieve zero energy homes. A detailed look at builders in the Mid-Atlantic states compares their choices to those of ZERH builders across the country. While ICF and SIP homes with ground source heat pumps are the highest performers in terms of energy savings, light framed construction also performs well in the Mid-Atlantic when the framing is 2x6 24 in. o.c. and when 1 or 2 inches of exterior continuous rigid foam is included over the framed wall.

Light-framed construction is by far the most popular construction type in the United States for builders of just-to-code homes. From this it can be inferred that transitioning code builders to zero energy home construction could be achieved with relatively minor changes in construction technique, for example using 2x6 24 in. o.c. instead of 2x4 16 in. o.c. along with other advanced framing techniques, which together allow for at least 30% more insulation in the walls. Installation of higher performing mechanicals, like high-efficiency heat pumps, furnaces, and water heaters, ENERGY STAR appliances, and all LED lighting would add considerably to energy savings, without changing construction methods to any great degree.

Builder innovation and initiative, combined with government and academic research, have helped to show the feasibility of zero energy construction. Market forces, including national home labeling programs such as DOE's Zero Energy Ready Home program and ENERGY STAR, and competitions like DOE's Housing Innovation Awards, together with legislation like the California and Oregon mandates, are helping to push wider adoption of zero energy construction. While zero energy homer are too small a percentage of new home starts to be considered main-stream, several drivers are coming into play to push new home builders toward zero energy construction. The California mandate is anticipated to bring 100,000 new zero energy homes to *each year* (Higgins-Dunn 2019), and there are signs that other states and cities may follow California and Oregon's lead in mandating zero energy construction. The IECC continues to move the bar forward on efficient construction; the 2012 and 2015 IECC were considered rigorous enough to serve as the insulation requirements for the DOE ZERH program. Residential solar panels have dropped dramatically in price from $11/watt installed in 2010 to <$4/W in 2017 (Trabish 2018), making it more financially feasible for average builders and home owners to installing large enough PV systems to achieve net zero energy usage.

As shown in the Mid-Atlantic project examples, when the additional upfront costs of building to DOE ZERH are added to the purchase price of the home and financed over a 30-year mortgage, monthly energy cost savings exceed added monthly mortgage costs in most cases (by as much as $287 per month). Publicizing these financial benefits, along with the comfort and health benefits of ZERH, may jelp provide market pull by encouraging home buyers to ask for zero energy homes.

The relative ease with which net zero energy level construction could be introduced into current construction practices, combined with these market forces, provides a feasible path forward for widespread implementation of zero energy homes.

More information on the 225 projects that have participated in the Housing Innovation Awards to date can be found on DOE's Tour of Zero website, https://www.energy.gov/eere/buildings/doe-tour-zero.

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High-Performance Windows – More than just a Pretty Hole in the Wall

Katherine A Cort and Theresa L Gilbride
Pacific Northwest National Laboratory, Richland, Washington[1]

ABSTRACT

As more stringent building energy codes and better insulation products combine to yield better performing walls, window efficiency is coming into sharper focus. The U.S. Department of Energy (DOE) has supported several projects through its national laboratories to improve the thermal performance of windows. At Pacific Northwest National Laboratory (PNNL) in Richland, Washington, the PNNL Lab Homes, two fully monitored identical side-by-side manufactured homes, have been used to test the performance of several window improvements including triple-pane windows, storm windows with low-emissivity (low-e) coatings, smart automated interior insulated shades, and exterior shading products. Findings will be presented on these studies, along with impacts. For example, PNNL's Lab Home research on low-e storm windows has helped to support a new ENERGY STAR certification, industry standards, and utility incentives. Preliminary findings will also be presented on current Lab Homes experiments focusing on exterior shades. The session will also present findings from related field studies and a market assessment of emerging high-efficiency windows technologies and discuss some of PNNL's planned field studies that will focus on validating the benefits and costs of the emerging thin triple-pane high-R window.

Introduction

Residential buildings in the United States currently require 8 quadrillion Btu/yr of energy for heating and cooling – that accounts for more than 40% of primary residential energy use (EIA 2015). Thermal transfer through residential windows accounts for approximately 10% of a building's energy use (Hart et al. 2019). Over the past 20 years, window replacement and window attachment retrofit technologies have been developed that significantly increase the options available to home builders, homeowners, and utilities when considering new windows or upgrades of existing windows. These options include high-R windows, including windows with thin triple-pane insulated glass units (IGUs), and various window attachment options like low-e storm windows (panels) which can be attached to the interior or exterior of the window, interior insulated cellular shades, and exterior shades.

This paper reviews past and current window-related research, including experimental evaluations conducted at PNNL's Lab Homes in Richland, Washington, and discusses how results of these studies are supporting utility incentive and market transformation programs. Photos of these technologies are provided in Figure 1 and the savings potential and application of these technologies are summarized in Table 1. The savings potential is based on a range of field, lab, and modeling studies, and is focused on heating, ventilation, and air-conditioning (HVAC) savings. These studies are discussed and referenced in the remaining sections of this paper.

[1] The mailing address for both authors is PNNL, P.O. Box 999, Richland, WA 99352, with respective e-mails: katherine.cort@pnnl.gov, and theresa.gilbride@pnnl.gov

Figure 1. High Performance Window Technologies include (from left to right) exterior low-e storm windows, insulated cellular shades, exterior shades, and thin triple-pane IGUs. *Sources*: PNNL, AERC, and LBNL.

Table 1. Savings Potential and Application of Windows Technologies Reviewed

Technology	Application	Annualized Savings Range
Low-e Storm Windows	Over single-pane or double-pane clear glass windows in all climate zones.	10-33% (annual HVAC savings)
Insulated Cellular Shades	Applicable with all types of new or existing windows in all climate zones.	3-34% (annual HVAC savings)
Exterior Shades	Best applications include unshaded south- and west-facing windows in cooling season (all climate zones).	12-25% (Cooling HVAC savings)[a]
High-R Thin Triple-Pane IGUs	New build or replacement windows in all climate zones.	7-16% (total energy savings)

[a]Not annualized and based on preliminary cooling season savings from 2019 Lab Homes study currently underway.

Glass alone is a poor insulator, with a thermal conductance of approximately 1 Watt per meter Kelvin (W/mK). Single-pane windows have an overall heat transfer coefficient (U-factor) of about 5.5 W/m^2K or 1 Btu/hr ft^2F, which is only R-1. The insulating properties of IGUs are described in terms of U value or its inverse, the thermal “resistance” value in R, where R = 1/U-factor. Sandwiching layers of trapped gas between layers of glass gives windows increased insulation value. Clear glass also transmits between 70% and 90% of its light and heat at all wavelengths, including infrared (IR) radiation so low-emissivity coatings that reduce radiation can improve a window’s performance.[2] Several new windows technologies, including thin-glass krypton-filled triple-pane IGUs and vacuum insulated glass units, hold promise of greatly improving primary window efficiency.

Window attachment technologies can improve the thermal and optical properties of the window via coatings (e.g., storm windows with low-emissivity coatings) or coverings (e.g.,

[2] Lawrence Berkeley National Laboratory’s International Glazing Database. Version 45.0. Accessed 3/7/2016 at https://windows.lbl.gov/materials/igdb/.

blinds or shades) that decrease solar heat gain, increase the reflectance of the window in IR wavelengths, and decrease the amount of thermal conduction or convection between indoor spaces and the outdoors. With automation or scheduled manual operation, operable shades and blinds can add a dynamic performance element to conventional windows, allowing solar gains when beneficial during the winter and reducing solar gains in the summer.

Previous Field Research and Case Studies

Table 2 summarizes findings related to high-efficiency window attachment and high-R window performance and associated energy savings based on recent case studies, energy simulations, and field studies. One of the most recent high-R window studies (Hart et al. 2019) includes a series of energy simulations that focused on assessing the energy-savings potential of a "drop-in" thin triple IGU in comparison to the "typical" double-pane residential window. The study demonstrated that, due to improvements in U-factor and other performance metrics, thin triple-pane windows have the potential to cut energy use in residential buildings by approximately 16% compared to typical double-pane low-e windows in heating-dominated climates such as Minneapolis, Minnesota. A number of field demonstrations and energy simulation studies focusing on low-e storm windows and insulated cellular shades have also demonstrated year-round savings in multiple climate zones.

Table 2. Summary of selected case studies focused on high-R windows and window attachments

Study	Description and Findings
Low-e Storm Windows/Panels	
Atlanta case study (2-year study) (EERE 2013) DOE, Quanta, Larson	A retrofit field study compared single-pane wood-framed windows with and without low-e storm windows in ten occupied homes. • ~15% heating energy reduction • ~2% to 30% cooling reduction (highly variable) • 17% reduction in overall home air infiltration
Philadelphia multifamily case study (EERE 2013) DOE, Quanta, Larson, NAHB, AGC Flat Glass, NSG-Pilkington	A retrofit field study compared old clear-glass storm windows with low-e storm windows over single-pane, metal-framed windows in two large multifamily buildings. • 18%–22% reduction in heating energy use • 9% reduction in cooling energy use • 10% reduction in overall apartment air leakage
Pennsylvania weatherization technical support (Zalis et al. 2010) DOE, Birch Point Consulting	An energy simulation modeling study compared 37 homes with range of window types in 7 climate zones. • 12%–33% overall HVAC savings
Chicago case study (Drumheller et al. 2007) DOE, HUD, NAHB Research Center, LBNL	A retrofit field study compared single-pane wood-framed windows with and without low-e exterior storm windows in six low-income homes. • 21% reduction in overall home heating load • 7% reduction in overall home air infiltration • Simple payback of 4 to 5 years
Insulated Cellular Shades	
Modeling cellular shades in multiple climate zones (Metzger et al. 2017) Silicon Valley Power, APPA	An energy simulation modeling study estimated savings from cellular shades covering multiple window types in 13 climate zones. • 10-34% HVAC savings for small existing homes with large window area • 3-29% HVAC savings for larger homes with large window area

	• Savings similar for double- and triple-cell cellular shades
Denver case study (Zirnhelt et al. 2015) Hunter Douglas and RMI	An energy simulation modeling study examining residential savings from cellular shades covering multiple window types in Denver, Colorado. • Denver Max Cooling Savings – 25% • Denver Max Heating Savings – 10% • Peak electrical demand reduction of 9% for new homes
LBNL Modeled Estimates (Curcija et al. 2013) DOE	An energy simulation modeling study examining five cellular shade product types over single-pane and double-pane windows in 12 climate zones. • Savings vary by product types, climate zones, and baseline, but annual energy dollar savings ranged from $280 to $470 for cellular shades
Window Retrofit Solutions (Ariosto and Memari 2013) PHRC	An energy simulation modeling study that examined multiple window attachments, including cellular shades • Reduction in U-factor of 38% for cellular shades
High-R Primary Windows	
Thin triple-pane savings potential (Hart et al. 2019) DOE, LBNL	An energy simulation modeling study compared thin triple technology to common double panes in NFRC certified products database. • 16% annual savings in heating dominated climate • 12% annual savings in mixed climates • 7% annual savings in cooling-dominated climate
Thin Triple Infrared Imaging (Fresno, CA, 2019) DOE, LBNL, CEC	Retrofit field study used IR camera to compare double-pane low-e, vinyl framed windows with thin triple-pane windows showing thermal improvements in windows with thin triple-pane IGUs (all else constant).
State-of-the-Art Windows Review (Jelle et al. 2011) NTNU, DOE, Research Council of Norway	An energy simulation modeling study comparing double pane, clear glass, aluminum-framed windows with high-r windows including: • Thin triple (with a stretched film center pane) and aerogel glazing had the lowest center of glass U-value of 0.28 and 0.30 W/m^{2}K, respectively. • Commercially available vacuum-insulated glass has a center of glass U-value of 0.70 W/m^{2}K.

NFRC = national fenestration rating council; LBNL = Lawrence Berkeley National Laboratory; CEC = California Energy Commission; IR = infrared; NTNU = Norwegian University of Science and Technology; HUD = U.S. Department of Housing and Urban Development; NAHB = National Association of Home Builders; Quanta = Quanta Technologies, Inc.; Larson = Larson Manufacturing Company; RMI = Rocky Mountain Institute; APPA = American Public Power Association; PHRC = Pennsylvania Housing Research Center

PNNL Lab Homes Research

Although field data and case studies provide valuable insights related to the savings potential of high-R windows and window attachments in specific applications or climate zones, the variability that occurs due to home type and occupancy behavior can make it difficult to isolate the savings from the window attachment and project these savings to alternative circumstances. To address this, PNNL designed its Lab Homes to provide a side-by-side platform for precisely evaluating whole home energy-saving and grid-responsive technologies in a controlled environment. The PNNL Lab Homes are two factory-built homes that have identical floor plans (see Figure 2) and were set up side-by-side with identical solar orientations on the PNNL campus in Richland, Washington. Each Lab Home has seven windows and two sliding glass doors, for a total of 196 ft^2 of window area. HVAC conditions can be controlled in the Lab Homes to appropriately tailor and calibrate building simulation models to account for relevant interactions, occupancy, climate zones, and baseline characterizations. To be representative of typical existing residential homes, clear double-pane windows were installed as the baseline technology. The "experimental home" is retrofitted with the fenestration technology under evaluation, while the matching "baseline home" remains unaltered. The experiments listed in Table 3 were conducted in the PNNL Lab Homes. These include studies on low-e storm windows, insulated cellular shades, exterior shades, and triple-pane windows.

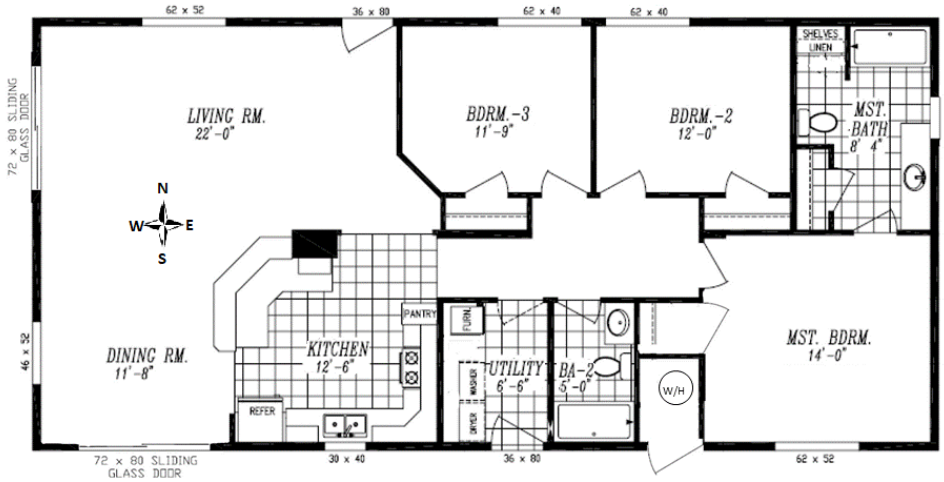


Figure 2. The PNNL Lab Homes consist of two manufactured homes with this identical floor plan set up side by side with the same solar orientation at PNNL's Richland campus in eastern Washington state.

Table 3. Summary of Lab Homes Window and Window Attachment Studies

Study	Description and Findings
Low-e Storm Windows/Panels	
Exterior Low-e Storm Windows (Knox and Widder 2014) DOE and Larson	Measured HVAC savings when attached over clear glass, metal-framed, double-pane windows. • 10.1% ±1.4, annual HVAC savings
Interior Low-e Insulating Panels (Peterson et al. 2015) DOE, Quanta, and NEEA	Measured HVAC savings when attached over 74% of window area (clear glass double-pane windows). • 7.8% ±1.5, annual HVAC savings
Insulated Cellular Shades	
Triple Cell Cellular Shades (Peterson et al. 2016) DOE, Hunter Douglas, and NEEA	Cellular shades over clear glass double-pane windows compared to uncovered windows and/or windows similarly covered with vinyl venetian style blinds (varied shade settings/operations): • Cooling HVAC = 10-14% savings (±2-7%) • Heating HVAC = 11-18% (±3-8%)
Double Cell Cellular Shades (Cort et al. 2018) DOE, Hunter Douglas, BPA, and NEEA	Cellular shades with various settings compared to vinyl venetian blinds with "typical use" settings (over clear glass double-pane windows). -Shades/Blinds always pulled down or partially down (i.e., "typical use") • Cooling HVAC = 6-13% HVAC savings (±1%) • Heating HVAC = 2-9% HVAC savings (±2%) -West-facing shades optimally operated or all shades optimally operated • Cooling HVAC = 10-15% HVAC savings (±1-2%) • Heating HVAC = 7-9% HVAC savings (±1%)

Exterior Shades	
Exterior Roller Shades, 1% Openness Factor (PNNL preliminary 2019) DOE and Springs Fashion	Exterior shades over west- and south-facing clear glass double-pane windows compared to uncovered windows and windows covered with venetian style horizonal slatted blinds. • 12-25% cooling HVAC (preliminary)
High-R Triple-Pane Windows	
Highly-Insulating Triple Panes (Widder et al. 2013) DOE	Triple panes compared to clear glass, metal-framed, double-pane windows. • 12% average annual savings • 12% heating season HVAC savings • 18% cooling season HVAC savings
(Larson = Larson Manufacturing Company; Quanta = Quanta Technologies, Inc; BPA = Bonneville Power Administration; NEEA = Northwest Energy Efficiency Alliance)	

Low-e Storm Windows

The traditional storm windows of the past consisted of a single piece of clear glass (or plastic) that was mounted in a wood or aluminum frame that was installed on the outside of an existing window. This window retrofit design focused on reducing thermal conduction and, to a limited extent, convection. Modern storm windows feature new designs that can be openable or fixed in place and are intended to be permanently mounted. In addition to conduction and convection, radiation is an important mechanism for heat gain and heat loss through windows. Low-e storm windows include a low-e pyrolytic coating that lowers the emissivity of glass for certain wavelengths, effectively reducing heat transmission through the storm window (see Figure 3). Uncoated glass typically has an emissivity of around 0.84, while low-e coated glass can have an emissivity of 0.16 or lower. When interior heat energy tries to escape to the colder exterior during the winter, the low-e coating reflects the radiative heat back to the inside, reducing the overall heat loss through the glass. The reverse transfer of heat occurs during the summer (Culp et al. 2015).

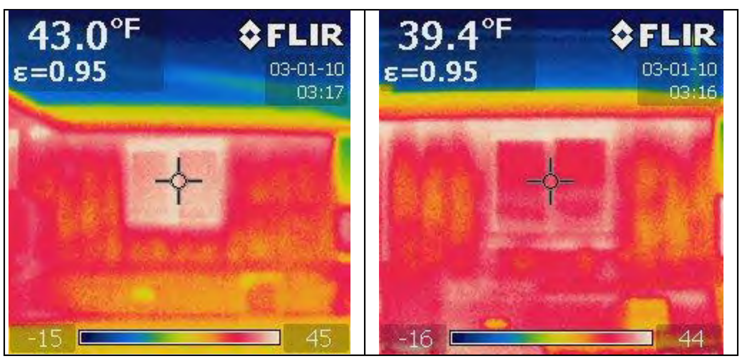


Figure 3. IR images of the exterior of a home without a low-e storm panel (left) and with a low-e storm panel (right); the light color of the window area in the home on the left shows significant heat transfer through the glass. Pictures were taken on February 2, 2015, when the average outdoor temperature was 34ºF.

Over a two-year period in 2013-2015, PNNL conducted a series of experiments in the Lab Homes to evaluate the thermal performance of both exterior and interior low-e storm windows when attached to a double-pane clear-glass window. Measured HVAC savings from the application of exterior storm windows averaged 10.5% for the heating season and 8.0% for the cooling season for identical occupancy conditions (Knox and Widder 2014). Based on these seasonal experimental results, the annualized savings were simulated to be approximately 10% (see Table 3). For the interior panel testing, the annualized HVAC savings were estimated to be 8% based on seasonal experimental results. Note, however, that due to limitations on the manufactured size of the interior storm windows, the sliding doors were not covered during the interior storm windows experiment, which resulted in only 74% of window area coverage during the test. During these experiments, thermocouple sensors on the surface of the glass depicted significant temperature differentials between the windows with and without storm windows attached, as depicted with the IR images shown in Figure 3 (Petersen et al. 2015). Because the primary windows on the Lab Homes are very air tight to begin with (i.e., very little infiltration) the storm panels resulted in only a modest reduction in infiltration for these experiments. In contrast to these results, testing in the field (in occupied homes) has shown significant reductions in infiltration when storm panels are installed (see Table 2).

Insulating Cellular Shades

Within the interior window coverings category, honeycomb cellular shades (see Figure 4) typically provide the highest added R-values because of their layered or concentric designs. Introduced in the 1980s, cellular shades are designed to trap air inside pockets that act as insulators. This design can increase the R-value of the window covering and reduce the conduction of heat through the window that it covers. Insulating shades can also impact solar heat gains. The insulating air pockets can include a layer of metallized Mylar that lines the air pockets, which minimizes conductive and radiant heat transfer, similar to the effect that a low-emissivity coating has on windows. Savings can be increased if the coverings are managed properly, by raising and lowering the shades at the appropriate times of day using either manual or automated means.

PNNL conducted multiple Lab Homes experiments to evaluate the thermal performance of triple- and double-cell cellular shades under various operation scenarios during the 2015–2017 heating and cooling seasons. These cellular shades were equipped with the Hunter Douglas motorization and scheduling technology, which allowed researchers to evaluate the thermal improvement under different operation schedules. To evaluate the full functionality of the shades and associated automation schedules, PNNL tested the cellular shades in comparison to a residential building without window attachments and in comparison to a home with the windows covered with standard vinyl venetian blinds. Experiments were also conducted with shade operation scenarios designed to reflect baseline conditions and energy use in the home when shades are used in a manner typical of many residential users (i.e., "typical use" settings), as informed by D&R International's 2013 behavioral study (Bickel et al. 2013). The savings are summarized in Table 3.

Figure 4. Hunter Douglas semi-opaque double-cell cellular shades which were tested in the PNNL Lab Homes, 2016-2017. Photo on right shows the amount of filtered natural light that enters the room when the shade is fully drawn down.

Some of the key findings from the studies are summarized below (Cort et al. 2018):

- High-efficiency cellular shades have significant energy-saving potential during the summer cooling season (25% HVAC savings compared to a home with no window coverings), but this savings decreases considerably if the larger view windows of a home remain uncovered during the day, particularly if these are west- or south-facing windows.
- High-efficiency cellular shades have significant energy-saving potential during the winter heating season, but at least some of the larger south- and/or west-facing shades should be operated (e.g., up during day and down at night) to fully realize these savings benefits.
- Cellular shades under "typical use" scenarios (i.e., some shades up and some shades down) do produce HVAC savings; however, when the high-heat-gain windows (i.e., large windows on west and south sides of a home) are left uncovered, the cooling season HVAC savings dropped from 25% to 5%.
- In all seasons and operation scenarios, cellular shades out-performed the typical vinyl horizontal slatted blinds (2%–15% average HVAC savings attributed to cellular shades).
- Commercially available automation could be coupled with thermostat setbacks to enhance residential demand-response programs and improve occupant comfort.

Exterior Shades

Exterior shades can come in various forms, including louvered shutters and roller shades. Exterior shades can protect existing windows from weather and provide solar heat gain control in the summer months (i.e., cooling season). They often can be adjusted to provide both view and privacy, as well as glare control. Exterior shades can be effective at blocking solar heat gain before it hits the building envelope or window, which makes this technology an effective energy-saving measure in the cooling season months. To examine the performance and comfort implications of exterior shades, PNNL is currently conducting a series of Lab Homes experiments applying black fabric[3] motorized exterior shades with a 1% openness factor (see Figure 5). Shades were installed over two large west-facing windows and one large south-facing window in the experimental test home, while interior vinyl blinds were used to shade these same

[3] Graber Lightweaves exterior shades, Springs Window Fashion.

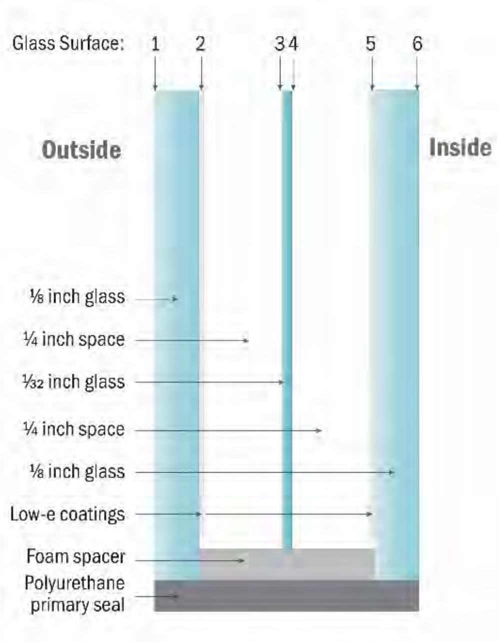
windows in the control home. The shades/blinds are kept down throughout the day. Experiments are ongoing, but preliminary results suggest that the application of exterior shades on these three windows resulted in cooling HVAC savings ranging from 12%-25% when compared to a home that uses interior vinyl venetian style blinds for these same windows.

Figure 5. Exterior shades are installed in the PNNL Lab Homes. The exterior shades provide privacy and reduce glare, while allowing views during the day. (Photo at right shows view through the shades from inside the home).

Triple-Pane and Thin Triple-Pane IGUs

The thermal performance of traditional primary window IGUs is determined by the combination of low-emissivity coatings, the distance between the glass panes, and the type of gas sealed between the glass panes. Adding layers of glass and gas can certainly increase performance. Triple-pane windows research by PNNL in the Lab Homes showed that conventional triple-pane windows can yield energy savings of about 12% annually (11.6% heating savings and 18.4% cooling savings in Richland, Washington) when compared with double-pane clear glass windows (Widder et al. 2012). The experiment also showed that the triple-pane windows provided more even temperatures throughout the home and warmer interior window surface temperatures during the winters (e.g., 76°F compared to 69°F in the baseline home). Standard triple-pane windows have been available for decades but have experienced very slow market uptake. Adding layers of glass adds weight and thickness to the insulated glazing unit (IGU) which can lead to costly retooling for the many window manufacturing plants who have production lines set up to manufacture window frames for double-pane IGUs.

Several options have been explored for developing higher performing windows without great increases in weight and thickness, including thin-glass triple-pane windows, thin film layers in the IGU, aeroseal gel, and vacuum insulated glass. While technically viable, production of many of these high-performance technologies has been limited and they have only captured a very small market share today due to the added complexity and cost of incorporating them into IGUs. To address this stagnation in both innovation and residential market uptake of the highest performance windows, DOE has undertaken a series of R&D efforts to address installation and market barriers.



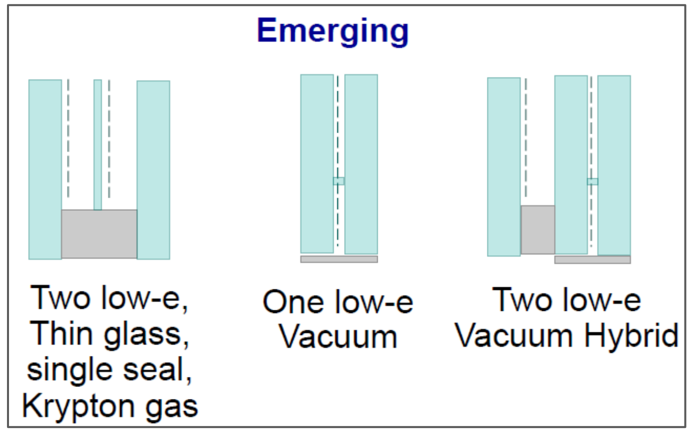


Figure 6. (Left) Thin Triple-Pane IGU; (Right) Three Emerging High-R Window Designs: the thin glass triple-pane IGU, Vacuum Insulated Glass, and a Hybrid design that integrates both VIG and conventional IGU design into a triple pane.

Aerogel and vacuum glazing are two of the most discussed IGU techniques that could significantly improve thermal insulation. Aerogel, a microporous, transparent material with excellent thermal properties, has shown promise in the laboratory but with over 30 years of R&D it is still not yet a commercially viable window option. Vacuum insulating glazing (VIG) is dual glazing with an evacuated gas space between the two layers of glass (see Figure 6). Small spacers, or pillars, are placed to maintain separation between the glass, and low-E coatings are used to reduce radiation exchange between the glass layers. A complex glass-to-glass seal at the edge is needed to hold the vacuum over many years. Commercial production of VIG is limited and, although there is ongoing development of this product in Europe, the U.S., and Asia, there is no existing production infrastructure in the United States (Selkowitz et al. 2018).

The "thin triple" IGU is another emerging technology that holds near-term promise as a cost-effective high-performance alternative, both from the supplier and consumer perspective. LBNL received a patent on the thin triple design[4] in 1991 and has worked to develop the IGU, which is ¾ inches thick like a double-pane IGU rather than the 1 ¼ to 1 ½ inch thickness of standard triple-pane IGUs. The thin-triple IGU uses two ordinary (1/8-inch) layers of glass sandwiching a thin (1/32-inch) layer of glass with a 1/4-inch gap on either side filled with

[4] Selkowitz, S.E., D. Arasteh, and J. Hartmann. 1991. "Thermal Insulating Glazing Unit," U.S. Statutory Invention Patent Registration, H975, Nov. 5 1991.

krypton rather than argon gas. Krypton performs better at this narrow gap space than does argon. The thin triple also has two low-e coatings (on the second and fifth surfaces) (see Figure 6). Some manufacturers have produced a thin-film version of the thin triple where the middle pane is a stretched polymer film rather than thin glass; however, this adds complexity to the production process and no manufacturer has undertaken production on a large scale.

Events over the past decade have increased the market viability of thin-glass triple-pane windows. The price of thin glass has dropped with its now widespread use in flat-screen TVs and monitors, cell phones, and tablets; the incremental OEM (original equipment manufacturer) cost for thin glass has fallen from $5/ft^2 in 2012 to about $0.60/ft^2 today. Krypton gas has also come down in price, from $3/ft^2 in 2012 to $0.50/ft^2 today, as supply has increased relative to demand now that halogen lights, which use krypton, are being replaced by LEDs. With these price reductions, the overall cost to manufacture thin-triple IGUs is estimated to be about $2-3/ft^2 more than the cost of producing a conventional double low-e IGU (not including supply chain and retailer markups).[5] An analysis by LBNL showed a simple payback of 5 to 7 years in all U.S. climates for a thin glass triple-pane IGU retrofit when the base case was an older double-glazed clear window and assuming a decision to replace the window was already made so there was no extra labor cost (Selkowitz et al. 2018).

In addition to its R&D efforts, DOE has sponsored complementary market-pull strategies including working with key stakeholders to identify and address barriers to high-R windows, test and validate emerging technologies, and develop market-sustainable solutions to the identified challenges. Barriers to adoption of standard triple-pane windows were researched from the home builders' perspective in a recent survey of high-performance builders in hopes of informing adoption strategies for the thin-triple technology (Gilbride et al. 2019). The builders interviewed for the study all participate in DOE's Zero Energy Ready Homes (ZERH) program, a labeling program for high-performance homes that integrates energy-efficient design elements with renewable energy systems that offset most or all of the annual energy consumption. For these home builders, a higher efficiency window could improve their ZERH score and provide a tradeoff against other building components to help meet a project's target energy score.

Of the DOE ZERH builders surveyed for this study, 41% use all triple-pane windows and another 28% install triple-pane windows in most or some of their homes. For builders who choose to install triple-pane windows, the overwhelming majority said higher performance was the primary reason. The most mentioned secondary reason that builders gave for using triple-pane windows was noise reduction followed closely by increased comfort and condensation reduction. Among builders who chose to install double- rather than triple-pane windows, reasons cited included cost, availability, not enough energy savings, no consumer demand, installation issues, and design issues (Gilbride et al. 2019).

Builders were also asked what impact, if any, triple-pane windows had on their HVAC systems. Half said it allowed them to reduce the size of their HVAC system. Over one-fourth reported that they can use mini-split heat pumps and that, even with ductless heat pumps, temperatures are even throughout the home, including along exterior walls with windows. A Habitat for Humanity builder from Michigan who installs triple-pane windows in all his homes,

[5] For perspective, the typical installed cost for a residential double-pane windows ranges from around $40/ft^2 (vinyl frame) to $120/ft^2 (or more) for wood-framed windows.

said that “having better windows has allowed us to have center throws for the HVAC ducts and we do not notice it being cold near the windows.” He noted that the insulating triple-pane windows and highly insulated walls he uses have allowed him to go to a smaller 15,000-Btu high-efficiency furnace. This builder noted that performance and significant water damage from condensation around double-pane windows in the winter were the primary reasons his affiliate switched to triple-pane windows (Gilbride et al. 2019).

A greater percentage of builders in the northern heating-dominated locations used higher performance triple-pane windows relative to builders in the south, which implies the overall benefit-cost ratio of these higher performing windows was perceived to be greater in these cooler climates. These findings align with the energy simulation results reported by Hart et al. (2019), which found triple-pane windows yielded the highest energy savings in cold climates like Minnesota.

Based on the assessment of barriers and potential consumer benefits, PNNL will be conducting studies in the PNNL Lab Homes to verify savings in comparison with double-pane clear glass windows. PNNL will also conduct field studies to validate benefits and address market barriers of the thin triple-pane windows. These will include field studies in occupied new and existing homes (single-family, multi-family, and manufactured homes) in Colorado, Michigan, Minnesota, Montana, New York, and Washington (Cort and Gilbride 2019).

Demand Response and Peak Savings

All of the window technologies examined in the PNNL Lab Homes produced savings that were commensurate with the peak demand period during the day, particularly during the summer months. Many types of blinds and shades have automated operation and can be set to open and close via predefined schedules for optimized management of solar gains throughout the year. With automated integrated controls, high-efficiency shades could be coupled with thermostat setbacks to enhance residential comfort and energy savings. For example, the PNNL cellular shade study included a demand response experiment that demonstrated that pulling down the cellular shades in addition to 4°F thermostat increase (set up) during the hottest period of the day not only produced overall HVAC savings (~17%) but also reduced the average maximum peak demand by an additional 700 Watts when compared to a home that did not deploy shades and only setup the thermostat.

Energy Rating, Utility Acceptance, and ENERGY STAR

One market barrier to achieving more widespread market penetration of energy-efficient window attachment programs and utility incentives is the lack of standardized ratings for such products. To address this issue DOE helped launch a voluntary independent rating council for energy-efficient window attachments, which has become known as the Attachment Energy Rating Council (AERC).[6] The purpose of the council is to develop a comprehensive energy rating, labeling, and certification program for window attachments that offers independent and accurate information about the energy performance of window attachment products. As of

[6] http://aercnet.org/

January 2019, AERC energy rating labels are available for storm windows,[7] and cellular shades are slated for certification and energy labeling in December 2019.

Until recently, energy-efficient window attachments have received only modest support in utility energy-efficiency programs; however, that may be changing. Bonneville Power Administration now recognizes the technology on its list of energy-saving measures.[8] In addition, Efficiency Vermont[9] and Wisconsin's Focus on Energy[10] have both completed very successful retail pilot programs focused on low-e storm windows, and Xcel Energy in Colorado will soon be launching a rebate measure focused on cellular shades.

In September 2018, ENERGY STAR added a certification for exterior and interior low-e storm windows.[11] ENERGY STAR is also evaluating the Attachment Energy Rating Council's proposed automation rating as part of its Smart Home Energy Management System initiative.[12]

Conclusions

The standard double-pane low-E argon-filled window (~R-3 insulating value) comprises over 90% of U.S. residential market sales and is able to meet all residential energy code requirements as well as most of the high-efficiency energy ratings (e.g., ENERGY STAR, Zero Energy Ready Homes) in the United States. The triple-pane residential window currently represents the highest energy performance (~R-5 to R-7) among the most commonly available residential windows; however, the conventional triple-pane IGU is both heavier and about one-half-inch thicker than the standard double-pane IGU, which requires window manufacturers to re-design their standard double-pane frame and sash to accommodate the added weight and width. Even though most major window manufacturers now have triple-pane windows available for purchase in multiple residential-style configurations, the overall market uptake of highly insulated triple-pane products remains around 2%, with little growth in the market share over the past decade (Selkowitz et al. 2018). Likewise, high-efficiency window attachments and shades also show relatively limited uptake in the residential market. In 2013, D&R International conducted a residential window coverings study (Bickel et al. 2013), which estimated that 82% of all residential windows have some sort of window covering; however, based on a review of shipment data, the most predominant window attachment by far is the relatively low-performing, vinyl, venetian-style blind, which makes up over 80% of shipments. This same D&R study also examined how residential occupants operated their shades and blinds and concluded that home occupants rarely move or adjust their window coverings throughout the day and the position of the window coverings is primarily driven by privacy concerns rather than energy performance (Bickel et al. 2013).

The research described here highlights the energy savings potential of window attachments and high-R windows. Considering the energy-savings potential of these high-efficiency windows and window attachments, these findings suggest there is a large market

[7] https://aercenergyrating.org/product-search/aerc-product-search/
[8] https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Pages/Low-Emissivity-Storm-Windows.aspx
[9] https://www.efficiencyvermont.com/news-blog/whitepapers/low-e-and-behold-low-e-storm-windows-provide-a-new-way-to-solve-the-window-conundrum
[10] https://focusonenergy.com/low-estorms
[11] https://www.energystar.gov/products/storm_windows
[12] https://www.energystar.gov/products/spec/smart_home_energy_management_systems_pd

opportunity to move consumers to higher-performance window technologies. For residential customers, the windows technologies highlighted in this paper offer a reduction in HVAC system energy consumption without sacrificing utility or comfort. On a broader scale, high-efficiency window technologies have great potential for reducing energy consumption in the residential sector and offer a cost-effective incentive option for utilities. The addition of energy ratings and labels for window attachment and field-validation research for high-R windows should help consumers, designers, builders, and home performance contractors make informed decisions about window retrofit and replacement options. There is also an opportunity to improve efficiency by encouraging "smart" operations of these devices, whether through education or automation. Together these opportunities could help to save some of the vast amounts of energy we lose through windows each year.

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LOW-SLOPE ROOFING SYSTEMS FOR MULTI-STORY RESIDENTIAL AND COMMERCIAL BUILDINGS

Rowland Smith[1], Ali M. Memari[2]

[1]Associate II, Wiss Janney Elstner Associates, Washington D.C. Office, 2941 Fairview Park Drive, Suite 300 Falls Church, VA 22042, E-Mail: rrsmith@wje.com

[2] Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering, Penn State University, 222 Sackett Building, University Park, PA 16802, E-Mail: amm7@psu.edu

Abstract

What exactly does failure mean? While many think of "building failure" as catastrophic condition where the structure collapses, it turns out the most frequent failures are serviceability level failures, meaning that some components stop functioning and cause problems for occupants or for the durability of the building. By this definition, we can classify roofing issues as one of the most common building failures. One of the most basic goals for building owners is to keep the building dry, in particular, when it comes to roofing systems. This goal cannot be achieved if the building is experiencing roofing failures and, in order to avoid this, an emphasis must be placed on the basis of design. By understanding the fundamentals of low-slope roofing systems that are common to multistory/high-rise residential and commercial buildings, one can begin to piece together the components that create and control a given system. For example, a building owner might ask "How will storm water be managed on my roofing system?" or "How does the climate of my building's location affect my roofing system?" The answers lie within the analysis of the components in these roofing systems.

The goal of this paper is to provide basic review of the most commonly used low-slope roofing systems. The most efficient way to avoid roofing failures is by not having them in the first place. Instead of discussing patches and fixes to existing issues, this paper is meant to offer some guidelines that can be useful in the selection process of the roofing system. Due to the complexity of roofing systems, an overview will be necessary prior to discussion of each specific system type. Part 1 will begin by introducing the functions and principles of roofing systems in general. Following that, Parts 2 and 3 expand on the most common types of low-slope roofing systems used for multistory buildings today.

PART 1: INTRODUCTION TO ROOFING SYSTEMS

General Roofing Functions

In order to understand what a roofing system is and what exactly it does for a building, it is best to start with a history of roofing construction. In primitive times, walls were constructed using mass masonry, a type of construction that relies on a thick stone barrier to inhibit the outside elements from getting inside. Similarly, roofing systems mostly consisted of one control layer that would deter the outside from getting in. The two main objectives were to improve occupant comfort and protect belongings by keeping water and uncontrolled air out of the building. As buildings became more advanced, additional control layers were added to these systems to increase the resistance to those unwanted elements. This advancement created better, more efficient shelter, but also added complexity to the system. How would these layers interact? In order to comprehend these interactions, we must understand the four (4) principal control barriers that make up a modern low-slope roofing system: water, air, vapor, and thermal control barriers.

Water Control Barriers

When humans started to realize that one layer simply did not perform the way we had imagined, additional layers were added to the building enclosure systems. On a general level, the function of the system did not change; we still want to keep water and unwanted air out. However, the additional layers added complexity to the system. Because roofing systems are constantly fighting gravity, supports were added to the system. Instead of one continuous water barrier, the barrier was layered in courses to prevent sagging or creep. We also learned that the outermost, or exposed, layer experiences natural deterioration over time and that protecting critical layers can go a long way towards increasing the longevity of the entire roof.

Air Control Barriers

Water is not the only environmental factor to be considered in a roofing system. After water, air is the next most important element to control. Keeping unwanted air out of the building, and conditioned air within the building, are desired in order to maintain thermal control throughout a building, and also to prevent moist air from entering in to places where it may stagnate or condense. Even if we assume that a roofing system is air tight, there are still two more environmental factors which need to be addressed: vapor diffusion and thermal diffusion.

Vapor Control Barriers

If we assume air and water are not penetrating through this system, the building should be warm and dry, right? The answer is maybe. If the system is not airtight, then vapor control is almost irrelevant because moist air will be able to penetrate through the air gaps. As Lstiburek mentions, "A point to this importance thing here, if you can't keep the rain out don't waste your time on the air. If you can't keep the air out don't waste your time on the vapor." (Lstiburek, 2010). If the system is watertight and airtight, then why are we concerned about vapor? As an example, think about a cold glass of iced tea "sweating" on a table on a hot humid day. The cold glass is below the dew point temperature in the room and the vapor in the air begins to condense on the glass surface. Buildings "sweat" in the same way, when there is inadequate management of temperature and moisture differences from interior to exterior environments, and if we are not careful, the condensation can cause damage.

Thermal Control Barriers

The final environmental factor that must be accounted for is thermal diffusion. In any mass masonry type of construction, it is apparent that a thick stone wall may prevent air and water from penetrating. However, it is not necessarily the best insulator. As we close our exterior barriers to air and water transfer, we must also consider the types of materials that are serving as the in between. Think about how well a metal silo will insulate versus a masonry or wooden structure. Two material properties are commonly used to quantify this idea, thermal conductivity and thermal resistance (i.e., R-value). The thermal resistance of the roof system is generally determined by the minimum requirements presented in the local energy code, but the selection of materials and installation methods for the thermal barrier within the roof assembly must still be carefully considered.

Major Types of Roofing Systems

The two fundamental roofing system configurations are steep-slope roofing and low-slope roofing. These two systems are defined by their stormwater management and the slope of the decking below the system.

Steep-Slope Roofing

Steep-slope roofing is defined by its water-shedding stormwater management. This idea is as simple as it sounds – any water that lands on the roof will flow down-slope and off the building due to gravity and shed away from the building. Steep-slope roofing is typically defined by the slope of the roof deck as equal to or greater than 25 percent (3 in./ft.). A very typical steep-slope system consists of three main elements: shingles, underlayment (roofer's felt), and substrate. The shingles are the first line of defense against water. Typically made of asphalt, clay, or metal, shingles must be able to shed water. The way to achieve this over a large area is to overlap the layers of shingles vertically as well as staggering courses horizontally to offset side joints.

The underlayment serves as the second line of defense to water penetration and as temporary waterproofing during the construction phase. It also can provide air and vapor control. In steep-slope roofing, the underlayment material is typically a felt (i.e., roofer's felt) or a synthetic material. Finally, the substrate provides continuity and acts as a transitional support layer between the roofing structure and the underlayment and primary roof covering. Gypsum board and engineered wood panels are common substrates because of their durability and relatively low cost. Steep-slope roofing systems are ideal for buildings that are not restricted by the adjacent areas and when footprint space is not terribly critical. This allows runoff stormwater to drain directly to the exterior. Due to footprint restraints and American architectural vernacular, steep-slope systems are typically reserved for residential buildings such as townhouses, single- and multi-family homes.

Low-Slope Roofing

Over time, low-slope roof assemblies were introduced to maximize usable interior space thereby improving the economy of large building construction; roof systems transitioned from steep-slope water-shedding assemblies to low-slope waterproofing barriers.

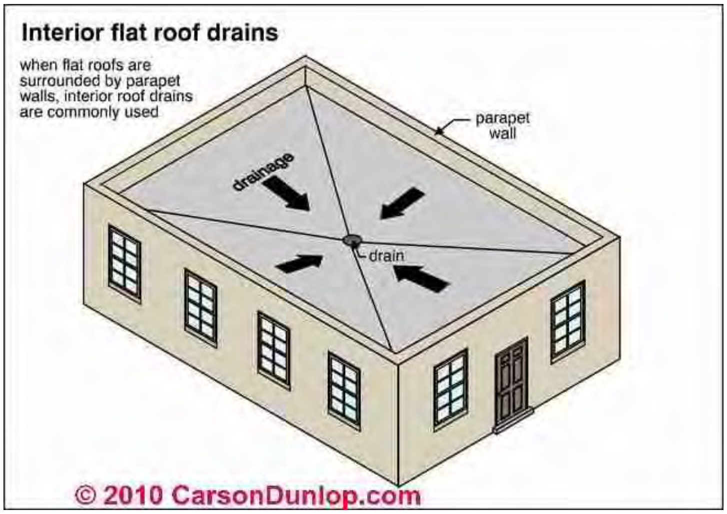

Figure 1. Simple Flat Roof Drainage System (Courtesy of Friedman, 2015; used with permission)

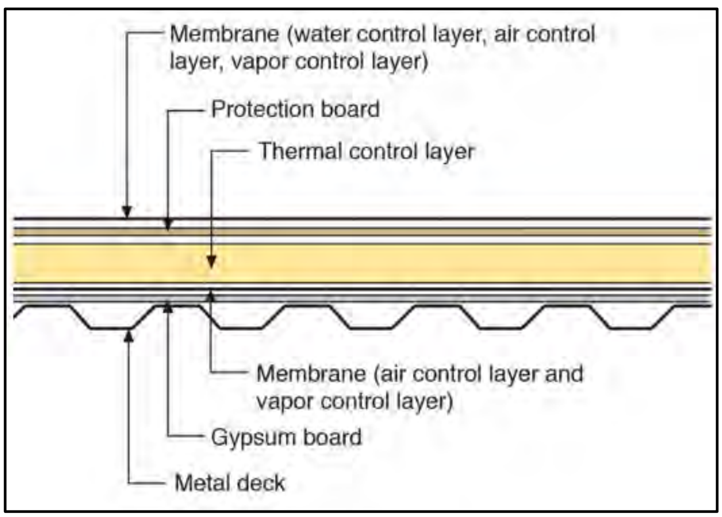

Figure 2. Low-slope Roof, Section View (Courtesy of Lstiburek, 2016; used with permission)

Low-slope (or flat) roofing is most commonly used in commercial settings. Instead of a water-shedding system, low-slope roofing systems utilize a watertight system that provides a path for stormwater to collect into roof drains (Figure 1). The roof drains and interior piping then carry the collected stormwater out of the building at its base. Though they are often referred to as flat roofs, Low-slope roofing systems are not truly flat – with few exceptions, the surface of the roof slopes towards the drains in a range of 2 - 25 percent (¼ in./ft - 3 in./ft).

Although we will get into more depth about low-slope roofing systems later on, it is important to understand the basic layers and functions of the low-slope system. Figure 2 is a detail section of a general low-slope system. Essentially, there are five (5) layers in this system: Roof membrane, coverboard, thermal insulation, air control layer, and decking. The roof membrane is the primary weather barrier against water and air movement. This membrane can be made up of a wide variety of materials, but the most common forms are either a bitumen based membrane or waterproof synthetic (rubbers and plastics) membrane. It is the primary barrier against the environment and therefore must be watertight. The next layer is a coverboard, which is typically a high-compressive strength material used to protect the insulation layer below and improve membrane durability above; cover boards may be optional depending on the assembly. Thermal Insulation is exactly what it claims to be. Its role is to inhibit heat transfer between outdoor and indoor environments. It may also serve a secondary function as an air and vapor control layer. However, the final barrier lies in the air and vapor control layer beneath the insulation. The permeability of this layer will depend on the project's location, but is essentially in place to inhibit vapor drive between interior and exterior assemblies. The final layer is sheathing, which serves as a fire control layer, but also as a substrate above the metal deck to provide a clean and relatively flat working surface.

PART 2: LOW-SLOPE ASPHALT ROOFING SYSTEMS

Asphalt Roofing Systems Overview

Asphalt roofing systems evolved from standard residential shingle roofing into a similar system of waterproof, asphalt layers. Instead of a small, loose-lapped shingles, the low-slope asphalt roofing is a series of fully-bonded large-format overlapping sheets or plies. Sheets have a dimensionally wider face and offer a variety of attachment methods. Wider faced sheets means less seams which makes sealing those seams very important. Instead of using roofing nails, the sheets are typically attached watertight with heated bituminous material (hot asphalt) or cold-applied bitumen mastics/cements. Another way to think about the asphalt system components is to compare it to the ingredients in concrete; where felts (or fabric reinforced sheets) are the aggregates for support and bitumen is the cement paste for stabilization. In this application, bitumen is also the waterproofing agent. Built-up and Modified Bitumen roofing will be analyzed in Part 2.

Built-Up Roofing

General System and Application

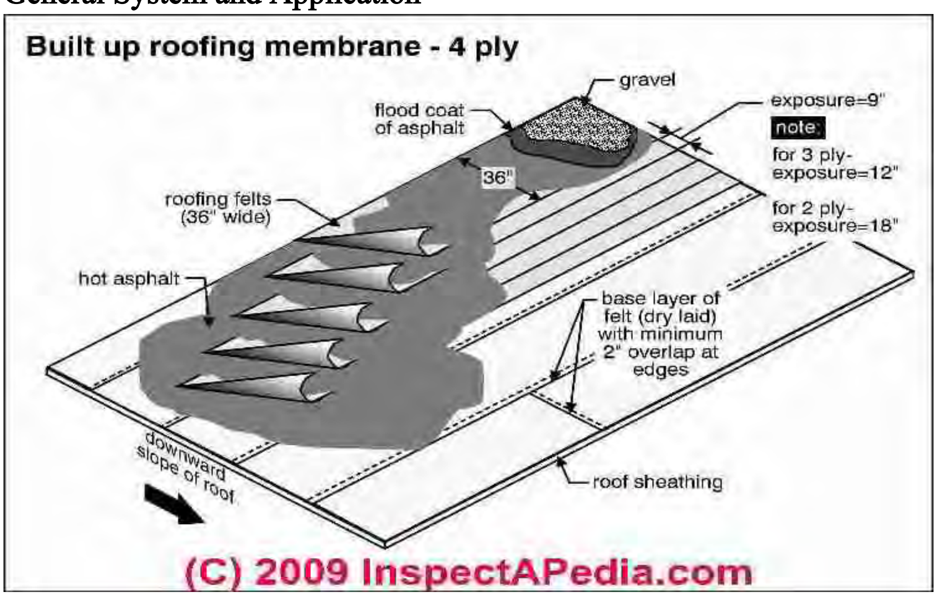

Figure 3. Built-up Roofing Detail, 4-ply
(Courtesy of Friedman, 2016; used with permission)

Built-up roofing (BUR) gets its name from the layering that occurs during installation. Built-up roofing has multiple overlapping layers of roofing felt or plies that are adhered together using hot or cold bitumen. The bitumen arrives in a solid form and is then heated to the point where it is a viscous liquid, or arrives in sealed containers where the bitumen is suspended in liquid form with plasticizing chemicals/solvents. A layer of liquid asphalt is first applied to the substrate. Then, layers or rolls of fiber felts are laid over top of the asphalt layer. This process is then repeated until a strong composite system, typically consisting of two to five layers, is established. These layers serve as the structure of the system, helping to provide a strong, composite water barrier. After these are left to cure or cool, a flood coat will often be applied to fully encapsulate the top felt ply. Often small gravel will be adhered into the surface of the flood coat for extra protection against UV radiation, heat gain, and foot traffic.

Total Assembly

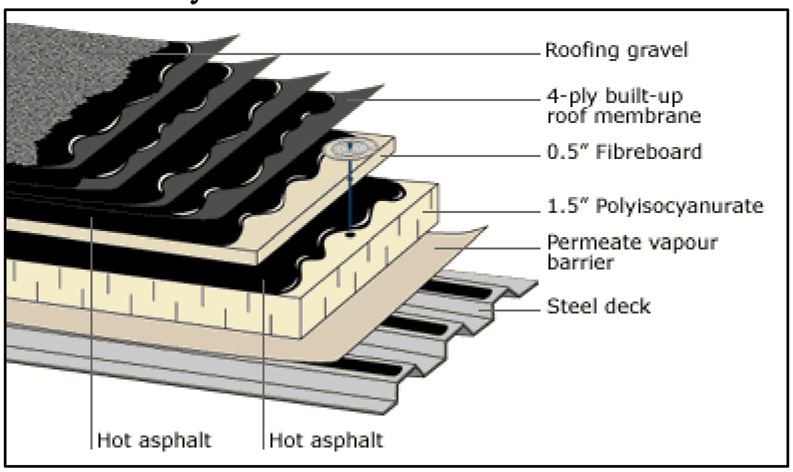

Figure 4. Built-Up Roofing Assembly
(Courtesy of Southern Coatings, 2019; used with permission)

Figure 4 is one example of a Built-up roofing assembly which we will dissect to understand the roles of each layer. Starting from the top layer, this system utilizes roofing gravel as its own entity. We mentioned earlier that gravel is for weather protection, and especially for protection against UV radiation since the asphalt-based membrane beneath is not fully resistant to deterioration from UV, and the membrane color is black and will absorb radiant heat. This layer differs from a mineral-surfaced sheet because the gravel is not manufactured into the sheet itself, rather it is applied in the field during installation. Below the gravel is a typical 4-ply built-up roof system. These 4-ply layers serve as the primary water barrier for this system. These layers will typically be adhered to one another by mopping bitumen between the layers to achieve a continuous, redundant water barrier. Next, there is a ½ inch fiberboard which acts as a rigid substrate for the first ply layer of hot asphalt, and also as a separation board between the membrane and the insulation. In this particular assembly, the fiberboard is mechanically attached to the metal roof deck for wind uplift resistance and adhered to the insulation below with another layer of asphalt. This final layer of hot asphalt also will help to fill in the joints of the insulation below to create a more continuous air control layer. Now on to the insulation, the thermal barrier of this system. This system uses a polyisocyanurate (polyiso) insulation, a rigid cellular foam insulation board. Polyiso has a relatively high thermal resistivity making it a common modern choice for our thermal barrier. The joints between overlying layers of coverboard and insulation should be staggered both vertically and horizontally to mitigate air movement within the assembly. Lastly, there is a vapor-permeable barrier between the insulation and steel deck. This layer serves primarily to stop the liquefied bitumen from passing to and through the metal roof deck during roof installation, but also provides air and vapor control on the interior side of the insulation. We should also note that the vapor barrier in this assembly is adhered directly to the steel deck below. The vapor barrier adhesive is likely used to hold the vapor barrier in place until the cover board is fastened through and down to the decking. The vapor barrier material is not rigid, and over time (if not during installation) the vapor barrier will likely deform due to the lack of support between flutes of the steel decking. A substrate board between the vapor barrier and metal decking would help to mitigate sagging of the vapor barrier.

Summary

Although it is becoming less popular among owners and designers, primarily as a result of installation safety concerns with the use of hot asphalt kettles and its relatively labor-intensive (high cost) installation, there are still many benefits from using built-up roofing as the membrane for your roof. As a general rule of thumb, five years of service life is added with each layer of roofing ply (i.e., 3-ply equals 15 years, 4-ply equals 20 years) (Griffin and Fricklas, 2006, p. 209). Because built-up roofing used to be the most popular roof system, it is relatively easy to find contractors who are familiar with repairing and maintaining the system, but new installation contractors may be difficult to locate in some regions of the country where the roofing market has generally moved on from new BUR installations. Often times the irregularities in a roofing system, such as pipe penetrations or mechanical equipment, are where failures start. Penetrations are relatively simple to detail in built up roofs which allows for more flexibility in installation. On the other hand, because there are more components to this system, attention to detail during installation is imperative. Earlier we discussed that built-up roofs are topped off with a mineral (or gravel) surfacing to protect the membrane. In addition to protection, the mineral surface provides stiffness to the membrane. Although this stiffness is desired for membrane stability, it can also promote cracking under extreme temperatures. Built-up roofing will require routine maintenance to mitigate of these failures. Maintenance of built-up roofs requires the application of hot asphalt, which can be a hassle to coordinate on the roof of an occupied building.

Modified Bitumen Roofing

General System and Application

Figure 5. Mod-Bit Installation
(Courtesy of Rockholm, 2019; used with permission)

Modified Bitumen roofing (mod-bit) is a system of polymer modified asphalt sheets. Mod-bit is an evolution of built-up roofing that was originally spurred by the industry's focus on pre-fabrication to reduce overall installation costs, as well as rising oil prices and increased interest in alternate non-asphaltic roof membranes. In contrast to built-up roofing plies, mod-bit roofing sheets contain both the waterproofing and strength qualities needed for the roofing membrane. Mod-bit sheets are essentially hardened rolls of fabric-reinforced asphalt that have been modified with polymers to increase desired roof membrane properties, such as flexibility and weathering resistance. Mod-bit roofing can be considered as an intermediate development stage between built-up roofing and single-ply systems where, "…modified bitumens thus enable the roof designer to exploit the labor savings of a new factory-fabricated component without sacrificing the toughness of traditional built-up roofing" (Griffin and Fricklas, 2006, p. 265). Mod-bit installation (Figure 5) looks very similar to built-up roofing installation, but there are typically fewer total layers, less overlapping, and therefore less overall asphalt. Mod-bit roofing sheets can be adhered with the same hot asphalts as in BUR assemblies, cold adhesives, or by torch application. Cold adhesives contain much of the same components as the other adhesives we have mentioned, but as the name indicates, cold adhesives do not need to be heated for installation. The mod-bit sheets are mostly a bituminous material; therefore, torch-application simply melts the bitumen from the bottom of the sheet and uses it to fuse the overlying sheets together without any additional adhesives.

There are two predominant types of modified bitumen roofing sheets - APP and SBS - as defined by the bitumen modifiers. APP, or atatic polypropylene, is "plastic" modified bitumen. SBS, or styrene butadiene styrene, is "elastic" modified bitumen. In grossly oversimplified and generalized terms, APP has better UV radiation and weathering resistance, but less elastic flexibility to accommodate substrate movements than SBS. Selection of APP vs. SBS is oftentimes defined by an ingrained regional preference based on experience and performance history, but also manufacturer marketing efforts.

Total Assembly

In Figure 6, the top layer consists of a mod-bit cap sheet with a UV-resistant granular-surfacing infused into the sheet at the factory. The "250" number is a specification reference to the density of reinforcement in this membrane. Next, the base sheet has a top surface covered by a film that is burned off during torch-welding and a bottom surface that is sanded, which allows for hot-mop or cold adhesive applications. These two sheets should have horizontal and vertical staggering, like how insulation is layered. The "2.2N" refers to the base membranes nominal thickness of 2.2 mm (or 87 mil) and the "95" is the area density of the reinforcement, 95 g/m².

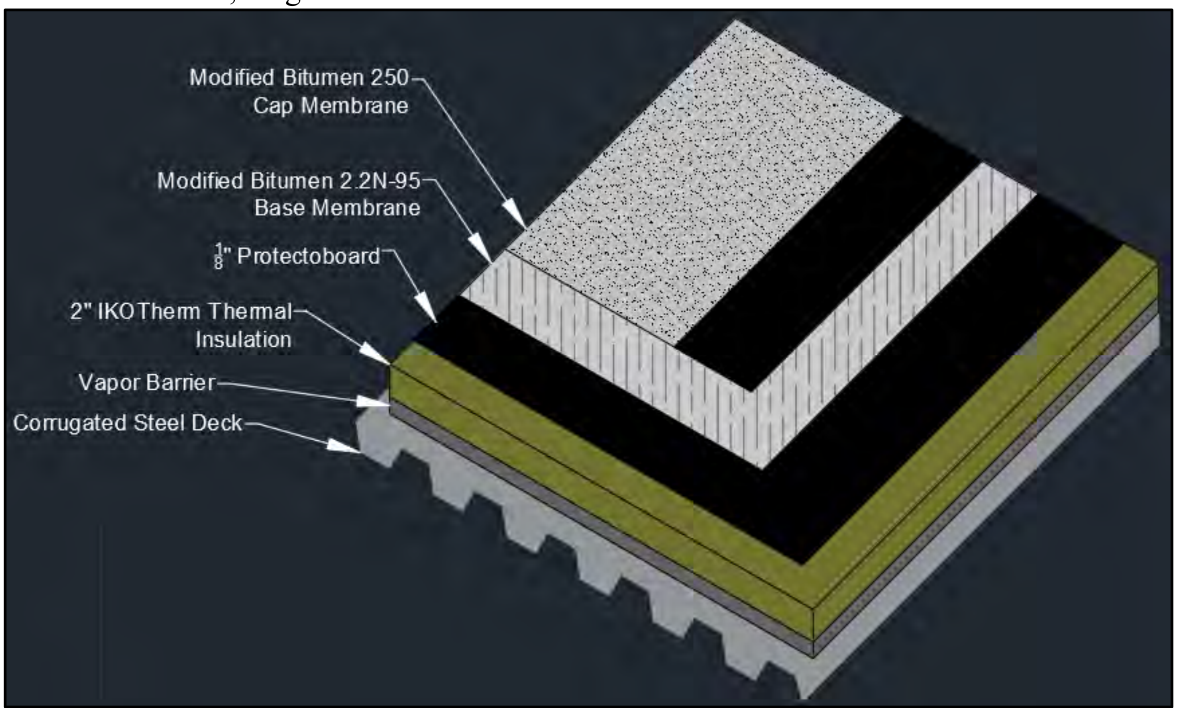

Figure 6. Modified Bitumen Roofing Assembly
(Image adapted from source: Roof Maintenance, 2015)

The *Protectoboard* is essentially a stable substrate, similar to the fiberboard in the BUR assembly. However, this *Protectoboard* material is also an asphaltic material, with the intention that it will act as an additional water resistant layer. It provides protection for the insulation below and adds another layer of waterproofing material, making this system a hybrid between a two-ply and three-ply mod-bit system. The thermal barrier is polyiso, rigid insulation. As we mentioned before, polyiso has a high thermal resistivity and provides some stability to the membrane system. Lastly, there is a vapor barrier between the insulation and steel decking for this particular assembly. Similar to the BUR example, the steel decking is corrugated so it would be advisable to include a substrate board between the vapor barrier and decking to prevent sagging and long-term fatigue failure of the vapor barrier. In most regions, we would expect this vapor barrier to be semi-permeable. This will allow any moisture that finds its way through the entire roofing assembly to be able to move back out of the system. Often times in hot-humid or hot-dry regions, the vapor barrier will not be included on the interior-side of the roof insulation because vapor drive from the building's interior is less likely to result in condensation within the roof system, than in cold climate regions.

Summary
More popular than built-up roofing but less popular than single-ply, mod-bit roofing is still a very reliable and cost-effective roofing system. The cost of labor savings of mod-bit is most obvious when compared to built-up roofing construction. Instead of three to five layers of felt plies field installed with intermittent coats of bitumen, mod-bit systems feature two to three layers of factory-manufactured material. In built-up roofing, we mentioned that more layers generally translate to a longer service life for roofing materials. A two-ply mod-bit system will likely have a shorter service life than a three-ply mod-bit. Even though mod-bit has fewer total layers than built up, the mod-bit membrane layers are stronger and more uniformly constructed, such that a three-layer mod-bit system can be constructed with similar service life expectations to four or five ply built-up. Often the service life of mod-bit systems can exceed 20 years without much maintenance (Improvenet, 2019). Mod-bit sheets are more flexible and ductile than built-up roofing, which makes detailing around pipe penetrations in the roof somewhat easier than with the plies of a built-up roof. Mod-bit was and still is a relatively popular roofing system, so contractors are generally familiar with the installation and repair.

We have discussed how mod-bit systems offer various methods of installation. Before selecting the type of mod-bit system to install on the building, it is important to consider the installation methods recommended by the membrane manufacturer and supported by the type of modified bitumen being used. SBS-modified membranes can be applied using hot-mopped-asphalt, cold-adhesives, or torch application. APP-modified membranes cannot be hot-mopped, and may only be applied by torch application and more-recently cold-adhesives. Each of these application techniques has advantages and disadvantages for the installation crew's safety, efficiency, operation cost, and quality of work.

PART 3: LOW-SLOPE SINGLE-PLY ROOFING SYSTEMS

Single-Ply Roofing Overview
Over the past few decades, the building industry has been shifting away from asphalt roofing systems and towards synthetic single-ply systems. In contrast to multiple layers of membrane that asphalt roofing systems utilize, Single-ply systems consist of a single membrane. Because there are fewer layers of roofing membrane, installation of Single-ply roofs can generally occur in a shorter duration than asphalt roofs. Roof installation is a major milestone for construction sequencing because it is a critical step in securing a dry building. Once the building is watertight, many of the interior installations that require a dry atmosphere can begin (e.g., drywall installation). Given this, any efficiency in roofing installation can be key to a successful construction project, while also providing labor cost savings for the roof installation itself. There are many formulations of single-ply roofing membranes previously or currently used in the construction industry. The three most common types at present will be analyzed in Part 3: EPDM, PVC, and TPO.

EPDM Roofing

General System and Application

Ethylene Propylene Diene Monomer (EPDM) is a synthetic rubber material that is common in single-ply roofs. EPDM sheets are manufactured in large rolls (10-50 feet wide) and like mod-bid roofing are installed as a single layer sheet with minimal overlap. In contrast to mod-bit, EPDM is a synthetic rubber and does not contain any asphalt. EPDM is a relatively strong, flexible waterproof membrane, where, "Their breaking strains range upward from 200 percent, compared with 2 percent or even less for built-up membranes" (Griffin and Fricklas, 2006, p. 293). This inherent material flexibility means that EPDM membranes do not need uniform attachment to the substrate below. Instead they can be ballasted, adhered, or mechanically fastened at their seams. A ballasted EPDM system is often referred to as "loose-laid" because the primary stability of the membrane is provided by laying ballast (commonly stone aggregate or concrete pavers) over the membrane. In this system, the membrane is only anchored to the substrate at the perimeter and at openings within the roof. The seams are typically adhered, taped, or adhered-and-taped together. The ballast typically adds an additional dead load of 10-20 psf, which must be accounted for in the structural design of the building, and may add cost to its construction. The movement and distribution of the ballast can be labor-intensive but overall installation time is still significantly reduced (Figure 7).

Figure 7. Ballasted EPDM Roofing Installation
(Courtesy of Goodman, 2013; used with permission)

Another installation technique that has been universal in our discussions about roofing systems is the cold-adhered attachment method. In cold-adhered systems, an adhesive is spread atop the substrate, and then the membrane is applied over top of the adhesive. After the membrane is applied, the adhesive will be left to cure, securing a bond between the substrate and the EPDM membrane. More unique to single-ply systems is the mechanical attachment method. EPDM sheets are laid over the substrate and are attached to the structural deck with mechanical fasteners at sheet edges. The adjacent sheet is then lapped over and attached with a seaming tape.

Total Assembly

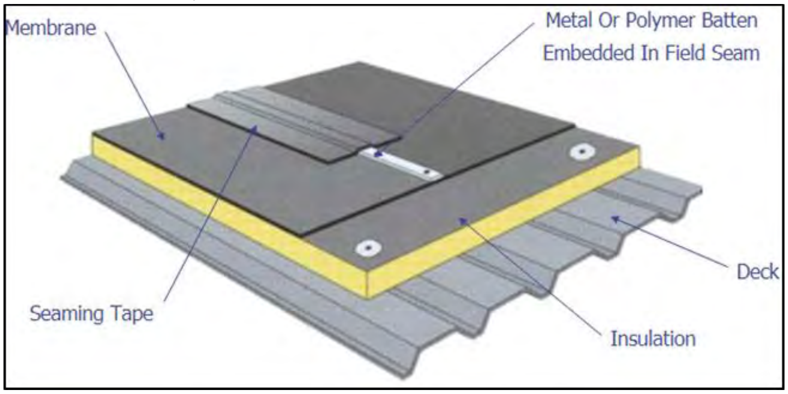

Figure 8. EPDM Roofing Assembly
(Courtesy of Hoff, 2019; used with permission)

Figure 8 is an example of an EPDM roofing assembly. First, let us take a look at the seaming of the adjoining EPDM membranes. The membrane sheet on the top side of the seam has been attached to the sheet on the bottom side using a mechanically fastened metal or polymer batten. After the two membranes are connected, a seaming cover tape is applied over the seam to provide watertightness. This step is similar to the taping method that we discussed for ballasted systems. Below the membrane is the thermal barrier of insulation. Remember that because the membrane does not require hot asphalt or asphaltic adhesives, there are more applicable insulation options. Although the absence of a coverboard may provide some cost savings, it forces us to select a rigid insulation of sufficient rigidity (compressive strength) to support the membrane system and overburden, and provide durability against food traffic or hail. Common insulation types utilized with EPDM membranes include polyiso, Extruded Polystyrene (XPS), and Expanded Polystyrene (EPS), but other types are also applicable. Insulation selection must be compatible with the membrane attachment scheme selected, anticipated foot traffic and/or overburden, assembly fire ratings, and have an ability to dry out after short-term wetting without significant deterioration in the event of a local roof failure and repair. The pictured assembly does not include an air/vapor barrier between the insulation and the roof deck. We should consider including a vapor control layer and substrate board below the insulation, especially in cold regions or whenever vapor drive from the interior is a more pertinent issue, or as required by local building codes.

Summary

As mentioned earlier, EPDM has many advantages regarding simplicity during installation. Installation of a single-ply is much faster than two- or three-ply systems. The variety of attachment methods offer versatility for the roof system assembly and construction installation. EPDM membranes are also much more durable in terms of breaking strain strength than asphalt systems. In a study done by the EPDM Roofing Association, EPDM membranes, especially ballasted, were found to have relatively unchanged tensile strength, tear resistance, and ultimate elongation after 20+ years of service and exposure. They additionally report that 30-year warranties are now available for EPDM systems (EPDM Roofs, 2019). Carlisle, a major manufacturer of EPDM roofing, has found that "…ballasted EPDM roofs have the lower warranty claim rates per square foot based on the infrequency of problems and system design" (Goodman, 2013). One of the limitations that EPDM has historically had is its seaming techniques. Because it requires self-adhering tapes or contact adhesives, EPDM might be a better selection on a roof with fewer penetrations and better drainage slope.

PVC Roofing

General System and Application

Polyvinyl Chloride (PVC) roofing is another common single-ply membrane type, so the installation and function of the system is similar to EPDM. However, unlike EPDM, PVC is classified as a thermoplastic material; EPDM is a thermoset material. PVC roof systems support a variety of attachment methods: loose-laid ballasted, through-membrane mechanical fasteners, electromagnetic induction welding to concealed fasteners, or adhered with bonding adhesives. One of the major differences between EPDM and PVC membranes for roofing purposes is their welding capability, whereby the thermoplastic membrane becomes “plastic” when heated to a certain temperature and then returns to its solid form upon cooling. Hot air welding is an application method when the membrane is heated with hot air using a hand-held gun welder (Figure 9) or automatic welding machine to temperatures where the membrane becomes pliable and hot enough to fuse the seams of overlapping PVC materials.

Figure 9. Hand Gun Welding
(Courtesy of Schofield, 2019; used with permission)

Automatic (or “robotic”) welders are preferred because they are programmed to operate with uniform heat application and speed to create tighter seams, are safer, and faster for crews to use than hand gun welders. The programming can be adjusted and calibrated for to each membrane type/thickness and ambient jobsite conditions at the time of seaming. However, these automatic welding machines are typically only useful for long straight membrane lap seams and cannot be used for detail work; hand welders are needed for detail work. Although welding provides advantages in terms of installation efficiency, the real advantages comes with the quality of seams. When properly welded, the seams on thermoplastic roofs (PVC is a thermoplastic) are actually stronger than the membrane itself (Fricklas, 2007). Additionally, PVC membranes can be welded at any time throughout their service life.

Induction welding is an attachment technique that combines mechanical fasteners with the weldable properties of PVC. Fasteners fitted with PVC bonding plates, are installed in the membrane substrate (secured to the metal roof deck) prior to membrane installation, and then electromagnetic induction welders are used to weld the backside of the PVC membrane to each bonding plate. Induction welding offers an advantage over traditional mechanically fastened membrane systems because it does limit fastener locations to seams or require covering membrane patches at field fasteners. Though we mentioned that thermoplastics can also be attached using other methods, those methods are covered in the EPDM section and most of their attributes remain the same for thermoplastic membranes.

Total Assembly

Because PVC is a single-ply roofing system, this assembly will look very similar to the figure that was analyzed for EPDM. We will analyze Figure 10, a fully adhered PVC roof assembly. The top layer is the roofing membrane, a fully adhered PVC material modified during manufacture with a KEE plasticizer. (Note: KEE plasticizer is a solid-state plasticizer that can be added to PVC material during manufacture to improve long-term exposure resistance and improve dissimilar material compatibilities that would reduce membrane lifespan through plasticizer migration. KEE-modified-PVC and KEE membranes are both available at an increased material cost over PVC membrane not modified with KEE).

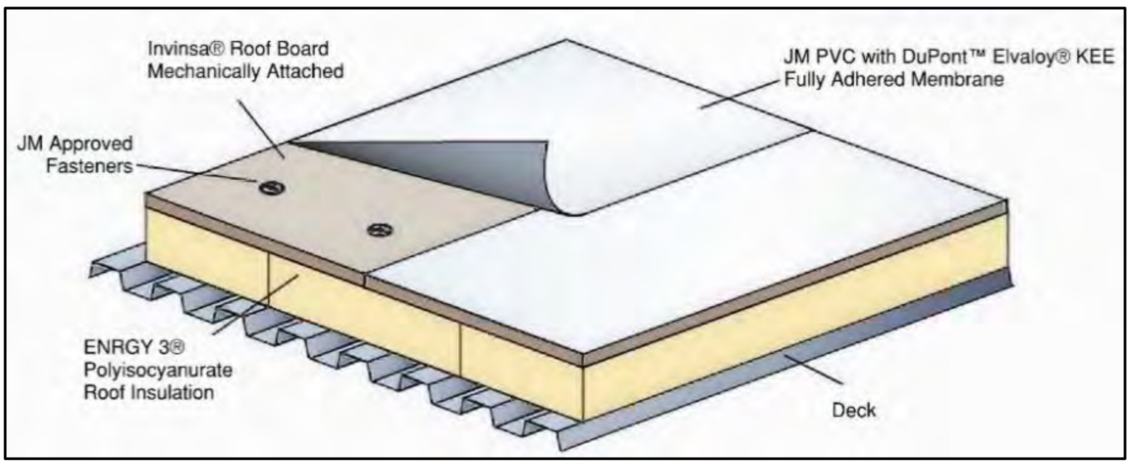

Figure 10. PVC Roofing Assembly

(Courtesy of Shapiro, 2019; used with permission)

Below the PVC membrane is mechanically fastened Invinsa® Roof Board, a high density polyiso coverboard with coated fiberglass facers to provide resistance to mold growth and an acceptable substrate for membrane adhesion. Unlike fiberboard or gypsum coverboard, the high density polyiso coverboard can meaningfully contribute to the thermal barrier of the assembly. This board is mechanically fastened through the lower layers and into the metal decking below. The ENRGY 3® Polyisocyanurate is very similar to the coverboard but is lower density and more economically efficient for use as the main thermal barrier for this system. We should also note that it is important to separate the insulation layer from the PVC membrane, especially when the insulation is a polystyrene board and the PVC membrane has not been modified with KEE plasticizers. Polystyrene boards are incompatible with direct contact to PVC roof membrane, resulting is plasticizer migration and loss of roof membrane flexibility/durability long-term (Smith, 2016). Figure 10 uses a polyiso insulation, so that is not so much of a concern in this system, but a coverboard helps to provide redundancy to the system as a preventative measure. Like the EPDM assembly, there is no vapor barrier in this example, which may not be appropriate for all buildings and locations.

Summary

In this section we introduced thermoplastic roofing membranes and focused more specifically on PVC membranes. Thermoplastics have a different chemical makeup than thermosets (EPDM) which gives them different material properties. Thermoplastic membranes are capable of being heat-welded which offers great efficiency and quality of installation. Because seaming is completed in a more homogenous manner, without pressure-sensitive adhesives, thermoplastics are advantageous on buildings with many roof penetrations. In addition, PVC membranes can generally be more easily welded at any time throughout their service life than TPO membranes. PVC membranes contain plasticizers to create flexibility. Due to relatively cheap materials, efficiencies of installation, and increased popularity, thermoplastics are a relatively cost-effective roofing option.

TPO Roofing

General System and Application

Figure 11. TPO Roofing Assembly
(Courtesy of Dykstra, 2016; used with permission)

Thermoplastic Polyolefin (TPO) is a thermoplastic material very similar to PVC. TPO, however, does not contain chlorine which can make thermoplastics difficult to adhere to. TPO is modified with ethylene-propylene (EP) rubber to mitigate those adhesion issues while providing low-temperature flexibility. Additionally, TPO does not require plasticizers. Because TPO is a thermoplastic, it offers a similar variety of attachment methods: ballasted, through-membrane mechanical fasteners, electromagnetic induction welding to concealed fastener plates, or adhered. Mechanically fastening TPO is very common because it is the fastest and cheapest method for contractors to install. The fasteners allow for spacing between connection points, whereas fully adhered systems are uniformly attached to the substrate. However, the VOC-limit-compliant adhesives used on a fully adhered systems typically require a temperature of 40°F or higher. If the roof is being installed during the winter, additional construction measures may need to be taken (e.g., temporary heating enclosures). As we have been discussing, TPO is very similar to PVC so many of the same principles are carried throughout both assemblies.

Total Assembly

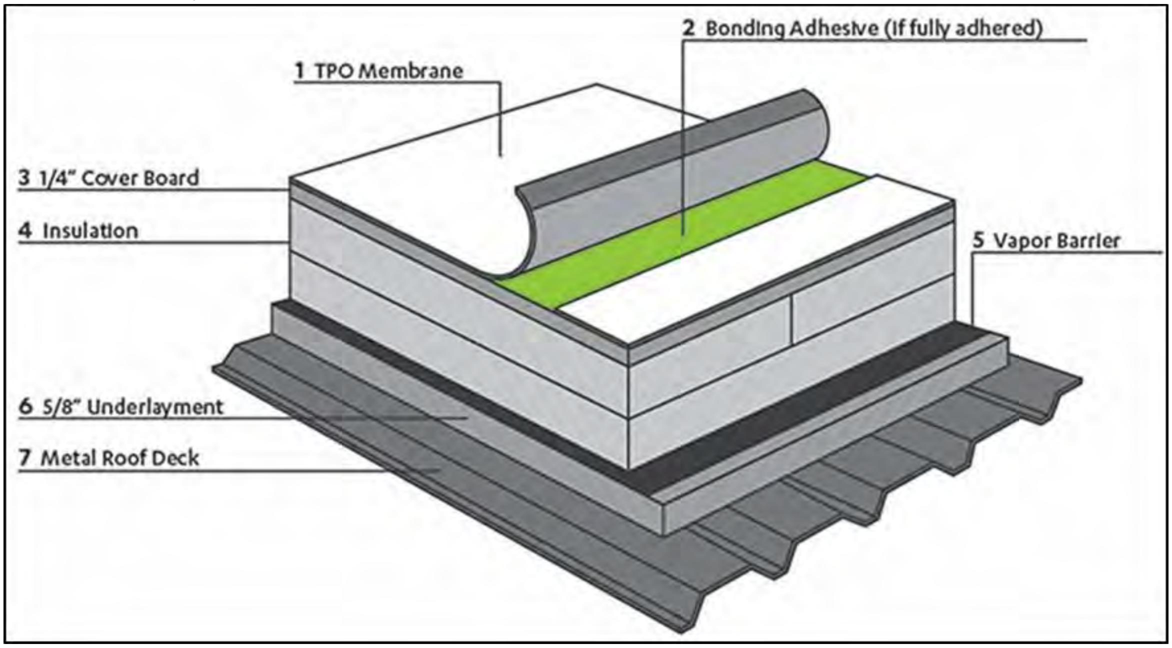

Figure 12. TPO Roofing Assembly
(Courtesy of Dykstra, 2016; used with permission)

The top layer of this assembly is a TPO membrane which appears to be fully adhered. Membrane lap seams will be hot-air welded. Below the membrane is a cover board to provide the membrane with stability and improved puncture resistance. Although not specified in this detail, the coverboard would commonly be fiberboard, fiber-glass faced gypsum roof board, or high density polyiso. Next, we have two layers of insulation, most likely a polyiso material. This is the first example that we have seen with two layers of insulation. Insulation thickness, and resultant R-value, will depend on local building energy code requirements, but the key takeaway here is that insulation is typically recommended for insulation in at least two layers with staggered overlying seams to mitigate air movement through the assembly and improve thermal efficiency. This example does not specify the attachment method for the insulation, so we have some options. In most cases, the insulation can be attached using a different method than the roofing membrane, so it could be adhered, fastened or adhered and fastened. After our thermal barrier, we can see the vapor barrier layer and a substrate board (5/8” underlayment) providing full support (and probable fire resistance) over the metal roof deck.

Summary

In this section we furthered our discussion on thermoplastic roofing membranes and more specifically on TPO membranes. Thermoplastic membranes are capable of being installed with a variety of different methods. Different attachment methods can determine construction barriers and can affect the assembly of the entire system. Additionally, TPO does not require plasticizers. That being said, it is important to consider the physical composition of TPO. The layer of polymer above the scrim is the waterproof layer and its existence is crucial to the integrity of the overall membrane; this is true for TPO, and any other single-ply reinforced membrane for that matter. Once moisture can infiltrate to the reinforcing scrim, the membrane deterioration will accelerate rapidly. The top polymer layer is much thinner than the actual thickness of the entire TPO sheet. Typical TPO sheet thickness are 45-, 60-, and 80-mil. As a very general rate, the top layer of polymer in TPO deteriorates by roughly 1-2 mils every year (Graham, 2013). On average, an undisturbed 45-mil TPO membrane will only last twelve years, whereas an 80-mil TPO membrane might last upwards of thirty years. Like its PVC cousin, TPO is advantageous for roofs with a lot of penetrations due to hot-air welded seaming capabilities and the membrane's flexibility. Similar to PVC and some EPDM, TPO also is manufactured in a variety of different colors, making it favorable in areas where heat gain is a concern or membrane solar reflectance is mandated by building code.

Summary and Conclusions

We began this report in Part 1, by explaining what exactly the function of a roof is in terms of water, air, vapor, and thermal barriers. Once the functions were established, we dove into the characteristics that differentiate a steep-slope roof from a low-slope roof. Because this report is meant for commercial buildings, we focused on low-slope roofs. Two types of asphalt roofs, built-up and mod-bit, were analyzed in Part3. After the asphalt systems had been established, Part 3 focused on single-ply roofing systems. Of the single-ply systems we focused on the three most common types: EPDM, PVC, and TPO.

This report is meant to give building owners a background of the most common commercial roofing systems. Many times when designers or builders ask for an owner's input on decisions, it comes with the burden of needing to educate the owner before explaining the situation. The idea behind this report is to provide owners with some of that knowledge prior to having those conversations, to ensure a meaningful yet concise conversation about their building.

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Thin shell concrete enclosures in residential buildings

P. I. Moyano Fernandez[1]

[1] Assistant Professor, Department of Architecture, Washington University in St. Louis, One Brookings Drive, St. Louis, MO 63130
Phone: 314-935-3361, email: moyano@wustl.edu

ABSTRACT

Building enclosures fulfill different functions at different scales. They define, connect and separate indoor and outdoor environments while controlling the thermal flow to create habitable spaces. In addition to performing as the air, water, moisture and temperature barrier between exterior and interior conditioned space, building skins can also serve as part of the building's structural system. But most importantly, the outermost layer of the exterior wall is the component of the building that receives the greatest exposure to natural forces. Therefore, it needs to perform effectively over the lifetime of the building. As a physical interface of spatial and environmental exchange, the design of building enclosures must be comprehensively assessed in terms of function, aesthetics, feasibility, durability, maintenance and cost. Consequently, building enclosure systems are sophisticated assemblies generated through complex processes that merge design, science, technology and craft.

Concrete has a long history as a building material. But, it was not until the last few decades that precast concrete flourished to become a viable and competitive alternative to other more traditional, well-established materials within the building industry. Yet, precast concrete is still rarely used in the single-family residential market in United Sates. With the development of new technological advancements in building materials, concrete has seen several improvements, among which the reduction of its thickness is one of the most remarkable. Today, concrete has achieved unprecedented thinness, diminishing its weight and still maintaining its strength and integrity.

This paper discusses the use of Ultra High Performance Concrete (UHPC) in thin shell concrete assemblies as a performative component of residential building envelopes. The CRETE House, Washington University in St. Louis's proposal for the 2017 Solar Decathlon, is introduced as a case study of the use of an innovative precast concrete wall assembly in a single-family residence.

Key words:
Concrete, precast concrete, precast sandwich wall panel, UHPC, building enclosures, CRETE House, thin shell concrete, Solar Decathlon 2017

PAPER

Concrete then and now. Concrete is the most common man-made substance on earth. An equivalent of forty tons of this material exists for every person on this planet; meanwhile, an additional one ton per person is added every passing year (Courland, 2011). Its plasticity provides this construction material a unique versatility, making it ubiquitous in visible and invisible applications throughout the history of civilization.

As a remarkably adaptable material, concrete allows for endless morphological configurations, while offering a wide range of possibilities, both to the technology and design fields. It is plastic and malleable when mixed; becomes hard, strong and durable when cured. It can be cast in place or pre-manufactured. Concrete can be pumped, poured, cast, sprayed, molded, formed, carved, split, cut and 3D printed. It is susceptible of multiple finishes such as stained, dyed, painted, textured, troweled, printed, rough, coarse, sand blasted, etched and polished. It can hold a wide spectrum of fine and coarse aggregates, byproducts of other industries (fly ash, silica fume, among others) and reinforcement types. All of these attributes makes concrete a very adaptable and sustainable material.

Although, we can track the use of concrete as far back as to the Egyptian and Roman civilizations, its long history as a building material somehow virtually vanished in the Middle Ages, until it was gradually revamped starting in the eighteen century.

> In a historical perspective, the works carried out during the centuries between those of the romans, but before the inventions of the eighteen century appear as brilliant but sporadic attempts to update a technique with extraordinary potential, waiting for a new empire to take form that would substantiate and determine the progressive establishment of that technique, the empire of what would be defined as nineteenth to twentieth century capitalism, with its demands for economic construction by non-specialized workers, and speed of execution of magnificent works of engineering for a new dominion of the landscape (Gargiani, 2013).

Concrete opened up a vast range of possibilities providing modern architecture a versatile material to explore new kind of structures and assemblies. As Palley has remarked, “It took the explosive growth of industry, construction and population in the twentieth century to reawaken the ancient art of stone making. Today the use of concrete has swelled into a torrent, which is sweeping away all before it. The world is being paved over” (Palley, 2010).

Despite its widespread applications by the construction industry, today concrete is still not widely used by the US housing market beyond building foundations. However, significant efforts to promote the use of the material in the residential market, including *domestic concrete* (Collins, 1959), were made early in the twentieth century by cement manufacturers. In the 1905 *Architectural Record* article entitled “Villas all Concrete”, de Kay points out that unlike in wood, stone and masonry construction, concrete provides uniformity and unity to the walls due to the absence of joints. In addition, the author continues by highlighting the durability, fire and waterproof capabilities of concrete exterior wall assemblies. Contemporary to this, there were other attempts of prefabrication as well as other innovative uses of concrete such as a concrete homes cast in a single mold by Thomas Edison. Edison designed a system that consisted of detachable molds, costing a fraction of traditional houses. Concrete was pumped in few hours and once the material was cured, the molds were stripped in four days (Building News, 1906).

Precast Concrete. Concrete can be cast in place (also known as site cast or cast in situ) or precast (also known as cast off-site). Site cast concrete is a flexible method adaptable to virtually any design. However, it is costlier, more labor and time intensive, as well as contingent to job site impacts and weather conditions. Conversely, precast concrete is manufactured and cured off-site usually in climate controlled facilities, which results in unparalleled quality assurance and a safer process, that allows for design flexibility with much shorter production times. These characteristics, in addition to strength, durability and cost, have made of precast concrete a preferred method increasing its demand significantly in the construction market in the last years.

Prefabrication or precasting has been associated with reinforced concrete since the mid-nineteen century (Koncz, 1968). Precast concrete, originally known as “artificial” stone production, rapidly gained momentum in the early years of the twentieth century. By 1918 the British Precast Concrete Federation was formed (Taylor, 1991). As Koncz notes, “The prefabrication of residential buildings in concrete and reinforced concrete was taken in hand after the First World War. The most advanced experiments were made with storey-height wall panels, installed with cranes in Germany, namely, at Braunheim and Munich” (Koncz, 1968). Yet, similar precast systems were also being developed around this time in other European countries as well as in America initiating a new era in construction.

Standardized precast concrete products such as double tees, hollow core slabs, and beams have been used extensively in infrastructure in addition to commercial applications offering a wide range of benefits when compared to traditional materials and construction methods. In the last few decades, precast concrete has positioned itself within the building industry as a viable and competitive alternative to other traditional and well-established systems. As new technologies have emerged, concrete has experienced a number of improvements. Perhaps, the most important has been the reduction of its thickness which has been brought about by the development of concrete admixtures and alternative reinforcing technologies. These methods have stretched the material to unprecedented thinness thereby, diminishing its weight while at the same time maintaining its strength and integrity.

Precast Sandwich Wall Panel. Precast sandwich wall panels are comprised of two concrete wythes separated by a layer of rigid foam insulation. In the United States, sandwich panels became commonly used in the precast industry as early as the 1960s. However, precedents can be found as far back as the beginning of the twentieth century. In 1900, an eight-story office building in Washington DC, was designed by Leon E. Dessery. Some of its exterior walls consisted of a 3” outside layer and a 4” to 5” inside one, reinforced with 3/4” wrought iron bars, and linked at intervals with ties (The Builder, 1900). Over a century later, such original concrete wall panel assembly evolved to incorporate rigid foam insulation in the once empty air chamber.

Today, there are three types of sandwich panels: non-composite, composite and partially composite. A *non-composite* sandwich panel is analyzed, designed, detailed, and manufactured so that the two concrete wythes act independently. Generally, there is a structural thicker wythe and a nonstructural thinner one. *Composite* sandwich panels are analyzed, designed, detailed, and manufactured so that the two concrete wythes act together to resist applied loads. The entire panel acts as a single unit in bending. This is accomplished by providing full shear transfer between the wythes. *Partially composite* sandwich panels have shear ties connecting both sides, but those connectors do not provide full composite action. The bending stiffness and strength of this panel type fall between those of fully composite and non-composite sandwich panels (PCI Committee on Precast Sandwich Wall Panels).

Ultra-High Performance Concrete (UHPC). UHPC is typically formulated by combining portland cement, supplementary cementitious materials, reactive powders, limestone and or quartz flour, fine sand, high-range water reducers, and water. Fibers such as high carbon steel, PVA, glass, and carbon among others, are generally included in the mixture to achieve specific requirements. (The Portland Cement Association).

In addition, given its high flow and self-compacting characteristics, the material is highly workable and easy to mold. It also provides high precision when reproducing textures as well as intricate mold configurations, which are challenging when working with traditional concrete panels. A wide range of custom color pigments can be added to the mixture and clear-coat sealants can be applied to further protect the surfaces from fading, surface staining, and graffiti.

UHPC is 10 percent denser than conventional concrete, due to its optimized gradation of the raw material components. The nanometer sized, non-connected pores throughout the cementitious matrix contributes to its imperviousness and durability against adverse conditions or aggressive agents (Henry, 2014). UHPC performs well in terms of abrasion and chemical resistance, freeze-thaw, carbonation, and chloride ion penetration. Based on ion transportation predictive modeling, it would take 1,000 years for UHPC to have the same level of chloride penetration as high-performance concrete does in less than 100 years. The potential for building façades with a millennium-long design life, along with little to no maintenance and less environmental impact over time, is a huge paradigm shift from the way sustainable infrastructure is viewed today (Henry, 2014).

Solar Decathlon 2017. The participation of Washington University in St. Louis in the 2017 Solar Decathlon competition offered a unique opportunity to test the concept of a concrete single-family residential home using an unprecedented precast wall assembly. Precast concrete panels were designed to provide the building with high-performing characteristics in terms of thermal mass, structure and resiliency while being aesthetically pleasing. The intent was to demonstrate the material feasibility as part of a prefabrication process which relied on mass-production and product optimization. One of the main challenges of this competition was the nomadic nature of the building. Therefore, the design was heavily dependent on precise and well-calibrated panels and connections, a reliable and rapid assembly/disassembly process and dimensions in compliance with ground transportation limitations. Although concrete is often perceived as a static and heavy material, this innovative precast system provided a versatile alternative capable to accomplish the competition strict demands and conditions in addition to offering a light-weight and more flexible alternative than traditional precast concrete.

CRETE House. Washington University in St. Louis's first ever entry into the U.S. Department of Energy Solar Decathlon was based on the design and construction of the CRETE House. The multi-disciplinary team consisted of more than 150 talented students mentored by skilled faculty and industrial partners. The house heavily relied on a number of collaborations with precasters to execute the project entirely out of concrete panels. In particular, the team collaborated with Gate Precast and Ductal Lafarge North America Inc. for the production of the wall panels. The house was first assembled on Washington University's campus and then transported to Denver where it participated in the 2017 Solar Decathlon Competition (see Figure 1) from October 5-15. The CRETE House was awarded second place in the Architecture Contest.

Figure 1. CRETE House, Denver, CO (Photo by Richard Nodle)

The CRETE House proved precast concrete to be a compelling and sustainable construction option for the single-family residential market in comparison to traditional wood light frame systems. High performance precast concrete structures are inherently resilient protecting against fire, moisture, mold, insects, seismic events, extreme weather conditions and man-made phenomena such as blasts, force protection and acoustic mitigation. This innovative integrated advanced building technology project was designed to provide a strong, durable and maintenance free envelope.

The massing of the house consisted of a single precast concrete 2:1 rectangular volume with an east-west orientation conforming an area of 995 sq. ft. with a central core that divides the interior space into two private rooms on the east side and a public area (living, dining and kitchen) on the west side (see Figure 2). The central core contains all wet areas including a full bathroom, the main counter for the kitchen, the laundry area, mechanical, electrical, plumbing and fire suppression systems as well as storage for the bedrooms.

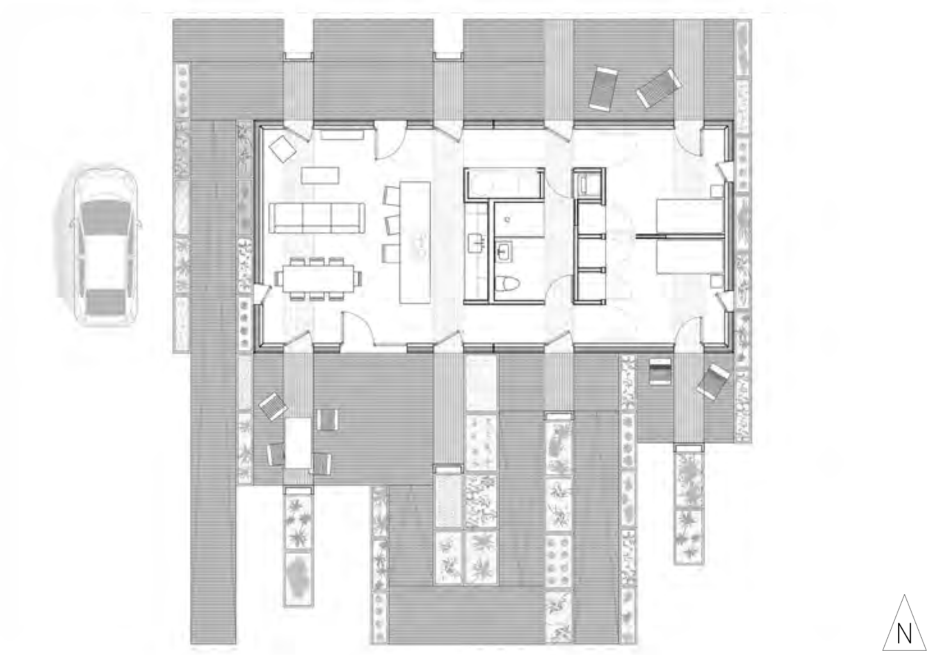

Figure 2. CRETE House floor plan

The house was originally designed as temporary housing for visiting scientists at Tyson Research Center in Eureka, Missouri; where it was intended to be permanently installed after the competition. Full height windows and doors allowed for natural light penetration and cross-ventilation. The massing of the house is modulated by north-south protruding concrete gutters, determining the location of building openings. The gutters also performed as sun shading structures. Another important attribute of the gutters was that besides framing the outdoor space, they were the armature of a home garden system that would facilitate a self-sufficient lifestyle. The gutters were designed not only to collect water, but to serve as a vertical planting surface supporting a hydroponic system that would allow for the growing of fruits, vegetables and herb that could be harvested nearly year-round (see Figure 3). An additional benefit of the guttering system was that this ecological house was equipped with a cistern located below the deck, where rainwater collected from the roof through the gutter system was stored. As a result, this water could then be later pumped from the cistern to the vertical and horizontal planters as needed, thereby, minimizing the use of potable water for irrigation purposes (see Figure 4).

Figure 3. Productive landscape

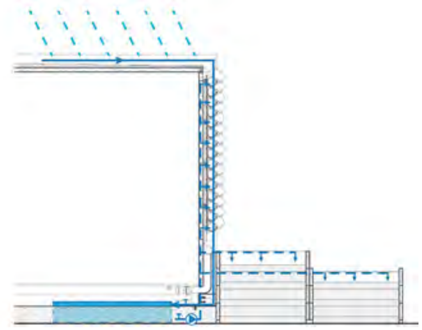

Figure 4. Integrated rainwater harvesting and irrigation systems

Given the nomadic nature of the project and for convenient transportation and erection, the building was developed as a panelized modular system. The precast concrete system consisted of exterior structural non-composite sandwich wall panels, composite floor slabs, strip footings, single wythe roof slabs, gutters, kitchen counter top and fiber cement planters. The non-concrete elements were minimized to steel framing components for the interior core, and aluminum frame for the composite outdoor decking planters. The windows, doors, electrical conduits and pre-cut electrical wiring and chases, radiant heating and cooling coils, lighting track racks, and all exterior finishing are highly integrated in the precast pieces.

The exterior shell of the house was erected in three days. Traditional precast construction usually employs welded connections. However, since the house had to be assembled and disassembled multiple times, the CRETE House relied on dry panel connection system that used embedded threads and bolts to connect all precast components. A total of forty structural precast components were assembled in sequence using multiple non-conventional connecting points custom designed for this project (see Figure 5). Since the vast majority of the house was built out of precast concrete panels, the finishes were developed based on the properties of the different types of concrete utilized in the project.

This panelized system substantially minimized on-site work, greatly reducing contractors and sub-contractors cost compared to traditional approaches. In addition, prefabrication drastically decreased manufacturing times and material waste while increasing the overall construction quality.

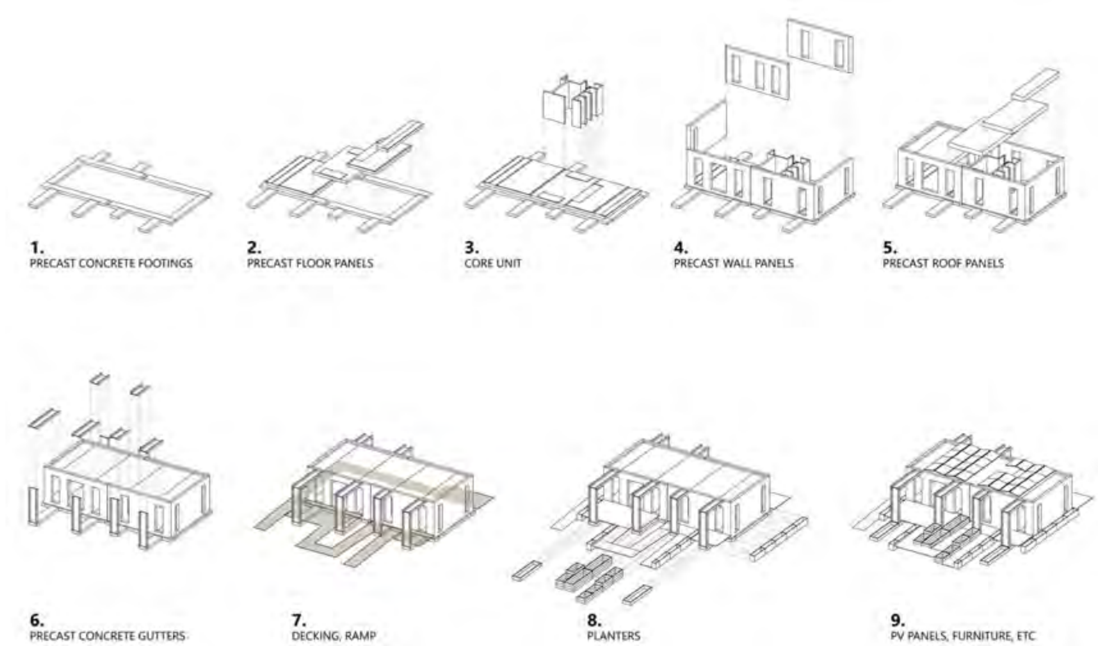

Figure 5. Precast concrete assembly sequence

Thin Shell concrete enclosure. As part of an integrated advanced building technology, the CRETE House enclosure was developed as a non-composite panelized precast concrete system with thin shell exterior walls using Ductal®, a type of UHPC. Ductal® is a very dense high quality cementitious material defined by its exceptional strength, ductility and durability. It provides compressive strengths up to 29,000 pounds per square inch (psi) and flexural strengths up to 7,000 psi. It is six times stronger than the average 5,000 psi compressive strength provided by traditional concrete. The material is blended with metal or polyvinyl alcohol (PVA) fibers to increase its flexural strength. The replacement of traditional steel reinforcing with these fibers allows for a substantial reduction of the overall thickness of the panel while maintaining its integrity and strength. In addition, UHPC's inherently waterproofing characteristics makes this innovative material a suitable alternative to building envelopes.

A total of six exterior wall precast concrete sandwich panels were built for this project. Each wall panel consisted of 4" structural concrete for the interior wythe of the assembly, 5" of rigid extruded polystyrene insulation (XPS) and 1.25" UHPC on the exterior wythe (see Figures 6 and 7).

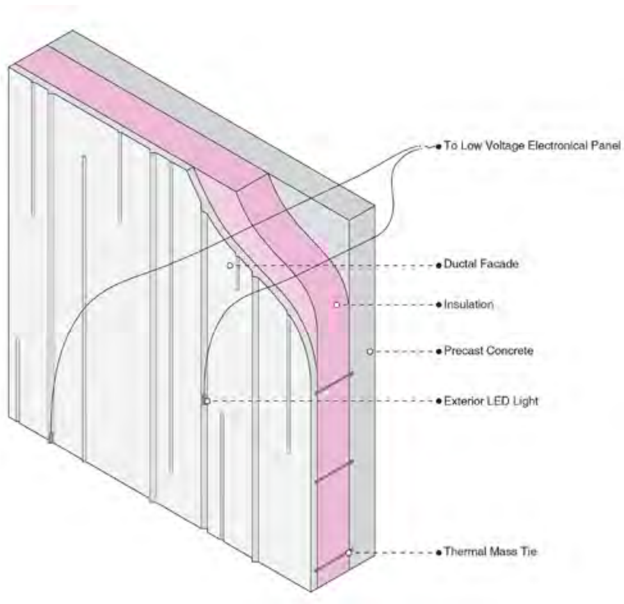

Figure 6. Wall Panel components

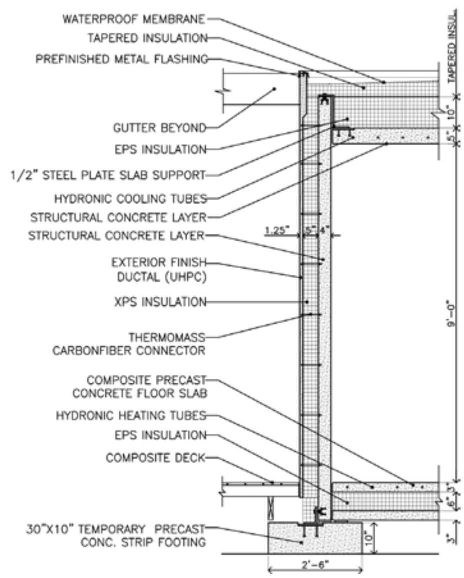

Figure 7. Detail Wall Section

This thin exterior layer drastically reduces not only the thickness of the wythe from 3” to 1.25”, but also the overall weight of the assembly in comparison to traditional precast sandwich panels, lowering the total volume of concrete and therefore, decreasing the initial and recurrent embodied energy. This was the first time that a UHPC wythe was used in a concrete sandwich panel as part of a structural wall assembly.

With a total R-value of 25.2 hr·°F·ft² /BTU, the assembly utilized Thermomass® fiber-composite tie connectors to neutralize thermal bridging through the insulation. From a thermodynamic standpoint, the concrete envelope had the ability to use its inherent thermal mass and thermal storage for comfort and energy savings. Its high specific heat capacity allowed the building to perform as an active thermal battery, a balancing system to moderate diurnal effects from climate fluctuations. During the winter the building mass, coupled with south facing glazing openings, maximizes the passive solar heat gain potential, minimizing the use of active mechanical systems and reducing energy use and associated costs.

Extreme Weather Resistant Envelope. Precast concrete panels are resilient against extreme weather including hurricanes and tornadoes. On average, the state of Missouri experiences over thirty tornadoes a year (Missouri Climate Center, 2011). In order to demonstrate the impact resistance capability of the CRETE House envelope, a tornado cannon test was conducted by Dukane Precast, one of the partners for the project. A series of 15 lb. 2x4 wood studs, representing debris often present during extreme storms, were blasted at three different wall sections samples at a speed at 60 mph, which is equivalent to an EF-1 tornado. In addition, a fourth sample was tested with impacts at 100 mph, which is equivalent to an EF-5 tornado with a 260 mph vortex matching the FEMA 320 live wind test for tornado shelter.

Below there are a series of figures illustrating the results of the cannon test conducted. Sample A (see Figure 8) shows a typical residential wood-framed wall (plastic exterior vinyl-siding, ½" exterior sheathing, R-19 insulation and ½" drywall interior). In this case, the stud penetrated the assembly completely. Sample B (see Figure 8) represents a typical commercial building brick wall, framed with 2x6 wood studs (full brick exterior layer, ½" sheathing, R-19 insulation and ½" drywall interior). In this second test, the stud penetrated the assembly completely. The precast concrete wall section shown in sample C (see Figure 8) is a mockup of the CRETE House (1.25" UHPC exterior wythe, R-19 foam insulation and 3" standard precast concrete). In this third test, the stud cracked the surface, but did not penetrate the assembly. Last, for sample D (see Figure 8) the thickness of the UHPC wythe was increased to 2.5" and the stud was shot at 100 mph and shattered with the impact without penetrating or cracking the wall at all.

Sample A | Sample B | Sample C | Sample D

Figure 8. Cannon Test - Sample A (vinyl siding): stud penetrated through assembly. Sample B (brick): stud penetrated through assembly. Sample C (1.25" UHPC): stud cracked, but did not penetrate assembly. Sample D (2.5" UHPC): assembly undamaged.

In summary, the precast concrete sandwich wall assembly with UHPC used in the CRETE House proved to be quite resistant against flying debris due to extreme weather conditions and safe for its occupants.

Enclosure design and integrated lighting. The unique pattern on a precast concrete façade of the CRETE House was made possible thanks to the use of a high precision material like Ductal®. The vertical pattern on the exterior envelope emulated the strong presence of trees in the surrounding forest at the house's final site at Tyson Research Center. Varying in depth, width, and length, the reveals and ridges provided a dynamic exterior finish by creating ever changing shadows throughout the day (see Figure 9).

In addition, large reveals, extruding 3/4" in and out of the surface, hid the exterior lighting integrated within the wall panels. Downwards-facing ¼" LED lights placed sporadically across the façade accentuated the pattern by creating slivers of light across the surface at night. The exterior lighting was seamlessly integrated into the precast concrete envelope highlighting its innovative feature (see Figure 10).

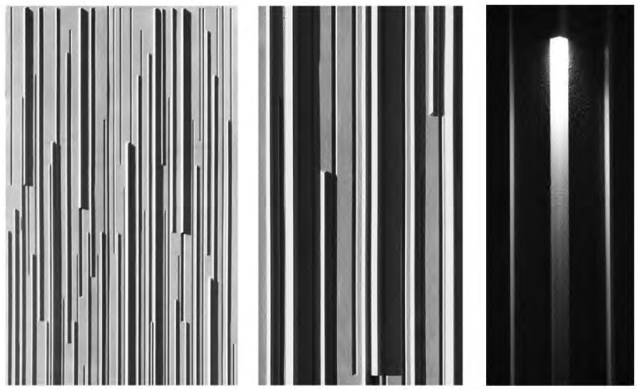

Figure 9. Façade Pattern: afternoon, evening and night

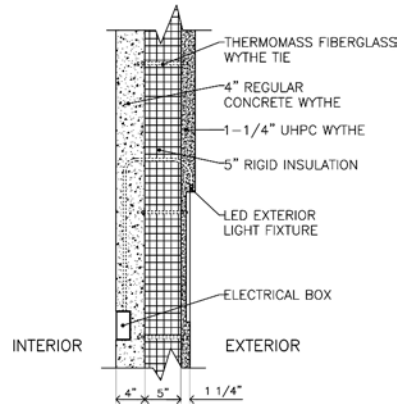

Figure 10. LED light fixture Integrated in UHPC wythe

Conclusion. Buildings produce substantial environmental disturbances, that range from the depletion of natural materials, to the generation of waste, and to methods of construction, operation and maintenance of such structures over their service life. According to the U.S. Green Building Council (USGBC), buildings account for an average of 41 percent of the world's energy use. Consequently, professionals and leaders of the building industry can greatly influence the way in which buildings and other structures impact the natural environment. Design decisions such as the selection of materials and types of assemblies can directly and indirectly reduce negative impacts. Current construction practices in the United States predominantly use materials with a relatively short lifetime, usually not more than thirty years. "We have built a disposable world using a short-lived material, the manufacture of which generates millions of tons of greenhouse gases" (Courland, 2011). Concrete construction, in particular UHPC, offers much longer lifespan buildings with minimum to no maintenance, while providing a stronger and more resilient alternative than traditional methods. High-performance building enclosures rely on design excellence as well as lower operational energy consumption.

The CRETE House showcases a precast concrete home as a viable option for the residential market that is efficient, safe, durable and resilient. It constitutes a test-bed for technological advances in architectural design, materials and construction. The project's ultimate goal is to demonstrate innovative design solutions that positively influence the building industry, and to provide the next generation of architects and engineers with new feasible options to minimize the impact of buildings to the planet.

The configuration of the building enclosure for the CRETE House was critical to the overall success of the building. Taking advantage of the concrete mass in terms of thermal, structural and aesthetic properties, the innovative precast concrete panelized system was able to maximize the performance of the enclosure while providing a robust alternative to withstand extreme weather events such as hurricanes and tornadoes. The use of a precast concrete panelized system that included a layer of UHPC on the outside face of the wall was intended to provide a longer life cycle option that cut down on material usage, weight, waste and production time, allow for a faster and more accurate construction process, increase its imperviousness and gain flexibility in design. The panels not only worked as the building enclosure, but also as the structural frame acting as loadbearing, resisting shear, wind loads and seismic actions. Consequently, the CRETE House effectively ameliorates the typical disruptive dynamic between the natural and build environment by using an alternative material that can successfully withstand extreme environmental conditions resulting of climate change.

The proposed construction system can be easily adapted to larger scale housing projects. Moreover, this unique panelized system is susceptible to be mass produced significantly reducing its cost, and therefore making it a very competitive alternative to traditional wood and steel frame construction in residential projects. Its superior fire resistance and effective sound barrier properties, among other characteristics mentioned above, makes precast concrete an optimal choice for multifamily projects. In addition, both sides of the precast wall panels can be finished off-site, reducing the overall time of construction.

The project provided very valuable learning experiences to all parties involved. The interaction between academia and the industry proved to be very productive and contribute to develop a holistic perspective on building technology, in particular applied to building envelopes. The opportunity to design, engineer and build an innovative precast concrete assembly such as the one used in the CRETE House was a demonstration of how a rigorous design along with the latest technological advances can lead to a high-performing, robust, durable and resilient alternative for single-family residential construction.

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Open Building:
Planning Multi-unit Residential Buildings for Change

Dr. Stephen H Kendall

Professor Emeritus, Ball State University Department of Architecture. Co-chair, Council on Open Building, 220 West Durand Street, Philadelphia, PA, 19119. 765.749.1312 / sk@infillsystemsus.com

ABSTRACT

This paper argues that there are pragmatic reasons to plan multi-unit buildings for change. Change of standards, life-style preferences and demographics among others are inevitable. Change is normal during the initial planning and construction of buildings but also over time. Adopting an infrastructure model of buildings helps.

An infrastructure model of buildings dis-entangles the long-lasting parts from the parts that change faster. In multi-unit residential buildings, this means disentangling the parts and spaces of the building that are shared by all inhabitants from those that belong to or are decided per/unit of occupancy. There is growing evidence that smarter planning-for-change practices pay off, producing more sustainable buildings. The name given to these emerging practices is Open Building.

This paper presents one case in the Netherlands and one in China. PATCH22 in Amsterdam was initiated by an architect / developer. Each floor plate in the 7-story CLT (cross-laminated timber) building can be divided into between two and eight units. Each floor and each dwelling can be different at no additional cost.

The Chinese case is UNITY TECH. This company has delivered more than 60,000 infill packages in the last three years, fitting out spaces one-unit-at-a-time in large multi-unit residential towers left empty by the general contractor. Using four-person installation teams, they complete each apartment in seven days. Every apartment is accounted separately. Unity Tech saves 50% in time and 65% on materials waste and offer a 3-year warranty. Using their product also offers savings on repair/remodeling for developers. Other companies in China are offering a similar service. Lessons from the OPEN BUILDING approach are drawn for application in the United States.

KEY WORDS: Infrastructure model; Open Building; Planning for Change

INTRODUCTION

Building design professionals must consider the time dimension in their work, because individuals, society and technology are not static. Because of social dynamics and an evolving technical repertoire, buildings cannot be designed with the assumption that they will remain unchanged. Investing in a building stock planned for changes in individual lives, social forces, and in technical standards is now an imperative of equal importance to investing in net zero-energy, fire-proof and earthquake-proof buildings.

At various times the consensus has been that fire-proof, earthquake proof and net-zero buildings cost too much. But does assuring that buildings are not destroyed in fires or earthquakes, or consume excessive amounts of scarce resources really cost more? From what narrow cost accounting perspective is that assessment made? As for planning for change, what residential environment of any sustained value does NOT undergo incremental change in small and big ways over time to remain useful? Floor plans are rearranged, big units are sub-divided and small ones combined, old parts are replaced by newer higher performing parts, buildings are enlarged or replaced, facades upgraded and uses changed. Investments in the remodeling industry are proof of this. This is so normal that it is often ignored when considering new construction or upgrading existing buildings.

Designing large multifamily projects prepared for change is long overdue. Our design methods, business practices, financing and regulatory systems need to catch up. This requires an infrastructure planning model called OPEN BUILDING. In this approach design tasks are separated: design of the parts expected to last are separated from the design of the parts that are expected to change. Separating design tasks assures that the urgent necessities of today do not block future priorities. Utility, transport and communication networks are familiar examples. Office, retail, laboratory buildings and even airport concourses are architectural examples. Smart interfaces stimulate innovation at each level of intervention without jeopardizing the functioning of the whole. Distributed rather than unified decision-making reduces risk and allows competition to flourish, and perhaps most important, brings inhabitants back into the game of cultivating built environment in a big way.

When we don't think ahead, the result of our design work leads to measurably increased waste, higher costs and friction between human life in all its variety and a building stock that has become far too rigid. If we expect to achieve a sustainable and 'circular' built environment it is imperative that we take planning for change seriously, both short-cycle and multi-generational change.

HOW INFRASTRUCTURE WORKS

Infrastructure is the basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or an enterprise (Oxford Dictionary). Including buildings in this definition is important and is the basis for the following discussion of why an infrastructure model makes sense in respect to planning multifamily residential buildings.

Infrastructure is characterized by a hierarchical physical and decision-making structure. There are 'levels of intervention' (Habraken, 1998). For example, in an electrical power infrastructure, the power generation plant is at the highest level. The next level is the step-up transformer, followed by transmission lines. Then come local step-down substations, and then low-distribution lines to buildings or customers. Each is an independent – but linked – level of intervention.

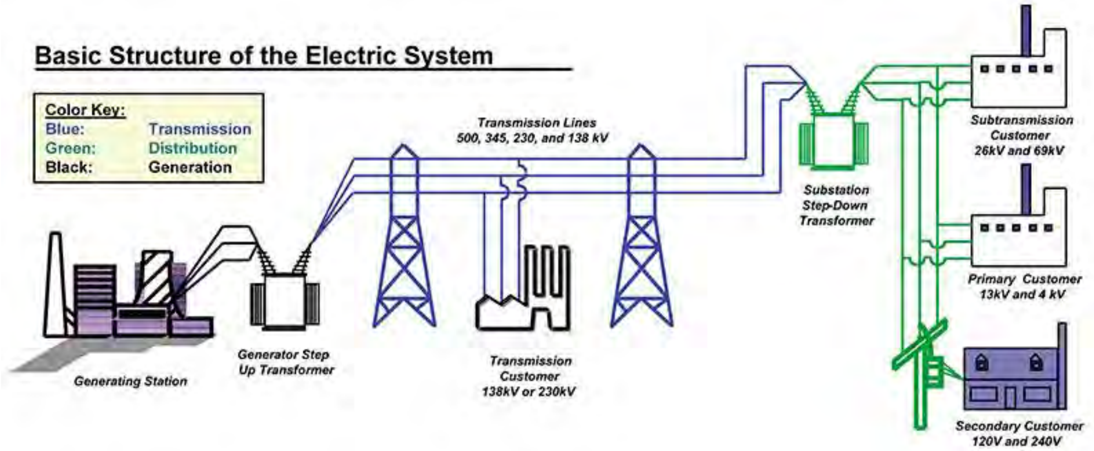

Figure 1. https://www.ucsusa.org/clean-energy/how-electricity-grid-works

Electricity generators are owned by electric companies, or utilities, which are in turn regulated by the state's Public Utility Commission (PUC) or the Public Service Commission (PSC). Transmission networks are sometimes managed by utilities, but some networks are managed by separate entities known as Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs). These companies facilitate competition among electricity suppliers and provide access to transmission by scheduling and monitoring the use of transmission lines. Distribution is the delivery of step-down power to end users, via substations.

Because the grid allows multiple generators and power plants to provide electricity to consumers, different generators compete with each other to provide electricity at the cheapest price. The grid also serves as a form of insurance – competition on the grid protects customers against fluctuations in fuel prices.

No single party designs, builds and regulates this system. Design tasks are separated, parts can be replaced without shutting down the entire system, and innovation occurs at different cycles at the various levels of the system. This utility system is a complex adaptive system, in a constant state of transformation. (Marston, 2018; Lepech, 2018)

AN INFRASTRUCTURE MODEL FOR BUILDINGS

Like an electrical infrastructure, office buildings, shopping centers, airport concourses, some military platforms and now some pioneering healthcare facilities are complex adaptive systems. They use separation of design tasks to organize decision-making. A client will ask an A/E firm to design a 'core and shell' or 'base building' in which the number of occupants or their requirements are not known and will change as may actual uses. These buildings have spatial and mechanical systems' CAPACITY to accommodate a variety of changing users. After construction begins (and continuing over the life of the asset) design decisions are made about the size of each independent occupancy as well as the layout of the floor areas each occupant controls. Sometimes, illustrative floor plans are provided, with knowledge that they are only illustrations and will change. Everything needed to make the space useful is installed, including all mechanical systems (ducts, pipes and wires) in each independent unit, connecting to the common systems used by all occupants installed earlier in the base building with prepared interfaces.

These examples illustrate how an infrastructure model of the build environment is already commonplace, EXCEPT in multifamily residential real estate. (Kendall, 2013)

CURRENT MULTIFAMILY PRACTICE

Current multifamily projects are more complex than most other real estate developments. They have more MEP systems per cubic meter than other project types, and they are more entwined with complex social forces and competing local and national interests.

The first problem is that most multifamily residential developers do not have an interest in future asset value. Lending institutions and regulators also do not like variety and change but instead work to resist these natural forces.

The current decision-making sequence for multifamily projects starts with a 'program of requirements.' Marketing experts are hired and, using polling and focus group data to segment the market with the help of psychographics. For example, the "DINK" cohort (dual income couples with no children) may include "thinkers," "achievers," and "experiencers." "Thinkers are practical consumers who seek durability, functionality, and value, while achievers, who are concerned with image, want prestige brands and finishes." (Braunstein, 2014)

Once the market segment or segments are identified for a project, floor plans are designed to match them. These plans are arranged on floor plates and in vertical stacks to optimize the placement of drainage and ventilation ducts, and a façade is wrapped around the assembly of units. When building permits are obtained, construction can commence, with speed-to-market driving the work. It matters little whether the project is wood-framed, concrete or steel. Off-site construction methods are typically used to speed some parts of the construction process.

Multi-unit projects are essentially conceived, financed, and approved as unibody entities. If it is a for-sale project, it is normally governed as a condominium – a kind of CID (common interest development) which is essentially a private government run by an elected Board of unit owners. Restrictive covenants define common elements, individual elements and limited common elements, and monthly fees are collected to prepare for repairs to common elements. Spaces inside individual units can be changed, but because of entangled MEP systems, any significant change will implicate other units. In rental projects, individual dwellings are made available through leasing agreements. Many developers immediately sell their projects; some hold them as assets. Such projects are not planned for change; in fact the opposite is the case. They are planned and regulated to remain unchanged.

To manage the inherent complexity of multifamily projects, the number of variables and decision-makers must be reduced. Standardization becomes important. It then becomes logical to eliminate the individual occupant from any but a passive role. This leads to the market segmentation noted above, which leads to standard floor plans and amenity packages for each imagined segment. This allows the current process to run.

The problem is that this way of working, while convenient for powerful interests, is at odds with the way the world works. Built environment is not static, nor is society static; preferences do change, and building standards evolve. Market segments deemed a good match with a current social demographic are unmatched to the next generation. The result is a residential building stock ill-prepared to adjust as life adjusts around it. Unlike office buildings prepared for change, the multifamily building stock is built to resist change.

USING AN INFRASTRUCTURE MODEL IN MULTIFAMILY PROJECTS

Current practice cannot be efficient or sustainable in the long run. This is why this paper argues for the introduction of another LEVEL of INTERVENTION in the multifamily residential decision-making process, mirroring what is conventional in office buildings: A FIT-OUT LEVEL, attuned to the independent dwelling unit. This paper argues that multifamily projects are complex adaptive systems and need to be designed accordingly using an infrastructure or OPEN BUILDING approach.

Two cases of how this can be realized are now discussed. One is an example of a multifamily project recently completed in Amsterdam. It is one of hundreds of similar OPEN BUILDING projects built in the last decade around the world. The other case is a pioneering company in China – UNITY TECH – that delivers one-unit-at-a-time residential FIT-OUT into empty multistory buildings.

PATCH22

PATCH22 was initiated by an architect / developer in Amsterdam. It is a 30m tall high-rise in wood built in 2014. The project incorporates numerous technical innovations to maximize flexibility. Using an access floor technology for routing horizontal mechanical services from a few centrally positioned vertical MEP shafts, each floor plate in the 7-story building can be divided into between two and eight completely independent dwelling units. Once unit sizes are fixed, floor plans can be changed without impacting other dwellings in the building.

Figure 2: Patch22 as seen from the southwest

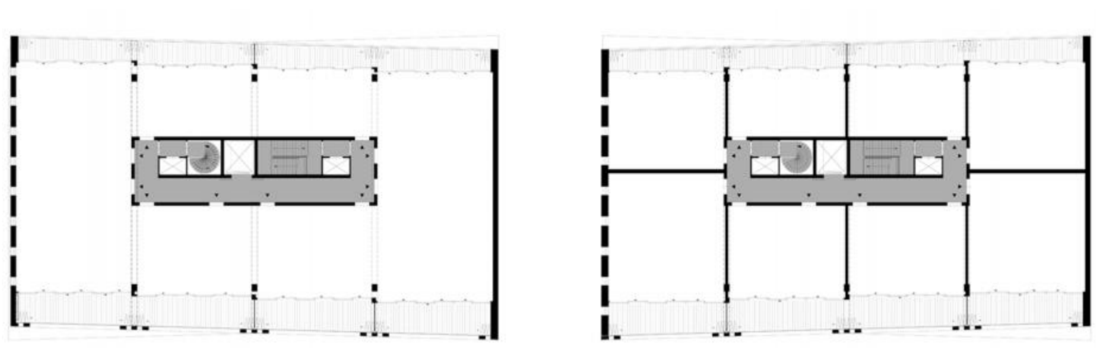

Figure 3: level 6 without division walls and level 7 with the maximum number of division walls (final design)

The design started with 200m2 apartments with load bearing division walls. But it was soon decided that buyers needed a financial exit-strategy in case the newly developing area of Buiksloterham area would not become popular. A straightforward 200m2 apartment would then be unsellable, so the building was designed to enable the large units to be divided into smaller affordable apartments. The six floors can be used as large lofts up to 540m2 with huge balconies, or as up to eight smaller apartments or as open office space, thanks to the lack of structural division walls, the generous floor height of 4m and the high floor load of 4kN. Apartments can be subdivided or merged, and the division into apartments will remain flexible in the future.

Flexibility can range from one time only, to repeated change. In reality all buildings can be modified but designing a building to be adjusted just makes modification easier. Offering buyers the possibility to design their own interiors inside a shared structure would mean that the design (ideally) has to be finished before a building permit is given. That would be 'one-time' flexibility. Modifications can of course be done later in the lifetime of the building but would be part of an overall renovation.

In PATCH22 the aim was to enable an 'over and over again' capacity for change. Inhabitants should be completely free in the layout of their apartments during the buildings' complete lifespan. This led to the decision to eliminate all vertical MEP shafts inside the tenant spaces, and to use removable division walls and a hollow floor system (one of several in the market) in which drainage pipes and wiring can be installed almost independently of the load bearing structure. Once a unit size is set, change is limited to 'everything behind your front door.'

The goal was to build a sustainable project ensuring that the structure, containing many precious materials, would remain useful to future generations, even if their future demands and desires cannot be known. Therefore the architecture, with the trusses in the façade, takes the long view, referring to the harbor cranes that used to operate there. The interiors are empty, but the wooden posts and beams give an initial atmosphere.

The architects did not design all the interiors but coached inhabitants in designing their homes. Some used interior architects; some used just drawing paper and pencil. When all the designs were finished, they were converted into working drawings so the general contractor could install drains and wiring in the hollow floors during construction. This compressed the total building time. After completion of the base building inhabitants could start executing their own interiors with their private contractors.

Figure 4: Apartment Van Langh / Stakenburg on levels 6 and 7

The main material for the structure and façade is wood, according to the Cradle2Cradle philosophy. With this in mind the architects solved the fire-resistance issue when building a high-rise in wood by adding 80mm extra wood to the structure so it would take the obligatory 120 minutes before a fire would affect the structural integrity. They were able to keep all the wood exposed. It also turned out to be cheaper to build a post and beam construction than load bearing walls in wood because the overall surface and the amount of extra fire resistance wood protecting the structure would be smaller. In a post and beam structure division walls can be added and removed later, improving flexibility.

Another constraint of using a wood structure is sound insulation. Because there is no mass to absorb sound, the structure has to carefully build up in different sound-independent layers. It is easy to make building errors or to influence the total structure by poor-quality additions later. Having inhabitants executing their own interiors in a wooden structure increases the risk of sound related issues.

In a building industry dominated by prefabricated and fully integrated building concepts the architects found that it was hard to facilitate flexibility. Regular building parts are aimed at solving regular demands and integrate rules and regulations for regular apartments for a regular public in a highly cost-efficient way. But when flexibility and changes are required, these regular building parts tend to get very expensive and require a lot of design planning and management. Therefore the design team decided to disentangle the structure and MEP services and to build as simply as possible.

Paradoxically the overall design still had to be very smart because all possibilities have to be foreseen so the base building does not impose overly limiting constraints on future infill. The design team managed to organize all the technical meters and required ventilation appliances outside of the units, so the inhabitants only had to focus on the spaces for living.

Vertical MEP shafts are the invisible organizers of floor plan layouts in traditional buildings. Meter cabinets, kitchens and bathrooms will always be executed close to the shafts to minimize the length of the drains and the floor dimensions that have to accommodate the required slopes for the drains.

In PATCH22 shafts would never be in the right place for an inhabitants' floor plan. The design team didn't know which units would merge into single apartments and therefore it made no sense to have shafts vertically through all the units.

To solve this problem two shafts were located in the central core (see Fig. 3). Drains, water and electricity were installed under the finished floor but in the depth of the floor structure (see Fig. 5), to just behind the front doors, where the inhabitants could have these extended to the desired position in their apartments.

To make sure that there was enough height for the inclination of the toilet-drain in the floor structure, an imaginary toilet was imagined in the outmost corner of the building, thus determining the necessary floor-depth dimensions.

Figure 5: Hollow Slimline floor system with free positioning of drains and wiring. (https://www.slimlinebuildings.com/PDF/en/news/building-for-eternity.pdf)

As Figure 5 shows, the Slimline floor system was selected to allow all horizontal MEP services to be installed from the space served. This is essentially a hollow floor with a removable top. The floor system is a combination of 36cm perforated steel beams and an 8cm concrete bottom slab. After installing drains and other facilities the floor is topped with a steel profile sheet and an 8cm anhydrite screed with floor heating. Because the top floor is part of the sound barrier between two apartments, this solution is defined as partly independent of the load bearing structure. Opening up the floor completely will require some breaking but is very easy to repair. By making strategically placed holes in the floor, the cavity of the floor can be entered and alterations inside the floor can be made. Initially the goal was to enable inhabitants to disassemble the top floor in original components, but that turned out to be more complex and more expensive than the anhydrite top floor and therefore practically less flexible.

Because of the central placement of MEP shafts alternatives were needed for positioning utility meters in apartments. The result was a shared room with all meters and main switches on ground floor and secondary electrical circuit breaker boxes installed inside the apartments, horizontally connected to the central shafts.

It is not necessarily cheaper to build this way. When structure and services are integrated the volume of the building can be smaller compared to this approach. It takes more building material and labor and the dimensions of the façade, the most expensive part of a building, increase slightly. Given the fact that (in a Dutch context) interiors in regular projects are often finished at extremely low cost, this project ended up at €1200,-/gross m^2 while at the time of construction in 2014

€1050,-/m2 was the standard for a finished building with a comparable sustainability score. Buyers invested another €800,-/net m2 to complete their (high-end) interiors.

In the Netherlands property owners don't own an apartment in a shared building; they own the right to use and trade certain legal units of the building. All owners are member of the Property Owners Association (POA) that owns the building. In Amsterdam the POA doesn't own the ground underneath the building but has a land lease contract. In PATCH22 the legal structure divided each floor into 8 legal units and bigger apartments are a combination of multiple legal units. Although this is permitted in Dutch law, it was not permitted in regular Amsterdam land lease contracts. It was even more difficult to arrange permission to legalize a flexible use for housing and working in each legal unit, because Amsterdam charges different lease fees for different functions and wants to keep control. But when selling started no one knew how big the apartments were going to be, where they would be located exactly and how they were going to be used. It took two years of negotiation with the city to draw up a new kind of land lease contract that would not impose paper restrictions on our very flexible building. (Frantzen, 2018)

A second project by this architect has recently been completed next to PATCH 22, called TOP UP (https://www.top-up.amsterdam)

FIT-OUT: A NEW LEVEL OF INTERVENTION IN RESIDENTIAL PROJECTS

This paper argues that working with an infrastructure model of the building stock is also the means by which our building and product industrys' productive capacities can be put to use most effectively. The separation of 'levels of intervention' is the basis for innovation. This is why the Open Building approach extends the idea of infrastructure into the fabric of buildings by explicitly designating an INFILL or FIT-OUT LEVEL. The INFILL or FIT-OUT LEVEL is the distinct and new design task characteristic of the Open Building approach. FIT-OUT is the bundle of products and services serving independent occupancies – an office FIT-OUT or a dwelling unit FIT-OUT. It meets the evolving demands of individual occupancies in large, multi-occupant projects, because it can be altered independently. While Open Building for urban design, office buildings and other project types is familiar even if not identified as "Open Building," neither residential Open Building nor a Residential Infill Industry are understood and are therefore the focus of the second case presented in this paper.

The habit in the building industry is still to organize ad-hoc contracts among many subcontractors each delivering labor and products to complete jobs, including when existing buildings are converted to new uses. General contractors continue this practice mainly to reduce risk to themselves, and by applying downward pressure on subcontractors to lower their costs. But management costs increase.

The barriers to the development of a residential INFILL INDUSTRY do not lie in the lack of availability of technical solutions. They lie in the conventions of the real estate, finance and construction industries and the intentional suppression of individual agency, to the benefit of those for whom standardization is paramount and profitable.

Identifying an INFILL or FIT-OUT level in multifamily residential projects is important for two reasons. Households today (consumers) are the engine of every national economy, but they are stressed and have been pacified in the multifamily sector. The current structure of the building industry is no help when the goal is returning leverage and decision-making power to every household in large residential projects. Compared to the kinds of services offered to households in, for example, the consumer electronics industry, the building industry is decades behind.

Assuring a scope of control or agency for individuals in a fast-paced housing process is important if for no other reason than the fulfillment of an innate human propensity to shape our material world. Second, it is vitally important to assure the regenerative capacity of buildings in an efficient way. The vibrancy of the professional remodeling markets in most countries as well as of the do-it-yourself and informal sectors are evidence of how fine-grained agency is already a huge, if chaotic and stressful, economic engine.

Integrated FIT-OUT service companies are the next step in the search for efficient variety, and for attracting large-scale investors and regulatory powers who have instinctively blocked change and variety to reduce risk. A FIT-OUT or INFILL INDUSTRY is one of the most important means by which our industrial capacity can be harnessed in the service of regenerative built environment.

UNITY TECH

UNITY TECH in China (www.henenghome.com) has delivered more than 60,000 'infill' packages into the multifamily residential market in the last three years. They fit out demised spaces left empty by the general contractor using four-person, cross trained installation teams (except electricians) and off-site preparation of RTA products. They complete each apartment in seven days including all piping, ducts and electrical wiring, doors, partitions, cabinets and fixtures.

Every apartment is accounted for separately. They save 50% in time and 65% on materials waste and offer a 3-year warranty for every Infill package. Their product offers savings and reduced risk for developers on repair/remodeling costs. Other companies in China are offering a similar service.

This company has showrooms in Beijing and Shanghai, and are expanding to other cities, staffed by interior designers who work directly with clients (currently large developers; soon individual occupants as well) using software to do virtual walk-throughs and pricing. They usually bring their clients to the sites directly. They have their own design teams and do not work with outside designers. They run 80% of the projects with their own work force (mainly in major cities) and in the 20% of their projects that are in smaller cities (they are working in 32 cities) they just send project managers there and hire and train local workers. Roughly 70% of the products are manufactured in their own facility, mainly the patented products (they have 15 patents). Common materials like metal frames and studs are purchased from other suppliers. They have distribution centers in every city. Everything is delivered from their factory to the center first to be labeled by room number. All the materials are processed in their facilities with the right dimensions to reduce on-site cutting.

The company is now using a third version of their system and will soon launch its 4th. v3.0 has an approximately 95% industrialization rate. In order to achieve the goal of a 100-year architecture, this version enabled the separation of pipes and wires from the building's structural system. Wet work on site is almost reduced to 0% (only the ceilings need painting). v4.0 enables true c2f (customer to factory) experience. They are upgrading their design method to BIM that seamlessly connects the factory MES system and their management ERP system.

Figure 6: An example of a 'base building'

Figure 7: An example of a demised space ready for fit-out installation

Figure 8: Day 1

Figure 9: Day 1

Figure 10: Day 2

Figure 11: Day 2

Figure 12: Day 3 (raised warm floor)

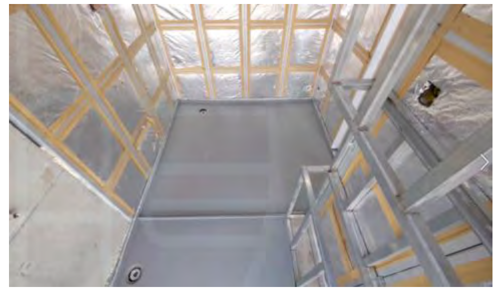
Figure 13: Day 3 (bathroom floor)

Figure 14: Day 5 (Above Ceiling MEP)

Figure 15: Day 6: (floor finishes)

Figure 20: Day 7 (completing bathroom)

Figure 21: Day 7 (finishing touches)

These Chinese companies are being encouraged by the release in 2018 of the *Design and Assessment Standard for Long-Life Sustainable Housing*, developed by the China Institute of Building Standard Design and Research (CBS) a national government agency. It is based on a similar law passed by the Japanese government in 2008 which itself has resulted in millions of long-life housing units in Japan. (Minami, 2016)

CONCLUSIONS

"We should think of our homes as a legacy to future generations and consider the negative environmental effects of building them to serve only one or two generations before razing or reconstructing them. Homes should be built for sustainability and for ease in future modification." (Kaufman, 2003)

Why does Residential Open Building lag in the United States, and why is a residential Infill industry slow to emerge. There are a number of reasons, outlined here.

1. Demand is either suppressed or nonexistent

• In large common interest developments, the banking and real estate development industries, along with the Government Sponsored Enterprises, have intentionally taken the power of self-determination away from people who buy homes. Standardization is an institutional priority, and it (standardization) has been sold to buyers as something that they should like. It's ironic. Once upon a time, people thought that becoming a homeowner gave you special rights to participate in decisions about your own home as well as the community. Now when you buy a home, all the decisions are made by the long-gone developer who commissioned the Covenants, Conditions & Restrictions and whoever got elected to the Board Of Directors of the condominiums and generally of the Home-Owner Associations. People have been convinced that they should give up their own freedom and control so that they can prevent their neighbor from having either--and they are so afraid of their neighbors (perhaps due to increasing diversity) that they think this is a prudent way to do things. (from an exchange with Evan McKenzie, author of Privatopia and Beyond Privatopia).

2. No supply

• There is no concept of separate design tasks in residential design and construction. The legal separation of property ownership is well-known but flawed because it ignores the actual technical entanglement that remains;
• Companies like IKEA, which already offer CAD design services for kitchens and bathrooms, etc. and deliver RTA parts of partial dwelling unit INFILL (but only parts classified as furnishings, appliances and limited equipment), are profitable with their current scope of services and have no incentive to expand into the MEP domain and other code-constrained and building-industry controlled parts of INFILL;
• Installers of MEP systems remain divided by product type and trade jurisdictions and are resistant to develop integrated services or otherwise cooperate for fear of losing jobs and because they profit from the current dis-integrated, quality-plagued and excessively costly (to the user) situation.

3. Technical entanglement

• MEP service distribution does not respect the independence of dwelling units (e.g. drainage pipes serving one unit still are distributed in the ceiling of dwellings below) and are still buried, including inside walls.
• MEP systems are changing faster and becoming more complex than other technical subsystems such as structure and partition walls. Their installation entanglement inhibits replacement with more advanced products when they become available without undue disruption and cost. When all-electric houses become the norm (when we stop using gas for heating and cooking) it will be very difficult because of buried MEP;
• Demising walls separating occupancies, and floors, are often entangled with MEP systems.

4. Legal / regulatory / financing obstructions

• HOA's establish rules to keep condominiums and neighborhoods "uniform."
• There is no legal clarity vis-à-vis 'movable' / 'immovable' ('trade fixtures' vs. 'fixtures');

• Building permits for residential projects require 'integrated' building design, driven by floor plans, exact fixture counts, etc.;
• Certificates of occupancy in many jurisdictions require that a bathroom and a kitchen are in place. This tends to lock-in all of the major MEP systems;
• Standardization is an objective of all parties because it is more predictable. Variety is problematic; variety decided per dwelling unit is considered high risk and troublesome. Who wants to deal with individual preferences and contracts?

5. The building industry lags in adopting 21st century methods

• The building industry has yet to harness the power of automation, 'kitting,' and integrated but nimble data management in a way that supports decision flexibility and offers variety corresponding with the natural variety of the population;
• Unlike the US Navy or auto industry, for example, the building industry is not yet recognizing the benefits of 'hybrid workers' and 'minimal manning,' or the use of cross-trained and therefore smaller crews. (UnSeem, 2019). In part this can be explained by the relatively low wages workers earn (usually with no benefits) and their relatively low skill levels and the acceptance of low-quality construction by the market.
• Referring to the Navy, the new littoral combat ships are built on the concept of 'modularity.' "There is a voluminous hollow in the ships belly, and its insides can be swapped out in port, allowing it to set sail as a submarine hunter, minesweeper, or surface combatant, depending on the mission." (op. cit. Unseem, 2019).

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MONITORING HVAC SYSTEM PERFORMANCE FOR AFFORDABLE HOUSING UNITS IN MONTGOMERY COUNTY, VIRGINIA

Fatemah EBRAHIM[1], Frederick PAIGE[1], Farrokh JAZIZADEH[1], and Quinton NOTTINGHAM[2]

[1]The Vecellio Construction Engineering and Management Program (VCEMP), The Charles Edward Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 200 Patton Hall, Blacksburg, VA 24061; email: freddyp@vt.edu

[2]The Department of Business Information Technology, Pamplin College of Business, Virginia Polytechnic Institute and State University, 1015 Pamplin Hall (0235), Blacksburg, VA 24061

ABSTRACT

HVAC systems are a top contribution to residential building energy consumption and thermal performance. This study demonstrates the ability for property managers of affordable housing units to monitor the performance of their HVAC systems across their building stock using smart devices and cloud computing. This paper presents a case study of an affordable housing development in Virginia which was recently renovated to improve and explore HVAC system performance with high financial precision to meet evolving federal regulations. Real-time building energy usage at the circuit-level, resident perceptions, property manager perceptions, and building specifications are all combined to provide a detailed understanding of current and future practices for wirelessly monitoring HVAC equipment. This paper focuses on HVAC performance describing the selection, utilization, and performance of appropriately sized and comparable one stage, two-stage, and variable speed HVAC systems. Preliminary data analysis has shown great potential for updating previous processes to calibrate inaccurate perceptions of behavior-driven energy use; leverage cloud computing for data analytics and visualization to improve data accessibility; and the inclusion of socio-political impacts into decision-making tools. We have also found a critical need to better incorporate the variability of system performance due to the high potential for installation errors and user errors. The findings of this study extend beyond the context of HVAC systems to various building systems that can be connected to the internet of things (IoT). The methodology of this study also provides guidance for better academic-industry-citizen engagement for the real-world testing and design of engineered infrastructure systems.

Keywords: HVAC Systems, Internet of Things, Affordable Housing, Sustainable Housing, Smart Thermostats, Energy Monitoring

INTRODUCTION

Deciding between paying energy bills or buying groceries is a tradeoff many low-income residents have to make. The 2015 Residential Energy Consumption Survey (RECS) reported that

31% of US households faced difficulties when paying their energy bills and 20% of the US households reported reducing expenses spent on food and medication to instead pay their energy bills ("2015 RECS: Overview," 2015). Difficulty accessing energy disrupts almost every aspect of modern life, which includes refrigerating food and drinks or working through the night. Therefore, this tradeoff which many low-income residents have to make, illustrates that energy security is a basic human need. Access to energy not only ensures that functioning in daily life but it also paves the way to a better standard of living, health care, and well-being of all individuals within a society. Furthermore, improving the energy efficiency of low-income housing units to match the level of the average US home would alleviate approximately 35% of the total energy burden on the people who need it most (Drehobl and Ross, 2016). There is a need to break this negatively reinforcing cycle of energy inefficiency, energy burden, and social inequality across low-income vulnerable communities.

This paper highlights the initial data-driven findings of a longitudinal field study, with an industry partner, which provides energy consumption data for an affordable housing community that caters to low-income residents. The industry partner recently upgraded the HVAC systems in their housing community and would like to investigate the benefits and drawbacks of this energy investment. The field study method is an underutilized method in academia due to the difficulty of accessing data and the extensive time required, but it allows us to analyze the energy performance and cost performance of these new systems alongside manufacturer specifications, utility company data, and landlord feedback and input.

METHODS

This paper reports the initial findings of a longitudinal field study, which documents the upgrades of one-stage, two-stage, and variable speed HVAC system upgrades across 39 different units in an affordable housing community in Montgomery County, Virginia. The initial findings reported within this paper include: (1) a preliminary analysis of data collected from 9 different units within the housing community, which includes energy analysis in terms of the performance of the respective HVAC systems while following the traditional model of energy analysis; (2) an exhaustive analysis of data collected from 35 units within the housing community, which includes energy analysis of the performance of the respective HVAC systems while following the traditional model of energy analysis; and (3) the study also introduces the second stage of the study, which will incorporate data from circuit-level eGauge data collected at the breaker panel within each household.

Manufacturer Specifications

The property managers evaluated numerous factors from the manufacturer specifications to determine which HVAC systems to install. The main factors that were taken into consideration upon determining system efficiency were the System Energy Efficiency Ratio (SEER) rating and cooling capacity. The SEER Rating on the single-stage, two-stage, and variable speed HVAC systems were 16, 17, and 18, respectively. Additionally, the cooling capacity of the single-stage, two-stage, and variable speed HVAC systems selected were 18,000-60,000 Btuh, 24,000-60,000 Btuh, and 24,000-60,000 Btuh, respectively. A higher SEER rating typically corresponds to more energy savings and greater comfort levels as it is used as a standard ratio for describing a system's efficiency (Wang et al. 2012). Similarly, a higher cooling capacity indicates an increased ability to remove heat from a building.

Data Monitoring and Analysis of Performance

The data analysis process is made possible through the data provided by the electric utility company, which is the property's energy provider. This data is reported on an aggregated monthly average basis, which displays total kilowatt-hours for two households within a single duplex unit. Additionally, these reported values are an aggregated monthly average of the energy consumption of all of the appliances within the building. Data analysis is performed across two time periods, P_1 and P_2, as shown in *Table 1* below, each corresponding with a different status in the project timeline.

Table 1. Analysis Periods Overview

Period	Corresponding Months	Status
P_1	November 2017 - May 2018	Pre-Intervention
P_2	November 2018 - May 2019	Post-Intervention

The time periods and corresponding months specified were in accordance with those provided to the researchers through the electric utility company. The status of pre-intervention is used to describe the period of time in which all of the HVAC systems installed across the different duplexes in the housing community were older one-stage HVAC systems. And the status of post-intervention corresponds to the period of time when new HVAC systems were installed across the community's duplexes.

Moreover, the time periods and their corresponding months fit relatively well into Virginia's heating season. Since Virginia is in climate zone 4A, it's heating season usually corresponds with the months of November to May and its cooling season usually corresponds with June – October. The month of May, however, is considered a swing month, which lies between seasons. Therefore in order to take into consideration the seasonal time effects in terms of energy and cost performance, we incorporated the heating degree days (HDD) into the normalization calculations for all of the months except May. For the normalization calculations associated with the month of May across both periods P_1, P_2, we normalized against cooling degree days (CDD). Degree days are a means of accounting for weather-related energy demands (Quayle and Diaz 1979), which help energy analysts account for the relationship between outdoor air temperature and energy consumption within a building. Both the HDD and CDD values were pulled directly from the weather station closest to the housing community studied (National Climatic Data Center 2017-2019) and used in the normalization calculations we performed.

The normalized energy consumption was utilized to perform an energy analysis on both pre-intervention energy performance and cost, as well as post-intervention energy and cost. The energy performance and cost analyses included the comparison of three one-stage HVAC systems, 27 two-stage HVAC systems, and five variable speed systems. Moreover, the data analysis surrounded the analysis of: (1) an analysis of energy performance pre-intervention and post-intervention, (2) One-Way Analysis of Variance (ANOVA) for energy performance, and (3) a cost performance for the pre-intervention and post-intervention periods. These analyses helped the researchers evaluate the efficacy of the system upgrades in terms of energy performance and cost performance across the entire affordable housing community. These analyses and their findings will help the researchers explain the urgency of updating the traditional energy analysis model.

Analysis of Cost Performance

In terms of cost analysis, the standard formula for Return on Investment was used as shown in *Equation 1* below. Such factors include the symbols described below in Table 2 as well as those shown in *Equation 2* below.

Table 2. Cost Analysis Nomenclature

Symbol	Unit	Description
ROI	%	Return on Investment
CI	$	Cost of Investment
GI	$	Gain from Investment
TED	kWh/month	Total Energy Difference
AVPT	$/kWh	Average Virginia Power Tariff
LS	years	Lifespan of HVAC System

$$ROI = \frac{GI - CI}{CI} \times 100$$

Equation 1. Return on Investment

$$GI = TED \times 7\ months \times AVPT \times LS$$

Equation 2. Gain from Investment

Furthermore, the formula for *Equation 2. Gain from Investment includes* factors such as Total Energy Difference (TED), Average Virginia Power Tariff (AVPT), and the Lifespan of the HVAC System (LS). The TED was found by calculating the difference in energy consumed for each duplex comparatively across the years $P_{2-1}$for each month and then multiplied by 7 months, which was the duration of both $P_1$and P_2. The AVPT is a value for the state of Virginia's standard rates and charges, which was reported by the energy provider. The LS value is the average lifespan of the HVAC system, which is approximately 20 years according to the US Department of Energy ("Central Air Conditioning" n.d.).

RESULTS

The results reported in this paper surround the values reported by the electric utility company, which reports aggregated monthly average values for each of the duplexes. While each duplex includes two townhomes, the values provided are an average of these two townhomes for each month across three time periods. The preliminary analysis consisted of an unevenly distributed sample size of thirty-five duplexes, which included three one-stage HVAC system installations, twenty-seven two-stage HVAC system installations, and five variable speed HVAC systems.

Analysis of Energy Performance

The aggregate energy consumption for the thirty-five units across the two time periods was normalized against HDD and CDD to produce the values displayed in *Figure 1* below.

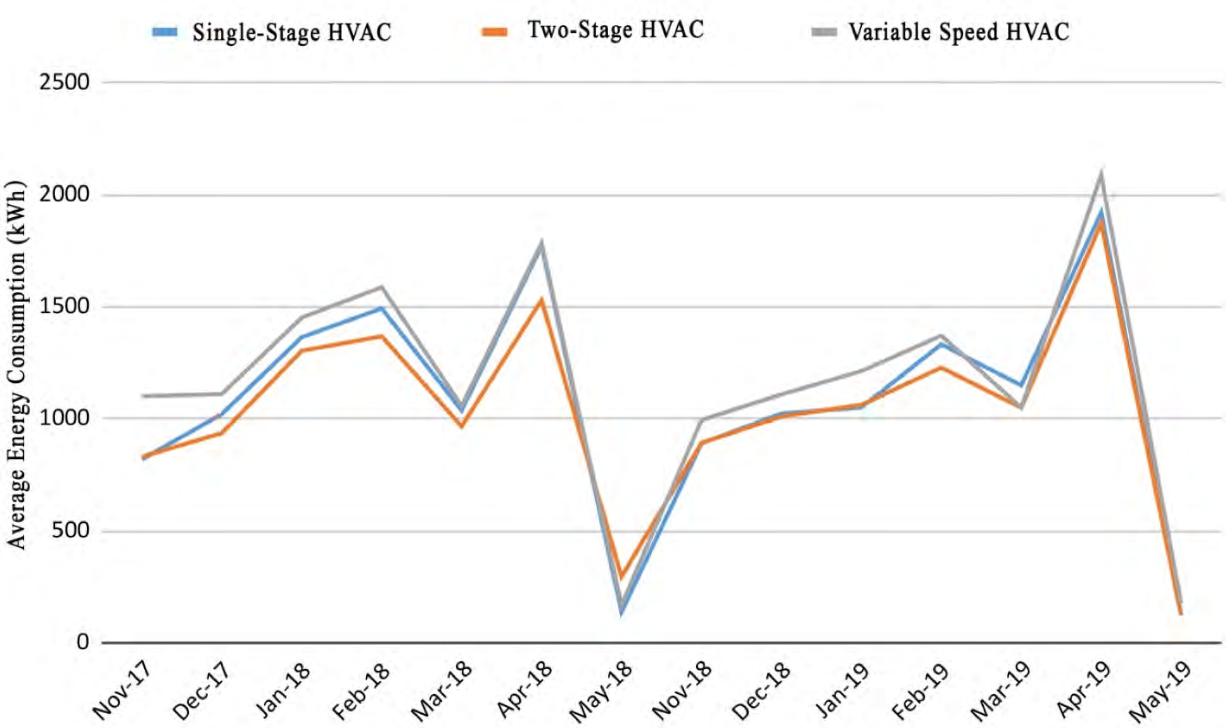

Figure 1. Total Average Energy Consumption (kWh/month)

The energy data monitored indicates that the residents with variable speed HVAC systems installed in their households were consistently using more energy than those with one-stage HVAC systems or two-stage HVAC systems. To further evaluate the energy consumption, we calculated the average energy consumption for each household pre-intervention and post-intervention. While all of the pre-intervention households included one-stage HVAC systems, the post-intervention time period included the installation of new one-stage, two-stage, and variable speed HVAC systems as illustrated in *Figure 2* below.

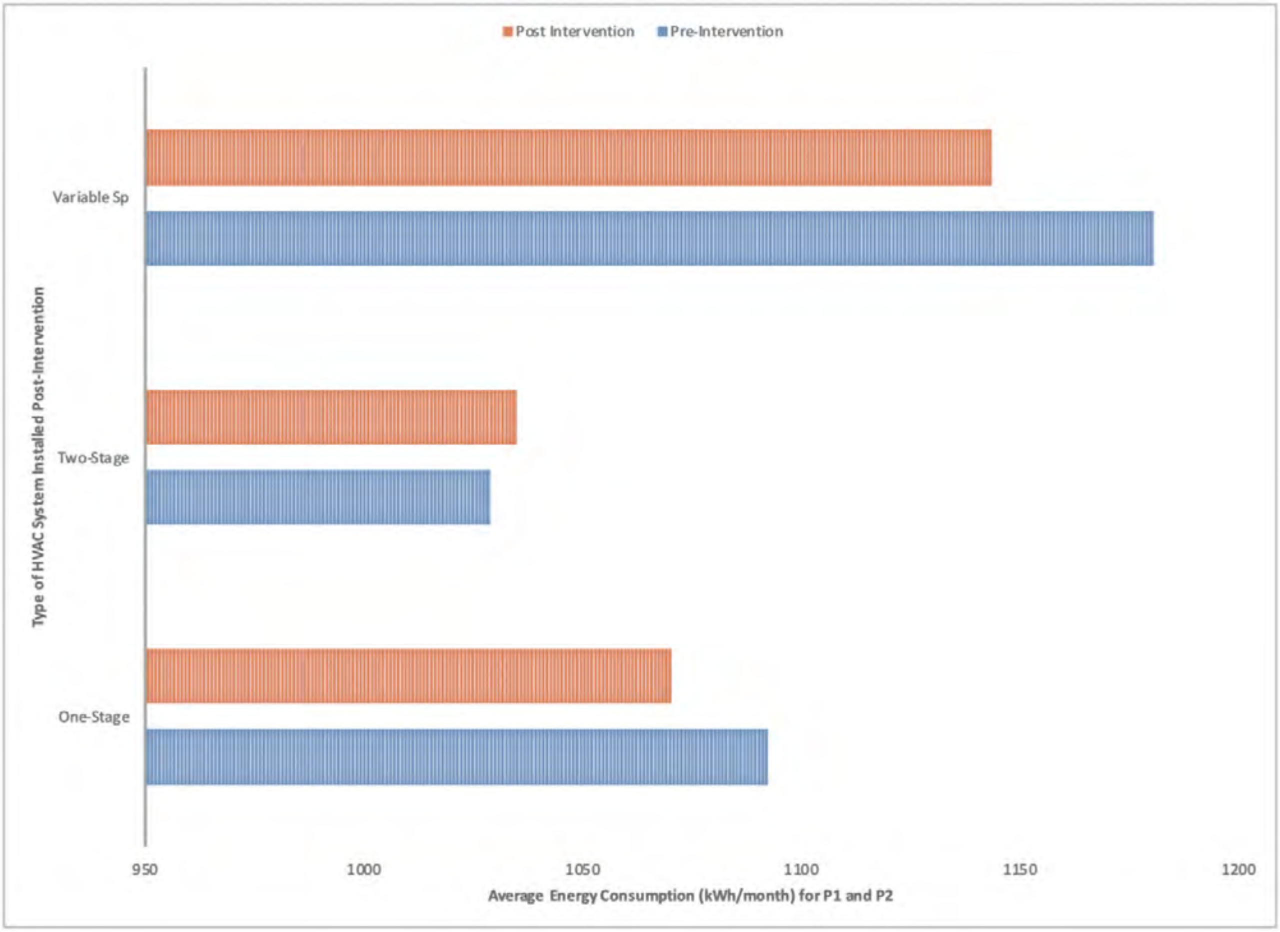

Figure 2. Average Energy Consumption (kWh/month) of Pre-Intervention and Post-Intervention

Through the calculation of the average energy consumption before and after the installation of new HVAC systems, as shown above, we were able to make two crucial findings. The first finding was that overall energy consumption in all of the buildings decreased after the installation of new HVAC systems. Moreover, during the pre-intervention period, the installed HVAC systems throughout all of the duplexes in the affordable housing community were single-stage HVAC systems. During the post-intervention period these HVAC systems were removed, and new one-stage, two-stage, or variable speed HVAC systems were installed.

ANOVA Testing for Energy Performance

One-way ANOVA testing was used to test the multiple treatments; or the installation of three different systems, to compare the average energy consumed for each respective HVAC system and determine whether there is a significant difference between the average energy used by the three systems. The input values for analysis were the aggregated monthly averages of the 35 units normalized against HDD and CDD for each respective system. In order to perform ANOVA, there are three assumptions that must hold: (1) the observations are normally distributed for each group, (2) all groups have equal variances, and (3) the error terms have a mean value of zero and are independent. While assumptions (2) and (3) hold, the assumption of normality is violated through visual inspection of the exhaustive data histograms for all of the HVAC systems across the three time periods respectively. In addition to a visual inspection of the histograms, a formal test of normality was also performed to deduce that the data does not follow the condition of normality. Therefore, in order to satisfy the condition of normality, the $\log_{10}(x)$ transformation, where x denotes the normalized kWh/month, was performed (Nottingham and Hawkes, 2013). The data points total sample size is 432 values, which excludes 82 outliers. All of the removed outliers corresponded with the month of May in both time periods. After the removal of the 82 outliers, the sample sizes for the normalized energy consumption of the duplexes with one-stage, two-stage, and variable speed HVAC systems were 36, 336, and 60 values respectively. This data is then plotted in three separate histograms each corresponding with one-stage, two-stage, and variable speed HVAC systems respectively as shown below in *Figure 3*.

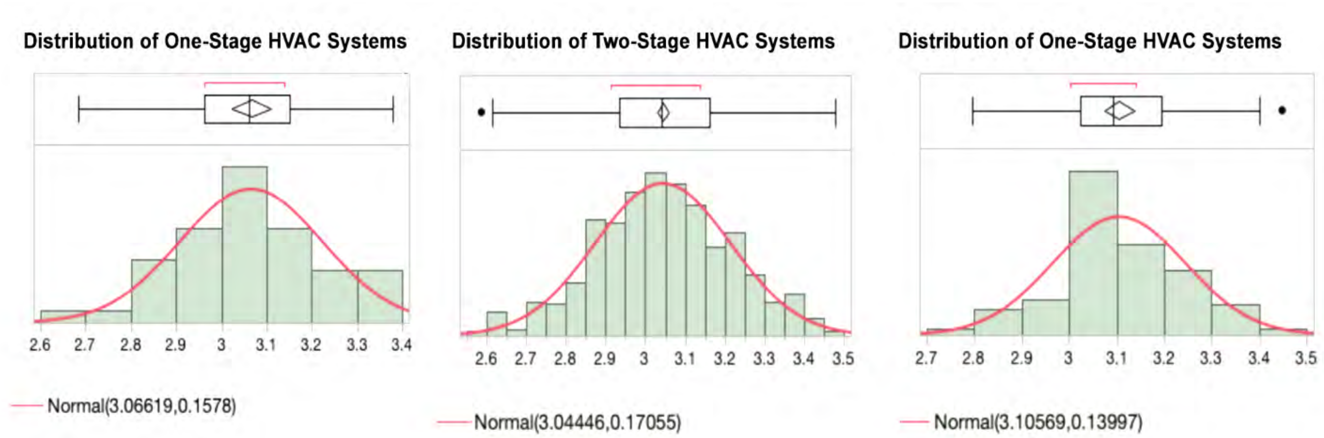

Figure 3. Distributions of Total Energy Consumption of Buildings with One-Stage, Two-Stage, and Variable Speed HVAC Systems

All three histograms appear, through visual analysis, normally distributed. The final and definitive check for normality is the formal test of normality, also known as the Goodness-of-Fit-Test, a summary of its results is shown in *Table 3* below.

Table 3. Goodness-of-Fit Test for One-Stage, Two-Stage, and Variable Speed HVAC Systems

Shapiro-Wilk W Test		
HVAC System	W	*p*-value
One-Stage	0.981109	*p*-value = 0.5868
Two-Stage	0.995814	*p*-value = 0.2403
Variable Speed	0.984715	*p*-value = 0.4232

The *W* values for all three HVAC systems are within the critical value accepted range, which is 1.00 < *W* < .95 range, indicating that the datasets for each follow the conditions of normality. The null hypothesis is that the data follows a normal distribution and accordingly, a small *p*-value would indicate a rejection of the null hypothesis, which would mean that the data is not normally distributed (Nottingham and Hawkes, 2013). But in all three cases the *p*-value is greater than 0.05, which indicates that the null hypothesis holds true and the data is normally distributed.

Thereafter, the One-Way ANOVA was paired with the Tukey's HSD multiple comparison procedure to perform the pairwise comparisons between all three HVAC systems. Thus, we compared the means of untransformed energy consumption of the one-stage HVAC system with the two-stage HVAC system, and the one-stage HVAC system with the variable speed HVAC system, and the two-stage HVAC system with the variable speed HVAC system as shown in *Table 4* below.

Table 4. Summary of One-Way ANOVA Comparisons

One-Stage versus Two-Stage HVAC Systems	$\bar{x}$ = 2411.242466 kWh/month	*p*-value = 0.378384	Not statistically significant
One-Stage versus Variable Speed HVAC Systems	$\bar{x}$ = 2461.3406 kWh/month	*p*-value =0.854014	Not statistically significant
Two-Stage versus Variable Speed HVAC Systems	$\bar{x}$ = 2392.69697 kWh/month	*p*-value =0.415509	Statistically significant

The untransformed data was used in the Tukey's multiple comparison procedure in order to analyze the energy performance of each of the duplexes and their corresponding HVAC systems directly as opposed to the transformed data. Through these analyses, we found that there was a statistically significant difference between the means of the energy consumed with two-stage versus variable speed HVAC systems installed. There is a statistically significant difference in the amount of energy consumed in the duplexes, which had two-stage HVAC systems installed compared to those with variable speed HVAC systems.

Analysis of Cost Performance

To analyze the cost performance of the HVAC system upgrades, calculations for Return on Investment were performed on all 35 units which consisted of first calculating the Gain from Investment (see *Figure 4* below). The Gain from Investment was determined by calculating the Total Energy Difference (kWh/month) between the second time period and the first time period. Additionally, the average Virginia power tariff and the lifespan of the HVAC systems was factored into the calculations.

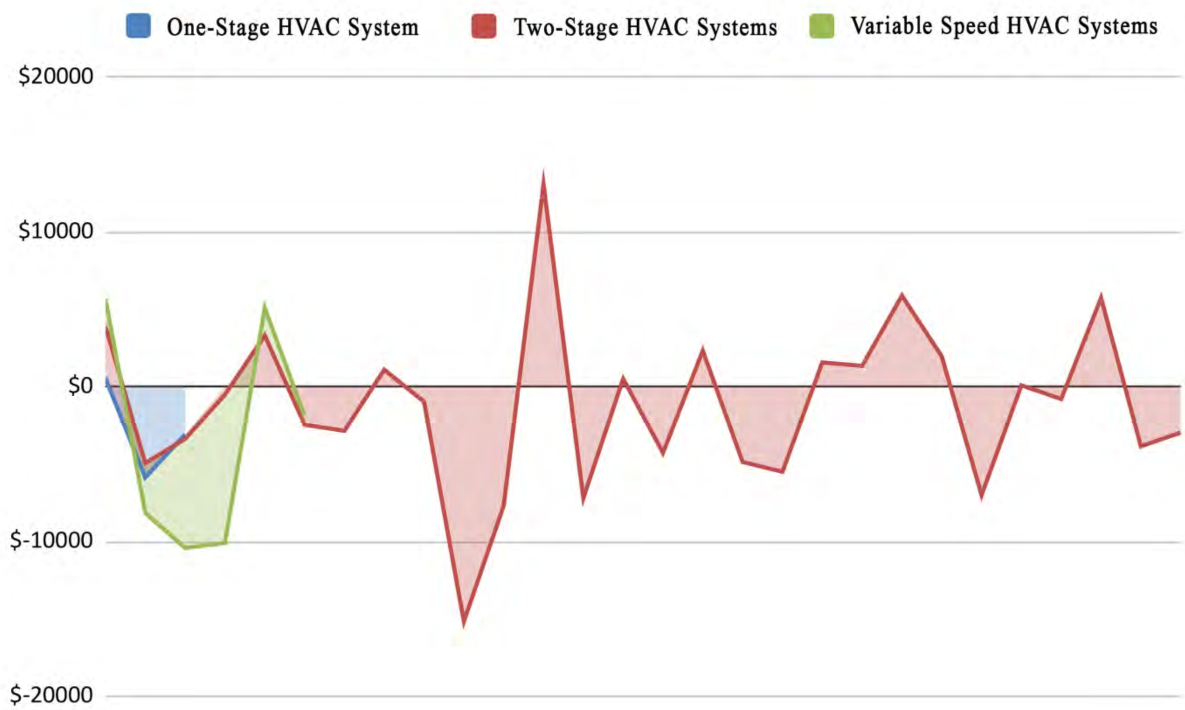

Figure 4. Gain from Investment for One-Stage, Two-Stage, and Variable Speed HVAC Systems

The majority of the values shown in *Figure 4* above correspond with negative values, meaning that there was no gain from the investment over the lifespan of the HVAC system for all three systems. With more variable speed HVAC systems than any other system, we made more calculations in order to perform the ROI calculations. The average ROI for each HVAC system is shown in *Table 5* below.

Table 5. Average ROI for One-Stage, Two-Stage, and Variable Speed HVAC Systems

HVAC System	Return on Investment
One-Stage	−40.40%
Two-Stage	−81.73%

Variable Speed	-54.14%

All three systems yielded a negative Return on Investment over the lifespan of the HVAC system. The most significant loss of capital is associated with the Two-Stage HVAC system, which yielded a -81.73% ROI. The one-stage HVAC system proved to be the soundest investment from an economic standpoint where it yielded a -40.40%, which although a sunk cost, was not as steep as its two counterpart HVAC systems.

DISCUSSION

Manufacturer Specifications

Through the manufacturer's specifications, there is overlap between cooling capacities of the two-stage HVAC system and the variable speed HVAC system. Although there is overlap between the cooling capacity of the one-stage, two-stage, and variable speed HVAC systems, looking at both the cooling capacity and the SEER rating points to the superior performance of the variable speed HVAC system. The SEER rating specifically points to the fact that the variable speed HVAC system should outperform the one-stage and two-stage HVAC systems when installed. But through both the energy performance and cost performance analyses, the results of the analyses contradicted the manufacturer specifications.

Data Monitoring and Analysis of Performance

One of the foundations of energy analysis for this paper, was the normalization calculations, which were contingent upon incorporating HDD or CDD. A higher reported HDD value would indicate that on a specific day, more energy will be used to heat the building. And contrastingly, a higher reported CDD value would indicate that on a specific day, more energy will be used to cool the building. The months that had higher HDD values than CDD values, which were all months except May 2018 and May 2019 were normalized using the HDD value. And since May 2018 and May 2019 saw higher CDD values, which corresponds with residents cooling their buildings, the energy consumption for those months for each system were normalized against CDD. Normalizing energy consumption against HDD and CDD essentially allowed us to compare all of the different buildings and different HVAC systems with weather-related energy impacts factored into analyses. Additionally, incorporating the CDD values for the month of May across both time periods along with the removal of the outliers allowed us to meet the conditions of normality in order to apply ANOVA testing.

Analysis of Energy Performance

Furthermore, the normalized energy consumption values were then used for all of the energy performance analyses. That is not to say though that we were able to perfectly incorporate weather-related energy demands into the normalization calculations for May, especially since most of the outliers in the energy performance analysis still corresponded to those months. This raises the question of whether normalizing against the higher of the two values, HDD or CDD, is in fact an effective normalization tool for swing months such as May where resident interactions with the systems are abnormal compared to other months. This also prompts better incorporation of energy-driven behavior use of residents, which is the direction this longitudinal study is heading.

In order to perform the analysis of energy performance, we first evaluated the normalized total average energy consumption across both the pre-intervention and post-intervention time period. This helped to narrate the story of energy consumption across the two time periods and specifically when looking at each month in each respective time period. Upon inspection, this analysis did not seem to definitely illustrate which buildings with one-stage, two-stage, and variable speed HVAC systems was performing better in terms of energy efficiency. Therefore, we performed a comparative analysis of the average energy consumption for each newly installed HVAC system and this allowed us to compare the performance before and after intervention.

While the researchers had hypothesized that the variable speed system upgrades would provide the highest energy savings for each duplex post-intervention, both the total average energy consumption and the average energy consumption analysis depicted otherwise. The total amount of energy consumed decreased after the installation of new HVAC systems, which was a finding that was consistent with expectations based on manufacturer specifications. The buildings with variable speed HVAC systems installed did not see the greatest energy savings, rather those buildings are the ones that were found to be consuming the most energy. The two-stage HVAC system was found to outperform the two other systems in terms of energy savings after the installation of the new systems. This finding is counter to manufacturer specifications of variable speed HVAC system SEER rating, which is superior to that of the two-stage HVAC system.

While the manufacturer specifications provide that variable speed HVAC systems outperform two-stage HVAC systems, the preliminary results from the field study proved otherwise. Both the preliminary analysis and the exhaustive analysis included two forms of analysis, which include (1) total energy consumption (kWh/month) and (2) average normalized energy consumption (kWh/month) of each HVAC system, though they provided different results, the findings of which are summarized in *Table 6* below.

Table 6. Summary of Findings of Superior HVAC System Energy Performance

	Total Energy Consumption (kWh/month)	**Average Energy Consumption (kWh/month)**
P_1	One-Stage HVAC System	Two-Stage HVAC System
P_2	Two-Stage HVAC System	Two-Stage HVAC System

The superior performance of the two-stage HVAC system across both tests could provide important insight into residents' interaction with these systems. While variable speed HVAC systems are designed to outperform their counterparts, that is only if residents are aware of how to use these systems, which may not be the case in this housing community. These initial findings encouraged us to perform a one-way ANOVA analysis to test the multiple treatments; or the installation of three different systems. We hoped to compare the means of the energy consumed for each respective HVAC system and determine whether there is statistical significance between these means.

Before applying the one-way ANOVA test, we checked for the condition of normality, which was not initially met until the normalized energy data was transformed and the outliers were removed. Then, One-Way ANOVA was paired with a Tukey's HSD multiple comparison analysis where we found a statistically significant difference between the means of the normalized total energy consumption in the buildings with two-stage HVAC systems and that of the variable speed HVAC system. This was an interesting finding because although the two HVAC systems are very similar in terms of manufacturer specifications, specifically their cooling capacities, the buildings with two-stage HVAC systems were found outperforming. And the statistical significance points to the fact that not only are residents with two-stage HVAC systems using less energy, but they are actually using significantly less energy than those with the superior HVAC system. This calls into question the behavior-driven energy use of the residents, the level of detail of data collection and reporting, and the efficacy of traditional energy analysis.

Furthermore, the authors would also like to acknowledge that the data has numerous limitations as the data provided was through the utility company, who provided average aggregated totals of the energy consumption per kWh/month for all of the duplexes, which house two townhomes, as opposed to providing the energy consumed within each townhome. The reported values are also of the energy consumption of all appliances as opposed to each individual appliance. This makes it difficult to deduce whether the reduction in energy consumption can be associated directly with the HVAC systems or if other systems are coming into play. Information about the number and age of the residents, which was requested by the researchers to better understand the behavior-driven energy usage, was denied. The aforementioned limitations are recurring in the traditional model of energy analysis. Additionally, the distribution of the systems across the 35 units is not even, which meant that in order to each the condition of normality and apply ANOVA testing during the exhaustive analysis, we had to eliminate 82 outliers.

Analysis of Cost Performance

The findings made through the analysis of cost performance were also counter to expectations in numerous ways. The initial assumption had been that the energy performance analysis results and the cost performance results would be mirror images of one another. And where there were significant energy savings, we would see significant cost savings. But that was not the case where we saw no return on investment on all three HVAC systems. Additionally, we found that the one-stage HVAC system would cost the least loss of capital through its lifespan. This was while the expectation was that we would find the two-stage HVAC system, which saw the best energy performance out of the two other systems, was the most cost-efficient energy investment. This proved to be false and the two-stage HVAC system performed the worst in terms of cost.

CONCLUSIONS

This paper reports the initial findings of a longitudinal field study, which is just in its beginning phases, but the findings thus emphasize the need to update the energy monitoring and analysis process to increase accuracy and efficiency. While the results found thus far were contrary to expectations and manufacturer specifications of each of the respective systems, this suggests that when upgrading and installing new systems, energy literacy for all building stakeholders is equally as important as the systems being installed. Additionally, field observations by the research team have uncovered resident and landlord errors in the use of the thermostats controlling the system. Performing qualitative analyses such as surveys to better understand the occupants' experiences with the HVAC system upgrades are underway and will provide insight into similar projects. The preliminary data analysis emphasizes the need to update previous processes of energy analysis to accurately communicate and make decisions regarding energy-efficient technologies while leveraging cloud computing for data analysis and visualization to serve as a decision-making tool.

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Teaching Passive House in Academia

M. Rogero[1], K. Klingenberg[2], A. Kwok[3], and W. Grondzik[4]

[1]Associate Professor, Miami University, 101 Alumni Hall, Oxford, OH, 45056. 513-529-4903, rogeromr@miamioh.edu.
[2]Executive Director, Passive House Institute US (PHIUS), 116 West Illinois Street, Suite 5E, Chicago, IL, 60654. 312-561-4588, info@passivehouse.us.
[3]Professor, University of Oregon, 210 Lawrence Hall, Eugene, OR, 97403. 541-346-3656, akwok@uoregon.edu.
[4]Professor, Ball State University, 405 Architecture Building, Muncie, IN, 47306. 765-285-2030, wtgrondzik@bsu.edu.

ABSTRACT

The Passive House Institute US (PHIUS) conducts an active training program for professionals who wish to become proficient in passive house design and analysis. This training is provided via the CPHC (Certified Passive House Consultant) credentialing process. PHIUS has similar certifications for builders and raters, but the CPHC certification and related training is the core of its educational strategy. Historically, PHIUS CPHC training was delivered via face-to-face workshops. More recently the CPHC training adopted a blended delivery format; with both online and face-to-face components. The target audience for PHIUS training has traditionally been those seeking advancement or initial credentials via a continuing education experience. This has predominantly meant post-school adults.

Even more recently, PHIUS made its CPHC training curriculum available for delivery through academic institutions. This allows students enrolled in a higher education program (most commonly architecture) to engage the CPHC training materials while a student and under the aegis of his/her university. This academic engagement can result in a CPHC certification for students who successfully pass the PHIUS certification exams. The certification can then be taken into practice upon graduation.

This paper presents the rationale behind PHIUS offering its proprietary training to students and describes experiences with conducting such training within an academic institution—including reports from Miami University of Ohio, the University of Oregon, and Ball State University. These reports from three universities address universal concerns (enrollments, schedule, and student success rates) as well as institution-specific insights.

THE PHIUS PERSPECTIVE

The Passive House Institute US (PHIUS) is a 501(c)(3) non-profit established in 2007 (PHIUS 2019a). The PHIUS vision statement is to "make high-performance passive building commonplace." A longer version of this statement in the PHIUS business plan speaks of the climate crisis and how passive building can both mitigate and adapt to climate change. As a society and civilization we must get to Zero, not just Net-Zero but Absolute Zero, in terms of emissions (from both embodied and operational energy). From the current PHIUS perspective of operational energy efficiency, this implies the ability to operate on 100% renewable energy.

To drive this mission PHIUS established the first passive house curriculum for professionals in 2008 and created a professional designation and certificate called "CPHC®" (Certified Passive House Consultant), a registered trademark (PHIUS 2019b). The goal was to create professional capacity among architects and builders in the market to design and execute passive buildings. The trainees then became change agents in their own right in their home locales and spheres of influence, promoting passive building techniques and the benefits of passive building where they worked. This knowledge diffusion activity, and eventually related policy and utility incentives, seeded the passive building market that is now burgeoning .

PHIUS started working with universities early on. The PHIUS Executive Director taught a passive house design studio in 2005 at the University of Illinois at Urbana-Champaign and was hired again in 2009 to teach the CPHC curriculum to the University of Illinois Solar Decathlon team. This curriculum is centered around passive building principles, high-performance building science, and an energy modeling tool specifically developed to aid with the design of ultra-energy-efficient buildings.

The Illinois students took to passive house immediately. They understood and applied passive principles, and quickly learned to use the energy modeling tool that made complex design decisions easy and their effects instantly visible. The Decathlon team was wildly successful: It placed second behind the German Passivhaus Team that year (trailing by only 10 points out of 1000) and it placed first and second in all energy-related categories.

That experience made clear to PHIUS that there was an enormous potential for change. But to realize this potential, PHIUS needed to provide students with access to the training materials that were not taught as part of the regular curricula in architecture and engineering schools (PHIUS 2019c). In many academic programs, this gap includes most of the CPHC curriculum.

For the first time in 2015, trained consultants who also taught in architecture schools began to integrate parts of the CPHC curriculum into their courses and seminars. In 2016 PHIUS launched a trial outreach program, making the formal curriculum available to faculty members who also were trained CPHCs for a nominal fee. The first faculty member to employ the curriculum in academia was Shelly Pottorf at Texas A&M University Prairie View (TAMUPV). Mary Rogero at Miami University in Ohio followed shortly thereafter. The TAMUPV team applied passive building principles and used the modeling tool for their design entry in the 2016 U.S. DOE Race to Zero competition; the team was the overall Grand Prize winner. The TAMUPV team repeated their success in 2018, again integrating lessons from the CPHC curriculum and taking the overall Grand Prize in the Race to Zero. Notably, the team members were undergraduates at a predominantly minority school!

A team co-advised by Mary Rogero also participated in the Race to Zero and had similar success. Teams she helped advise placed first in the multifamily housing category in 2018, and first in the school building category in 2019. In 2017 Alison Kwok joined the group of pioneering faculty members when she offered the curriculum at the University of Oregon. Also in 2018, Walter Grondzik taught the CPHC curriculum in a course at Ball State University in Indiana. In the fall of 2019 Jonathan Bean began teaching a CPHC course at the University of Arizona. Ryerson University (in Canada) has also taught the course.

At the completion of the university CPHC programs, students are eligible to take the PHIUS certification exams (online and takehome). If they pass they obtain the CPHC, the leading passive building professional credential in North America. Many university students have reported that having that designation on their resumes has made a difference: it caught the attention of potential employers and made the students more competitive in the job market.

From the beginning, PHIUS has found that students—in engineering, architecture, and other fields—take to passive building enthusiastically, and without hesitation. Because they have not been steeped in conventional office practices, students embrace passive principles without needing to be persuaded. They also like being part of a meaningful solution to possibly the biggest challenge in human history. Learning passive building empowers them.

It's cliché, but students are the future—and based on the limited experience to date, that future can be very bright in terms of energy efficiency and carbon reduction. PHIUS hopes to encourage and enable more schools to offer the CPHC curriculum. At the time this paper was written, two more schools have expressed interest in adding the CPHC curriculum to their offerings: the Carnegie Melon University School of Architecture in Pittsburgh and Thomas Jefferson University in Philadelphia.

THE MIAMI UNIVERSITY EXPERIENCE

What inspired university interest in passive house? Miami University has offered a seminar course in low energy/high performance design and construction since 2009. The course was focused on passive house methodologies but did not provide an opportunity for students to obtain CPHC certification. When PHIUS developed the online training component for its certification curriculum, it reached out to several schools to beta test the curriculum in a university setting. Through subsequent incorporation of the PHIUS curriculum, the Miami University course now provides an opportunity for students to get professionally certified as CPHCs.

How does passive house fit into the curriculum? Miami University offers the course as a 3-credit hour Buildings Technology elective that is offered in spring semester only. The course is primarily open to third- and fourth-year undergraduate and graduate students majoring in Architecture or Interior Design. Since the department added a minor in architectural studies in 2018, several non-majors have signed up for the class as a way to fulfill their minor requirements. Currently there are no prerequisites for the passive house course, but any student interested in taking the course as a second-year architecture major or a non-major must be approved by the professor.

Miami University experiences. The course is extremely challenging, with one student describing it as “drinking from a fire hose.” The course tries to prepare students mentally for the work and motivate them to stay with it, even though they may find the work difficult. The course is structured to allow for success in the course even if a student does not ultimately get certified. Table 1 compares the university passive house course structure to the PHIUS training structure.

Table 1. Grading elements comparison, Miami versus PHIUS.

Course Requirements		PHIUS Certification Requirements	
0%	Online Training (videos & quizzes)	Online Training (videos & quizzes)	complete
20%	Homework exercises		
30%	Midterm		
30%	Final Online Exam	Online Exam	70%
20%	Design Project	Design Project	30%
100%			**100%**

Students who are unsuccessful in passing the PHIUS certification exam are allowed to retake the test the next time the course is offered. On average, three students retake the exam every year and all have been successful in achieving certification.

Teaching challenges. One of the major challenges in teaching the CPHC training course is transforming the professional curriculum into a format that fits both the academic schedule and calendar and reorganizing it to match the instructional needs of the students. The PHIUS professional curriculum consists of 40+ hours of online videos that must be completed prior to attending a 5-day onsite workshop with an additional 32+ hours of instruction. Each video module has a short online quiz that must be completed, and students are expected to receive a cumulative grade of at least 50% in order to pass that module of the course. The PHIUS in-class sessions consist of detailed exercises involving mechanical system design, thermal bridge analysis, WUFI Passive energy modeling software, and case study presentations. The professional course is taken primarily by architects, builders, and engineers, but has also attracted policy makers, realtors, and would-be clients. For professional certification, participants must successfully pass a three-hour multiple-choice online exam and complete a detailed passive house design (takehome exam) with an overall average of

70% for the course. The design exam is given at the end of the onsite session and is due three weeks later.

By contrast, Miami University operates on a 16-week semester (15 weeks of instruction, 1 week of final exams). The average contact hours for a 3-credit hour seminar is less than 3 hours per week, leaving little time to cover, in detail, all of the components covered in the professional training in the classroom. Many students come with little or no previous knowledge of building science, let alone an understanding of construction details, so the course must incorporate the online training videos into the sequencing of class lectures and weekly meetings to ensure that students understand the fundamentals of the training, rather than being a completely independent endeavor.

Additional challenges are numerous. There are no textbooks to guide faculty or students, although numerous resources are available online. Faculty are provided course material files that can be shared with students; these include all the in-class exercises and a study guide, along with other valuable resources. Faculty must develop their own transition plan, adapting the professional curriculum to their academic calendar and student needs, although there has been much sharing and support between the few university professors who are currently teaching the training.

One of the biggest challenges of the course has been related to student computer problems. Although the software used in the training (Therm and WUFI Passive) are free to students, experience has shown that students have so many computer and software issues that it is difficult to work these programs into the class time. Therm is a little easier and has a small learning curve, but is not without its quirks. WUFI Passive, the primary software used in PHIUS project certification, is difficult to teach in one-hour spurts. Both software programs are PC based, and since most of our architecture students use MACs, they must partition off their hard drives in order to use the software. Rather than specifically train the students on the WUFI Passive software, its use is demonstrated to show what happens when various parameters are changed. Motivated students who are interested in learning the software have made use of online training videos offered on the PHIUS website and additional training has been offered outside of class for students interested in really learning the software.

Course demographics. The CPHC course is offered in spring semester only and runs parallel with a Solar Decathlon Design Challenge studio. Students who are enrolled in both classes are generally better versed in building science than their fellow students and have performed better on the PHIUS certification exams.

Historically, there has only been one second-year student in the course in any given semester, but these students have always been some of the highest-scoring students in the course. The first year the course was offered, a second-year student was the only one to achieve certification; getting a higher score than graduate students taking the course. Non-majors from finance, geography, and engineering have also performed as well, or better, than traditional majors. Table 2 provides a listing of course characteristics and student performance results for the three occasions that the CPHC curriculum has been offered at Miami University.

Table 2. Miami University CPHC course data.

COURSE DATA											
	G	UG	Majors	ONLINE		AVERAGE +70%	DESIGN		AVERAGE	TOTAL SCORE aver	CPHC
				low-high			low-high				
2017	2	21	Arc, ID	41.16	87.25	67 (45%)	8.18	70	33.2	56.87%	1*
2018	1	14	Arc	53.5	94.05	86.8 (67%)	4.55	90.91	56.2	73.68%	12**
2019	1	15	Arc, (2) Engineering, Geography	54.9	89.8	68.94 (44%)	11.82	80.91	62.1	66.88%	7***

*2nd year arch major
**Grad, 2nd year arc major + 4 arc from previous year
***NM Grad, NM, 2nd year arc major

G= graduate; UG = undergraduate; Arc = architecture; ID = interior design; design = takehome exam

Summary comments. We are always looking for ways to make course materials more accessible to students who come into the class from different entry points and with differential expertise, and who have different learning processes. The course materials contain many hand calculations that students must know, so we are developing better graphic illustrations to help reinforce the principles. We are at a disadvantage in our region as there are not many builders or practitioners with which students can engage. We are working to build a network of CPHCs who can "lecture" via Skype so that students can broaden their understanding of the methodologies of passive house design and construction.

THE UNIVERSITY OF OREGON EXPERIENCE

What inspired university interest in passive house? The University of Oregon's interest in passive house training began with a lecture given at the university by Katrin Klingenberg and Mike Kernagis approximately ten years ago. The lecture sparked enough interest for this author to take the Certified Passive House Consultant training with the idea that it might be a course offering in the future. The inspiration comes from the successful integrated design process where the professions need to communicate with each other—architect, engineer, contractor, client—everyone has to understand the science behind design. The reduction in energy consumption that passive buildings offer makes it easier to get to a net-zero energy goal. The PHIUS training offers a comprehensive understanding of the building envelope (enclosure elements). This is an exceptional "fit" within the curriculum at the University of Oregon, where students are vitally interested in such topics. We have also found tremendous support from PHIUS, a willingness to offer training to interested students in the form of a partial scholarship—essentially sharing the financial burden with students in order to jump start enthusiasm and interest in passive house. The first PHIUS designated Certified Passive House Consultant (CPHC) training course was offered in Spring quarter 2018; the course was offered again during Spring quarter 2019. We are able to offer as many passive house trainings to as many classes/students as possible during a one-year period for a $2000 fee to PHIUS.

How does passive house fit into the curriculum? At the University of Oregon, the CPHC course is taught as an advanced technical elective (a 4-credit course) for both undergraduate and graduate students. All students are required to take one advanced technical elective prior to graduation. Although we have many course offerings, in the past two years, the course has garnered so much interest that there have been waiting lists to enroll. The prerequisites for the course currently include building construction and environmental control systems courses. Thus, undergraduates typically take the CPHC course in their third, fourth, or final year; graduates in the three-year MARCH have taken the course in their second or third year; and graduates in the two-year MARCH typically take it in their first or second year. The training has not yet been offered as a design studio or to non-majors. A key challenge with offering the training at Oregon is covering all the material during a 10-week quarter.

The plethora of passive house consultants and projects in Oregon and the Northwest makes it fairly easy to offer guest lectures to interested faculty and the community, thus fostering a faculty and community "passive house" cohort. Since there is a lot of overlap with other classes, students and faculty are often invited to the guest lectures for the passive house class.

University of Oregon experiences. Passive house training enables a culture of design integration and is easily adapted into the curriculum at the University of Oregon. The spirit of enthusiasm and a thirst to learn more has driven a few individuals to volunteer as teaching assistants for the class in the next year. The Spring 2019 class had four teaching assistants who had taken the class in the previous year. The TAs had a good understanding of what the students needed in order to be prepared for the PHIUS takehome and online exams, because of their own mistakes (or successes). The TAs developed a *Jeopardy* game where the student teams would pick questions off the board. Teams of students could discuss answers, then raise their hands with the answer. The game tested general re-call of concepts and principles. They also developed "*speed dating*" where each student was given a term that they explained/described to each other within a time limit. In addition, they developed *calculation assignments* from the PHIUS practice exam questions. One or two questions to be completed by the next class meeting. During class, the TAs reviewed the derivations of the calculations step-by-step and answered questions. Fieldtrips were arranged to two passive house single-family homes, where the owner explained what the challenges were during the construction process.

Students remarked that if they take the passive house training class, they will be very well prepared for the required enclosures course typically taken in their third year; if they have taken the enclosures course already, they mentioned that they would likely do well in the passive house training.

Teaching challenges. Challenges of teaching the CPHC course within the university include reconfiguring the PHIUS professional training curriculum into a format that fits within a 10-week quarter and structuring it to match the instructional needs of an academic course. A University of Oregon 4-credit course is equivalent to approximately 35-40 hours of class time per credit (in class and out of class time), translating to 140 to 160 hours over the quarter (14 to 16 hours/week). Course activity is weighted to build in success for the course, not necessarily to "teach to the test." The grading categories and weights were: online videos/quizzes: 25%; attendance/participation: 20%; in-class activities: 25%; online final exam: 20%; takehome design project: 10%.

Another challenge is the timing of the online exam and the takehome exam. The PHIUS professional training holds the online exam on the last day of the 5-day in-class training. This online exam is best handled during "Final Exam" week at the University. The PHIUS professional training schedule assigns the takehome exam (which is due 4 weeks later) after the online exam—this scenario does not align in a university course. We assigned the takehome exam in week 5 of the 10-week course, it was due in week 9, final design reviews were in week 10, and students took the online exam during final exam week (week 11). This meant intense grading over a busy 10- to 14-day period to be able to get the grades in before the end of the quarter. We are discussing the pros and cons of disconnecting the takehome from the course.

Another challenge is time and cost. Graduate students pay quarterly tuition that covers 9–16 credits; undergraduates pay for each of their credits (resident: $1672; non-resident; $3796). Unless a student needs credits generally or specifically to complete the advanced technical course for graduation, it does not make financial sense to take the course. On the other hand, the comradery and peer-to-peer learning is extremely valuable.

One major shortcoming of a 10-week quarter is the inability to provide adequate coverage of WUFI Passive. A few students have taken the initiative to do online PHIUS tutorials to learn basic WUFI Passive skills. Experience shows that bringing in guest speakers to run through the various program steps and screens, however, is not enough.

Course demographics. Details regarding student numbers and performance associated with the CPHC courses offered at the University of Oregon are given in Table 3.

Table 3. University of Oregon CPHC course data.

YEAR	G	UG	M	F	ONLINE		AVG	TAKEHOME		AVG	TOTAL SCORE AVG	CPHC
					low	high		low	high			
2018	15	15	20	10	52.0	93.3	72.3	25.5	90.9	69.5	71.4	20
2019	15	7	15	7	47.2	98.0	73.2	40.9	92.7	77.0	74.3	17

G = graduate; UG = undergraduate; M/F = male/female

Summary comments. Success is measured differently by faculty and by students. Receiving the CPHC credential is a big deal for students as they go into the job market. For faculty, success generally means a well-enrolled course that is supportive of larger curricular goals. Linking these two perspectives, the University of Oregon is developing a passive house studio course where the final design for the studio will take the place of the PHIUS takehome exam. It would be very helpful to teach a WUFI Passive course prior to the studio. At Oregon, a "terminal" studio would be the ideal studio setting. A proposed sequence would be Fall quarter: WUFI Passive Seminar and other tools; winter/spring quarter: design studio.

Students have asked for more hands-on experience to help with understanding of wall assemblies and installing windows. Several years ago, one of the graduate teaching assistants for building construction assembled three bins containing materials for different wall types. Each material had Velco attachments, which guided students in creating a wall assembly. This idea is intriguing in the passive house context.

In future classes, we would encourage teams of students to conduct a blower door test so that they can get experience in understanding the functioning of the test equipment, common locations for leaks, and to get used to handling, transporting, and setting up the blower door.

THE BALL STATE UNIVERSITY EXPERIENCE

What inspired university interest in passive house? The dynamics behind the Ball State University offering of the CPHC curriculum are somewhat different from the Miami and Oregon situations. The faculty member conducting the Ball State courses is a long-term member of the PHIUS Board of Directors and a colleague and friend of the faculty teaching passive house at the other institutions. Ball State is now part of the PHIUS-in-academia network mainly because it seemed the right thing for this faculty member to do relative to the role of architecture in addressing environmental degradation of our planet and partly due to positive peer pressure. The startup effort was substantially eased by encouragement from PHIUS staff and support from these colleagues.

Ball State University and its Department of Architecture have substantial engagements with the environmentally responsible design and operation of buildings. A passive house course was a logical addition to an existing matrix of "sustainability" courses and initiatives. But, a faculty-down rationale for bringing passive house into the architecture program (Ball State) is very different than a grassroots (students-up) rationale (as perceived to be somewhat the case at Miami and Oregon). Rather than metering access to a course highly demanded by students, the passive house course at Ball State must be marketed to the students. In the middle of the semester when "drinking from a fire hose" is becoming an increasing challenge to time and intellectual capacity, why a student is in a particular course (because the topic is a core belief or simply an interesting area of study) can make a difference to success.

How does passive house fit into the curriculum? It was very easy to bring the CPHC training into the Ball State architecture curriculum. The building science that is the heart of the CPHC training curriculum could be addressed through either of two long-standing elective courses—nominally titled high-performance buildings and technologies for green buildings. Both courses are graduate electives within the Department of Architecture's NAAB-accredited Master of Architecture (MArch) program. The specific content of these electives varies from semester to semester at the discretion of the faculty teaching the courses. It is (and was) exceptionally easy to "convert" either course into a passive house course.

In fall 2018, the passive house curriculum was first presented at Ball State under Arch 632: High-Performance Buildings: Passive House. Twelve students were enrolled in this course; all were graduate students in the architecture program. The PHIUS CPHC training was again offered at Ball State in spring 2019. This second offering was made available under two courses: Arch 498 and Arch 598 (both with the title High-Performance Buildings: Passive House). Having the 498-course option allowed undergraduate students to take the course content without bureaucratic hassle. Spring enrollment included two undergraduate students and ten graduate students. The 498-course number is designated for independent study courses, which removes a minimum enrollment baseline from the course. The ease of implementing the passive house course in the Ball State curriculum cannot be overstated; enrollment is the key concern, not getting an appropriate course developed, approved, and in place.

Ball State University experiences. The courses offering the CPHC curriculum to Ball State students have (until recently) been well-enrolled. This creates a good group dynamic and peer-exchange opportunities within the courses. The PHIUS online content has been conveyed. After-content success in both the online and takehome exams has not been as prevalent as desired. The blame for this is placed on the instructor—mainly in terms of course grading setup.

The first CPHC course at Ball State completely separated performance on the online and takehome exams from the course grade. The course grade was informed by completion of PHIUS modules and active participation in class discussions. This seemed reasonable at the time—but essentially removed any incentive to do well on the PHIUS tests. Student performance on these tests was not good. The grading scheme for the second Ball State CPHC course was changed such that the student grade on the PHIUS online exam influenced (but did not determine) the overall course grade. This improved performance on the online exam but did not greatly affect takehome exam completion or success. The third (current) course offering repeats this grading scheme. Whether performance on both the online and takehome exams should feed into the course grade is under consideration.

Teaching challenges. The challenges of teaching the CPHC curriculum at Ball State are both universal and unique. A universal concern is the cost of the program—the licensing fee that PHIUS charges the academic institution. The fee is not unreasonable and is in fact great value for the benefits. Many departments, however, simply have no money available for this sort of expense. Faculty startup funds were used for the Ball State license fee in 2018-2019 (one license covered both semesters). In the absence of faculty funds in 2019-2020 the department struggled to pay for a license. The issue was resolved but will recur in future years.

Another universal challenge is the fit of the CPHC training material's scope and depth to the Ball State academic calendar (typically 15-16 weeks; a 10-week term is terrifying). The *drinking from a fire hose* analogy mentioned above is apt. At Ball State coverage of software (WUFI and Therm) was minimized. In the first and second course offerings the takehome exam was assigned a due date after the end of the semester (to remove this time block from the 15-week clock). This was not a brilliant decision in terms of completion rates—as might be expected. Only those who absolutely wanted the CPHC certification attempted to complete the exam on their own time. Conversely, it seems critical that academic instructors add value to the PHIUS materials; this usually involves spending time on additional activities not required of those taking the PHIUS training online.

Perhaps universal, but certainly personal, is the concern that an academic course be substantively structured and controlled by the academic institution and not by an outside entity. Many organizations have developed educations modules, of varying lengths, for adoption by university instructors. This is generally considered a positive because of the targeted and current expertise such a module presumably brings to academia. The "but" here is: so long as the external modules fit the academic needs of the faculty and program. The concern of the Ball State instructor is not technical content, but rather academic fit—which seems to result in a need to add academic value to the PHIUS package. This is not a criticism of the content developed by PHIUS, but rather a reflection on the fact that Ball State is awarding course credit and not PHIUS. PHIUS is however, potentially awarding professional certification. Herein lies the tension.

Course demographics. Change seems to be constant, and this is the case for passive house demographics at Ball State. When the CPHC training was first offered in 2018 and again in spring 2019 the elective courses that hosted the passive house content were an integral part of the MArch curriculum. Although electives, the courses were situated such that many MArch students would choose them as a means of completing a required technology experience. This structure in effect guaranteed relatively high enrollment numbers, but it also made it very difficult to engage undergraduate students in passive house (the university frowns upon cross-listed courses that mix graduate and undergraduate students). This dynamic also brought students into the courses who needed a technology course versus wanting a passive house course. See Table 4 for course enrollment data.

In fall 2019, a revised MArch curriculum was adopted. This new curriculum modified courses, course interactions, course scheduling, and the physical location of students (some still in Muncie and some now in Indianapolis). As a result of these changes (and student adjustment to the changes) enrollment in the fall 2019 CPHC course was not adequate to permit it to "make" (be formally offered as a regular course). Thus, this most recent Ball State CPHC experience is being provided as an independent study course, with three graduate students collectively engaging the same academic content. This is working, but enrollments drive course offerings and time will tell whether enrollments recover as the new program becomes better established and understood. Having graduate students in two separate cities adds more complexity to this transitional mix.

Table 4. Ball State University CPHC course data.

YEAR	G	UG	M	F	ONLINE		AVG	TAKEHOME		AVG	TOTAL SCORE AVE	CPHC
					low	high		low	high			
Fall 2018	12	0	6	6	na	na	na	na	na	an	an	0*
Spring 2019	10	2	6	6	45.8	85.4	62.2	40.9	55.5	48.2	na	2*
Fall 2019	3	0	3	0	na	na	na	na	Na	na	na	na

* one student from this class is currently completing the takehome exam (results to be determined)
** two students from this class are currently completing the takehome exam (results to be determined)

Summary comments. It has been a joy (perhaps a joyful challenge) to introduce passive house concepts to Ball State architecture students. It would be a joy to be able to continue to do so under the new MArch structure. Bringing students from other disciplines within the College of Architecture and Planning into the passive house courses would be wonderful; but very restrictive professional curricula and graduate/undergraduate course distinctions make this a challenge. The Department of Architecture is currently exploring options that could bring professionals in practice into graduate courses. This might be an interesting route to consider for the CPHC academic course. And a note about numbers: although Ball State to date has only delivered two CPHC credentialed students; these two represent 40% of the CPHCs currently listed as residing in the state of Indiana.

COLLECTIVE RESULTS

Student certifications. Table 5 summarizes the numerical outcomes of the university-provided CPHC training efforts for Miami University, University of Oregon, and Ball State University between 2017 and 2019.

Student immersion in building science and its design implications. Above and beyond the student CPHC certifications noted in Table 5, all students enrolled in the university-based PHIUS curriculum received an exceptional in-depth immersion in building science and its implications for design. This knowledge is critical to the ability of designers to envision and bring to fruition the low-energy (and high comfort and health) buildings necessary for society's engagement with the effects of greenhouse gas emissions. Some students in the Miami and Ball State programs received a double dose of building science—having participated in both the CPHC curriculum and the Solar Decathlon Design Challenge competition. The applied building science impacts of exposure to the PHIUS curriculum are alone enough to encourage design programs to engage the PHIUS CPHC training.

Table 5. Student numbers and outcomes; 2017-2019.

UNIVERSITY YEAR/SEMESTER	STUDENTS ENROLLED	STUDENTS CERTIFIED
Miami University		
2017	2 G; 21 UG	1
2018	1 G; 14 UG	12
2019	1 G; 15 UG	7
University of Oregon		
2018	15 G; 15 UG	20
2019	15G; 7 UG	17
Ball State University		
Fall 2018	12 G	0
Spring 2019	10 G; 2 UG;	2
Fall 2019	3 G	na

G = graduate; UG = undergraduate

Collaborations. Just before the completion of this paper, the authors and several other interested people assembled in Eugene, Oregon for a retreat that focused on implementing the PHIUS CPHC curriculum in academia. This informal assembly provided an excellent opportunity to share experiences, enthusiasm, and course materials. A concrete outcome of the retreat was a promise among participants to share existing course resources and to develop more such resources to fill identified academic gaps in the existing PHIUS training materials.

Additional universities. A recent addition to this review of teaching passive house in academia is news that the University of Arizona architecture program is now offering the PHIUS curriculum to its students via an academic course. PHIUS and its Board of Directors is also exploring funding and organizational structures that might make the PHIUS curriculum more readily available to minority-serving academic institutions.

CONCLUSIONS

Historically, the PHIUS CPHC training program has served the needs of those in the workplace seeking improved building science knowledge, specific information on the design and construction of passive buildings (single-family residential, multi-family residential, and non-residential), and entry into the passive building community via certification. Currently, PHIUS and its university partners are expanding this historic client base through the inclusion of students in buildings-related academic disciplines. Ideally students who graduate with a passive house certification can act as change agents within the firms that employ them. This change may involve the design of passive buildings; it should certainly involve the design of buildings that better address tricky issues of building science. Even students who do not obtain CPHC status have been immersed in knowledge that will improve their building design outcomes. Looking forward, PHIUS would like to expand the reach of its university outreach efforts while solidifying the success of its existing university partners.

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Mojave Bloom: Designing a Net-Zero Veteran's Transitional Home

Eric Weber
Associate Professor, School of Architecture, University of Nevada Las Vegas, 4505 S. Maryland Parkway, MS 4018, Las Vegas, Nevada 89154. 702-895-3031, eric.weber@unlv.edu.
Dak Kopec
Associate Professor, School of Architecture, University of Nevada Las Vegas, 4505 S. Maryland Parkway, MS 4018, Las Vegas, Nevada 89154. 702-895-3031, dak.kopec@unlv.edu.

ABSTRACT

Our team is incorporating emerging technology that support health outcomes and personal wellbeing into a design that supports energy efficient building design. This unique proposal has implications for empirical research and home design, and the important potential to address issues of health and affordable housing facing the southwest region's fast-growing population, our efforts center on supporting the reintegration of veterans into our community. Dubbed Mojave Bloom, this prefabricated net-zero energy transitional home for returning veterans struggling with Post-Traumatic Stress Disorder (PTSD) will assist its residents in developing skills required for successful reintegration into civilian life.

The house's inner courtyard is bathed in diffused light, filtered through the canopy of bifacial photovoltaic panels above. Living green walls flanking the space cool the dry desert air via evaporative transpiration, and recaptured water circulating through the hydroponic system produces a meditative sound of trickling water through the space. Raised planters offer additional seating, while grasses within sway in the wind helping create a sense of calmness through rhythmic visual stimuli.

One of the therapeutic qualities of the design is the maximization of personal empowerment by the user to control his or her environmental outcomes. This ability enables the resident to modify the home to meet their physical and social needs and adapt to weather conditions. Furthermore, nesting the outdoor space between the bedroom and primary living space maximized prospect (visual surveillance) for the occupants and refuge (the ability to conceal oneself) while healing from trauma. Thickened walls provide deep insulation, helping prevent heat gain/loss through the building envelope and create a barrier against assorted exterior noise that have the potential to trigger a PTSD episode.

Design Description

Desert Bloom creates an oasis from the bustling downtown of Las Vegas and the Mojave Desert's harsh environment. Drawing inspiration from the traditional Islamic sahn, or courtyard, this house turns inward, sheltering the resident from heat and noise, and achieving a model of alfresco living otherwise unattainable in the southern Nevada climate.

Designed to be a place of healing for veterans suffering the adverse effects of wartime trauma, the home connects the resident to their environment through a carefully orchestrated procession of sensory experiences. Its inner courtyard is bathed in diffused light, filtered through the canopy of bifacial photovoltaic panels above. The green walls flanking the space cool desert air via evaporative transpiration, and the reclaimed water circulating through the hydroponic system emits the meditative sound of trickling water through the space. Raised planters offer outdoor seating, adjacent to tall grasses swaying in the wind, which create a deep sense of calm associated with rhythmic sensory stimuli.

The sliding living green wall and operable window walls between the living spaces and the courtyard are designed to expand the living spaces into the outdoor volume, acting as a catalyst for the healing act of controlling one's environment. This ability to manipulate space allows the resident to transform the home to meet their needs, adapting to the weather as well as their personal needs for connection or refuge while healing from trauma.

Four monolithic walls give a sense of solidity and envelop the resident with a sense of safety and enclosure. The thickened walls provide deep insulation, helping prevent heat gain/loss through the building envelope and creating a barrier against exterior noise that may trigger PTSD. Carefully placed openings provide a visual reminder to the resident of their connection to the larger environment and community.

Ceiling Design

The ceiling design began as a metaphorical desert bloom, creating a sheltering effect which seemed appropriate at the sleeping space. Many desert flowers only open at night, remaining closed during the day to protect them from the desert's harsh sun. Our intent was to create a soft, acoustically quiet enveloping effect, which might feel protective for the occupant. In addition, by utilizing acoustically absorptive surfaces, ambient and intermittent sounds could be effectively attenuated, thus assisting the resident with sleep disorders.

Indirect lighting is provided by linear LED's set between Tectum panels, creating diffused indirect lighting, which reduces shadows and glare, known triggers for PTSD. Tectum is a sustainably produced wood product which is acoustically absorptive, producing a less live space.

Fig. 1 Bedroom Ceiling with Layered Panels

The ceiling expands above the living and dining areas, creating a subtle definition between functions in this otherwise undifferentiated space. The shapes are constrained by the fire sprinkler system; the geometries of the ceilings are direct reflections of the sprinkler spray pattern diagrams, ensuring compliance with the system's needs, while also providing a dynamic lighting experience, which is controllable using the home automation system. Direct lighting can be mixed with diffuse lighting from the ceiling panels, creating a relaxed or festive atmosphere as appropriate. The lighting is designed to reduce dark shadows, and all lights can be turned on or off at once as required to mitigate a PTSD event.

Designing for Veterans

The Design+Build Studio is competing in the Solar Decathlon as an opportunity to address sustainability and energy concerns, while simultaneously serving at risk members of our community.

The war in Afghanistan is longest war in US history and one-third of deployed service members return home with a combat induced disability. Many of them face years of rehabilitation for amputations, concussions, and PTSD. These challenges may result in substance abuse, domestic violence, incarceration, divorce, homelessness, and suicide. These men and women have chosen to serve their country, and we believe that it is our responsibility as citizens to serve them. We set out to address the challenges faced by returning veterans and help them transition to their new normal, and to incorporate best practices to assist veterans in this process.

Strategies for PTSD

There were 107 veteran suicides in Nevada in 2016 alone, significantly above the national average per the Veteran's Administration's 2016 Veteran Suicide Data Sheet, part of "A National Suicide Data Report 2005–2015"[1]. Suicide is one of many challenges PTSD sufferers experience. PTSD is often accompanied by depression, substance abuse, or one or more of the other anxiety disorders, and in some cases, this can result in higher incidents of domestic violence. In order to respond to an occupant with PTSD, we have designed the home to minimize the stimuli most likely to provoke a PTSD episode.

For visual stimuli we have designed an open layout to allow for prospect and refuge while within the home. Prospect-refuge theory figures prominently in architecture, landscape architecture, and interior design, and can be defined as follows:

> Prospect-refuge theory could therefore be described in general terms as a particular environmental pattern, made up of spatial and formal relations that educe feelings of safety and wellbeing. The environmental pattern is achieved through a careful balance between vista and frame that also evokes a sense of the unknown. This theory suggests that humans seek out environments which make them feel secure.[2]

One of the therapeutic qualities of the design is the maximization of personal empowerment by the user to control his or her environmental outcomes. This ability enables the resident to modify the home to meet their physical and social needs and adapt to weather conditions. Nesting the outdoor space between the bedroom and primary living space maximized prospect (visual surveillance) for the occupants and refuge (the ability to conceal oneself) while healing from trauma. The large gates that welcome visitors to the house can also be closed to provide a safe refuge for the resident, especially during a PTSD episode. The gates are specifically designed to allow the resident to see through them, while simultaneously allowing them to remain hidden, an essential quality for PTSD sufferers.

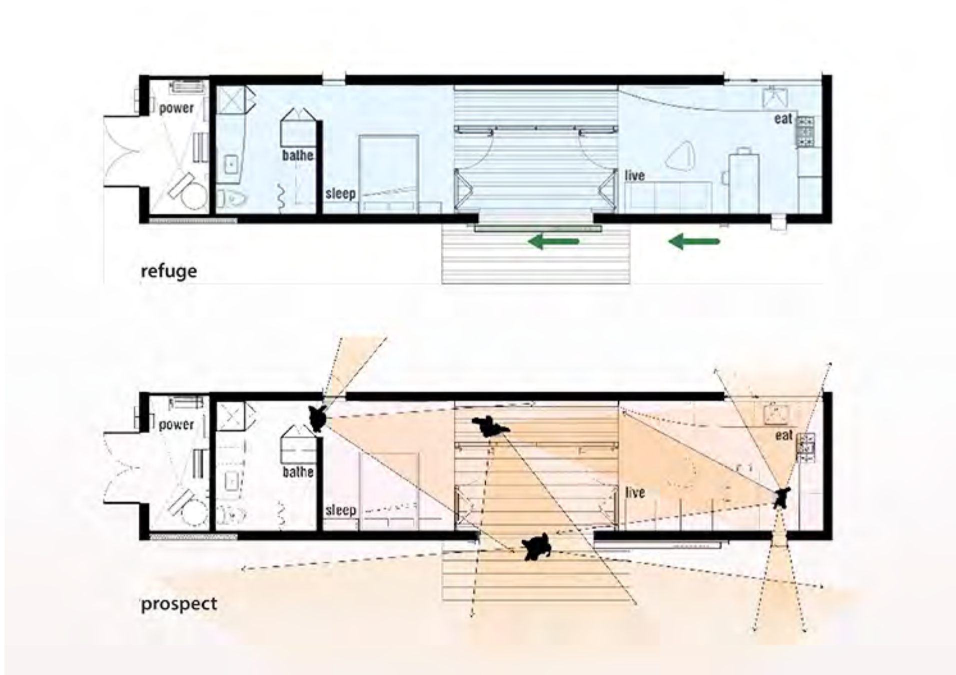

Fig. 2 Prospect and Refuge as applied to project.

Studies have also shown that cultivation, even just proximity to plants, helps to reduce stress in veterans who suffer from PTSD.[3] For this reason, an interior green wall is strategically placed within the primary corridor inside the Mojave Bloom house. This will give veterans a bit of nature to walk past, feel, smell, and care for.

> Reliving small "manageable doses" of traumatic memories whilst carrying out a simple and repetitive activity such as walking, digging, or sowing seeds, in tranquil and pleasant natural surroundings may, over time, "rewire" the brain's hyper-vigilant networks and help restore a more mindful state of awareness that is predisposed to remaining in the "learning mode".[4]

Construction System

Our team has developed a partnership with a local construction equipment manufacturer that has branched into manufactured buildings. They investigated shipping containers as a modular system and determined that there are a number of limitations to wider use of them as practical building system. In particular, the eight-foot width does not lend itself to effective architectural spaces, and when the corrugated sides are removed or perforated, it compromises the structural integrity of the structure. This necessitates adding structural reinforcement, significantly reducing their economic viability.

Our partner's solution has been to develop a system that relies on proprietary moment connections at the corners, and hollow steel sections (HSS members) between them. This system results in an assembly that does not rely on its infill panels for structural rigidity, greatly increasing their system's flexibility. Further, their system is able to accommodate widths up to twelve feet in width, which makes the system viable for many building types and potential uses.

Because the system does not rely on the infill panels for rigidity, they can be made of whatever system is appropriate for the project. In our case, the panels are wood framing with a non-structural spacing of 24” on center, with single-layer top and bottom plates. They are sheathed conventionally with 5/8” oriented strand board, and the cavity is filled with closed cell spayed foam insulation.

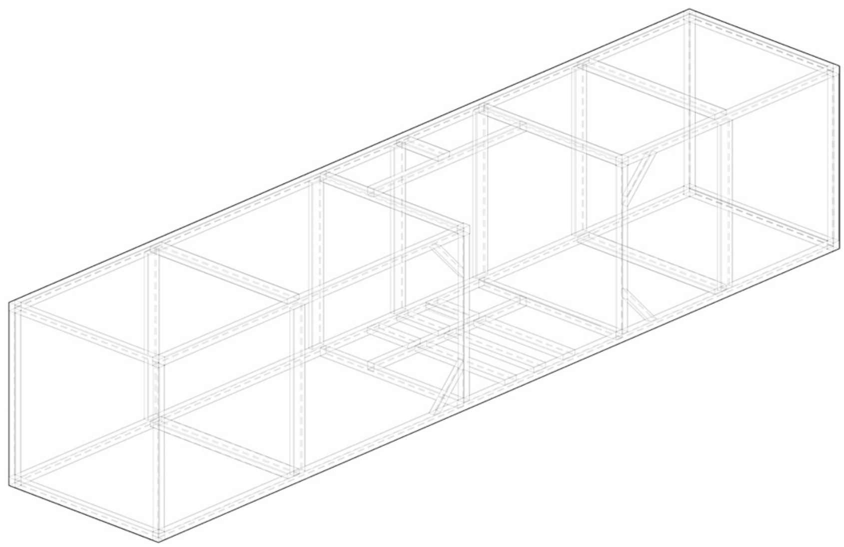

Fig. 3 Prefabricated Steel Frame Assembly

Due to the thermal bridging present in the wood stud assembly, as well as at the perimeter steel tubes, we are installing two-inch polyiso rigid insulation outside the line of the structural system. This R-14 material significantly reduces thermal bridging and adds to the overall insulation value of the assembly. The overall assembly results in a nominal R-47 wall system.

At the roof assembly, the building system typically utilizes 2x12 framing at 24” on center, with 3/4” tongue and grooved structural decking. The cavities between framing members are filled with eleven inches of closed cell spray foam insulation. To reduce thermal bridging, we are again using a minimum 2” R-14 rigid polyiso insulation, with thicker material as required to ensure roof drainage. The overall result is a nominal R-74 for the roof assembly. A short parapet occurs on three sides of the building, providing an opportunity to address thermal bridging through the top corners of the structural framing system; we will be extending the polyiso insulation over the frame at the fourth side, providing a minimum R-14 bridging resistance at this location. The R-55 floor assembly is similar in construction to the roof, except for thinner 6-1/2” spray insulation and the use of 1-1/8” tongue and grooved plywood floor sheathing.

At the windows which penetrate the wood structural infill wall assembly system, we specified aluminum clad wood windows, with tilt/turn operation. The folding glass door assemblies, including swinging entry door sections have a Unit U-value of .30. Tilt-turn windows by the same manufacturer meet this performance level, as well. Fixed glazing is wet glazed 1” insulated glazing units (Solexia+SolarBan 70XL) with low-e coating on surface 2, argon filled cavity; U-value of .24.

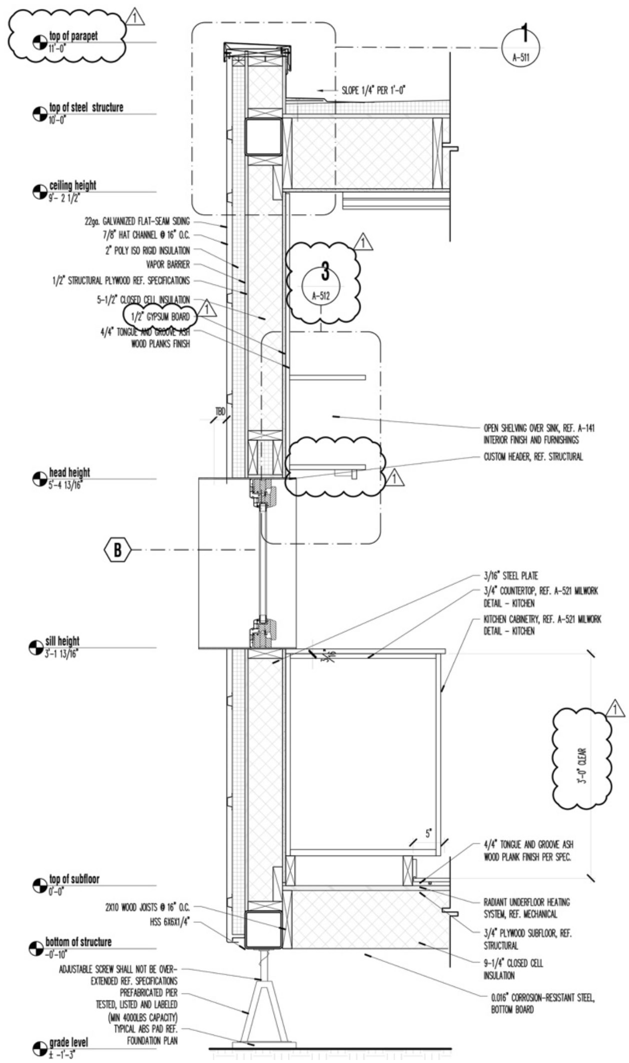

Fig. 4 Wall Section Indicating Construction System

Photovoltaic System

The home will have a roof mounted bifacial photovoltaic system. Bifacial panels were chosen for this application due to their ability to generate electricity from incident solar radiation, as well as from reflected light from other sources, most notably the low-slope roof on this house. The system will be designed to handle the required energy needs of the home for net zero energy operation. The panels on the roof will have the required access clearances around the systems. Because of the limited roof space of a transportable home it may be necessary to have some of the

PV system overhang the roof area and be utilized as shade structure for the home. In anticipation of this, the system spans over the entry court, and the panels become shading surfaces for the occupants below. We are currently looking at racking designs that will allow sections of the PV array to fold onto itself to be transported and then easily be unfolded as overhangs at the competition site. This may be possible without needing to disassemble any panels or wiring and significantly reduce the home setup time. The racking system may also be adjustable for solar angle due to the need to lower the transport height of the house. It becomes a relatively straightforward task to integrate some adjustability into the system with this approach.

Solar Thermal and Mechanical Systems

The house will utilize evacuated tube collectors that will be integrated to mount vertically in a small recess on the south wall during transportation of the home. A unique concept of the installation is when the home is set up two pipe unions located on the header tube of the collectors will be loosened to allow the bottom of the collectors and support structure to be rotated away from the home to set the collectors to the ideal installation angle. Afterwards the unions are tightened and the solar loop is filled. This installation allows the collectors to be adjusted to the ideal installation angle suitable for different locations. The collectors can also be adjusted seasonally or to optimize the heat collected for the needed water use. The bottom of the collectors, angled away from the house, will be protected with a planter located under the collector.

The home will use a commercially available Energy Recovery Ventilator (ERV) for makeup and fresh air. The system will also include an innovative system to condition the fresh air before entering the ERV. This unit will be a compact unit that will use Phase Change Materials (PCM) to lessen the effects of outdoor air temperatures and decrease the air conditioning required to heat or cool the fresh air. The compact unit will be designed with integrated washable filters to remove odors, allergens and small particles from the fresh air to improve indoor air quality. The PCM used is a commercially available encapsulated eutectic salt which are contained in foil packets and are approved for installation in the active plenum. The salts are flame resistant and do not put out harmful gases or fumes when heated. The PCM is designed to "freeze" and "thaw" at 78 degrees F which is ideal for ventilation applications. Installed in a heat exchanger in the fresh air inlet PCM will melt in high ambient temperatures and absorb heat from the incoming air. During cooler evening hours the absorbed heat can be rejected to the ambient or used to heat the incoming air allowing the PCM to re-freeze. During colder ambient conditions the PCM can be used for heat recovery and reheat colder incoming air. Testing at UNLV has shown the PCM installed in the active fresh air plenum greatly reduces the energy required to heat or cool incoming fresh air. The systems used will be controlled by the home automation system which will be able to switch through the different modes needed. Manual operation of each system will be possible for control redundancy. The status of the system, operational characteristics, and maintenance schedules can be viewed on the smart device home automation interface.

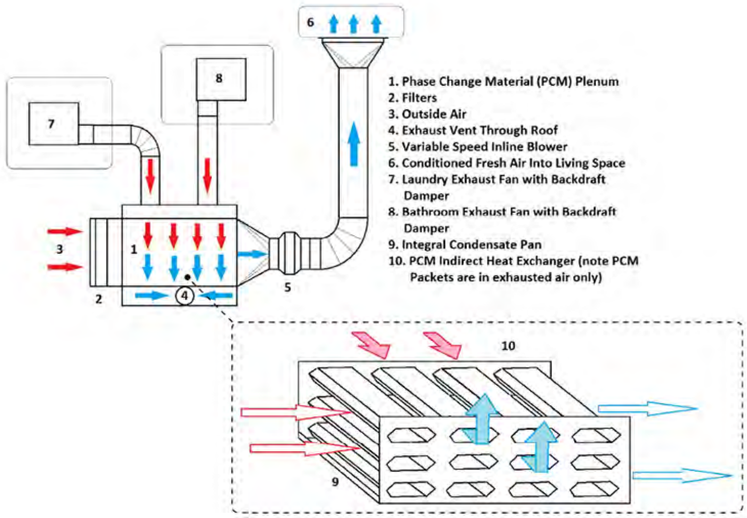

Fig. 5 Phase Change Material Plenum System

The home will have two mini-split heat pumps located in the main living room area and in the bedroom. Using two units allows redundancy in the systems in case of service issues. Also, two systems increase efficiency during partial load conditions when only one unit may be required to cool the interior space. The unit in the living room area will be located so as to direct air towards the kitchen area and large door/window systems to better condition the associated loads. The unit in the bedroom will be positioned to not only cool the bedroom but also direct air towards the living spaces, to assist in cooling these areas when the living unit is not running. Exhaust in bathroom and laundry areas will also aid in drawing conditioned air.

Conclusions

The Solar Decathlon offers architecture and engineering students an avenue for developing real world skills while simultaneously developing innovative responses to challenging design problems. It enables collaboration, teamwork, and effective communication skills, while simultaneously enabling students to explore solutions to some of society's most difficult problems. Designing for the veteran population in Las Vegas also enables students and researchers to gain valuable insights into best practices for responding to the veterans' specific needs. These lessons will be invaluable for both the participating students and faculty.

References

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Experiences with Race to Zero/Solar Decathlon Design Challenge

T. D. Collins[1] and W. T. Grondzik[2]

[1] Assistant Professor, Department of Architecture, Ball State University, 426A Architecture Building, Muncie, Indiana, 47306. 765-285-2028, tdcollins@bsu.edu.
[2] Professor Department of Architecture, Ball State University, 405 Architecture Building, Muncie, Indiana, 47306. 765-285-2030, wtgrondzik@bsu.edu.

ABSTRACT

Our institution has participated in three Race to Zero/Solar Decathlon Design Challenge competition cycles. During this time, we have worked with ten student teams, seen eight teams invited to present their projects in Colorado, and celebrated more than one team award. The Race to Zero student design competition, renamed the Solar Decathlon-Design Challenge for the 2019 cycle, has provided a range or opportunities and challenges for our accredited architecture program. Several of these elements will be presented in this paper.

The primary driver for our initial and continued participation in this USDOE-sponsored event is the framework for integrated design that it offers and demands. In our situation, this integration involves the expansion of design boundaries beyond traditional "architectural" considerations into technical systems and operational performance. The desire for more integrated design thinking is achieved by expansion of horizons among architecture students—rather than by the active involvement of additional disciplines in the day-to-day workings of the design studios. This may not be ideal, but it works. The structure of the competition requires that our students learn and understand more about buildings than they would in a studio with a less diverse range of systems engagement.

In this paper we will describe the structure and context of our studio; the infusion of building science into the studio setting; working with external partners and consultants in studio; and observations regarding successes and challenges. The main focus will be what makes this experience different from conventional studios and the role that the competition plays in demanding such differences.

RACE TO ZERO/SOLAR DECATHLON DESIGN CHALLENGE

In 2014, the US Department of Energy (DOE) created the Race to Zero (RTZ) as an annual design competition for college and university students. Two goals of the competition were to challenge "collegiate teams to apply sound building science principles to create cost-effective, market-ready designs that meet DOE's Zero Energy Ready Home program requirements" and to "advance building science curricula at universities" to prepare the next generation of architects, engineers, construction managers, and other professionals to solve real-world problems related to net-zero energy residential design. (USDOE, 2017)

For 2018/2019, RTZ was renamed the Solar Decathlon Design Challenge (SDDC) in an effort to combine DOE competition efforts and to distinguish the former RTZ competition from the traditional Solar Decathlon design/build competitions begun in 2002 and held every other year. From the perspective of the competing teams, however, there were relatively few changes to the design competition other than the name change. (USDOE 3) From 2014-2017, RTZ focused on four residential building typologies as divisions: attached housing, suburban single-family detached, urban single-family detached, and multi-family. For the 2017/2018 competition, a small elementary school commercial building type was added as a division. For the 2018/2019 competition, a small office building typology was added as a division and the multi-family type was changed to a mixed-use multi-family type. The divisions are unchanged for the 2019/2020 competition: three residential types, two commercial types, and one mixed-use housing type.

RTZ/SDDC requires that students develop collaborative teams. The teams develop a design proposal for one of the building typology divisions. The proposals are evaluated by a jury according to how well they respond to ten contest areas. These contest areas have changed somewhat over the years presumably in response to industry trends and/or feedback from teams and juries. For example, in 2016/2017, the contests were:

1. Architectural Design
2. Interior Design, Lighting, and Appliances
3. Energy Analysis
4. Constructability
5. Financial Analysis
6. Mechanical, Electrical, and Plumbing Systems Design
7. Envelope Performance and Durability
8. Indoor Air Quality (IAQ) and Ventilation
9. Innovation
10. Presentation and Documentation Quality

For 2018/2019, the contests were:

1. Energy Performance
2. Engineering
3. Financial Feasibility & Affordability
4. Resilience
5. Architecture
6. Operations
7. Market Potential
8. Comfort & Environmental Quality
9. Innovation
10. Presentation

Each year, DOE develops a new and comprehensive competition guide that describes the requirements for team structure, competition deadlines, parameters for the divisions, and details related to the evaluation contests. The guides establish expectations for the submitted proposals to: address a host of technical considerations, demonstrate compliance with industry standards, and integrate enclosure and HVAC systems into the overall design. See Figure 1.

While the NAAB accreditation requirements that govern US schools of architecture require that students demonstrate abilities related to integrated design and integrated decision making (NAAB, 2014), the high level of design development and refinement required by RTZ/SDDC—including verifying projected performance using software against industry benchmarks/targets—is not the norm and may contribute to the appeal for participating architecture schools.


01

Participation

Participants in the Race to Zero have the opportunity to provide creative solutions to real-world issues in our nation's housing industry. Invited teams will complete the required submissions and attend the competition event where they will present their designs to a panel of expert jurors, compare their efforts with other teams, learn from presentations by thought leaders, and engage a variety of organizations about clean energy careers. The winning teams will be recognized at an awards banquet, and the winning designs will be made available on the U.S. Department of Energy (DOE) Race to Zero website. The competition and winners will all be promoted through a variety of media outreach efforts, which will provide participants and their collegiate institutions an opportunity for national exposure. Collegiate institutions that participate in the Race to Zero will be recognized as leading institutions that are producing job-ready young professionals with cutting-edge skills. Builders who collaborate with teams will gain national and local recognition and will have the opportunity to interact with knowledgeable future design and construction professionals.

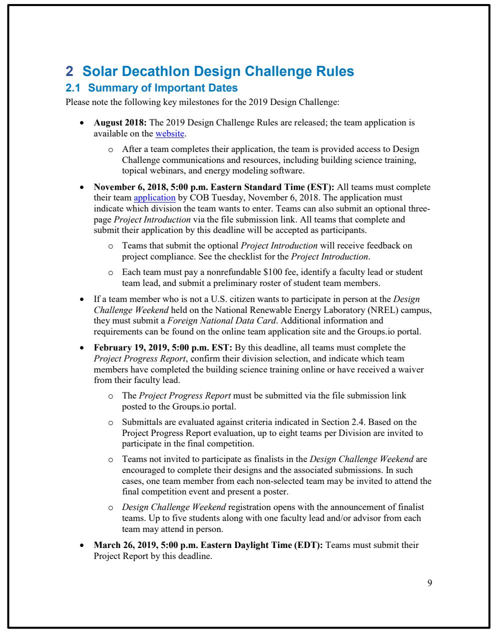
UNIQUE & VALUABLE opportunity to interact with knowledgeable future design and construction professionals.

The Race to Zero is designed to encourage student participation throughout an academic year that begins during the fall and ends in the spring with the project presentation and awards banquet.

View Previous Years' Winners

2016 Race to Zero Results

2015 Race to Zero Results


2 Solar Decathlon Design Challenge Rules

2.1 Summary of Important Dates

Please note the following key milestones for the 2019 Design Challenge:

- **August 2018:** The 2019 Design Challenge Rules are released; the team application is available on the website.
  - After a team completes their application, the team is provided access to Design Challenge communications and resources, including building science training, topical webinars, and energy modeling software.
- **November 6, 2018, 5:00 p.m. Eastern Standard Time (EST):** All teams must complete their team application by COB Tuesday, November 6, 2018. The application must indicate which division the team wants to enter. Teams can also submit an optional three-page *Project Introduction* via the file submission link. All teams that complete and submit their application by this deadline will be accepted as participants.
  - Teams that submit the optional *Project Introduction* will receive feedback on project compliance. See the checklist for the *Project Introduction*.
  - Each team must pay a nonrefundable $100 fee, identify a faculty lead or student team lead, and submit a preliminary roster of student team members.
- If a team member who is not a U.S. citizen wants to participate in person at the *Design Challenge Weekend* held on the National Renewable Energy Laboratory (NREL) campus, they must submit a *Foreign National Data Card*. Additional information and requirements can be found on the online team application site and the Groups.io portal.
- **February 19, 2019, 5:00 p.m. EST:** By this deadline, all teams must complete the *Project Progress Report*, confirm their division selection, and indicate which team members have completed the building science training online or have received a waiver from their faculty lead.
  - The *Project Progress Report* must be submitted via the file submission link posted to the Groups.io portal.
  - Submittals are evaluated against criteria indicated in Section 2.4. Based on the Project Progress Report evaluation, up to eight teams per Division are invited to participate in the final competition.
  - Teams not invited to participate as finalists in the *Design Challenge Weekend* are encouraged to complete their designs and the associated submissions. In such cases, one team member from each non-selected team may be invited to attend the final competition event and present a poster.
  - *Design Challenge Weekend* registration opens with the announcement of finalist teams. Up to five students along with one faculty lead and/or advisor from each team may attend in person.
- **March 26, 2019, 5:00 p.m. Eastern Daylight Time (EDT):** Teams must submit their Project Report by this deadline.

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Figure 1. Excerpts from competition guides. 2016/2017 RTZ participation requirements (left), 2018-2019 competition schedules (right). (USDOE 3, 2019; NREL, 2017)

The typology divisions include specific building area (or unit area) and site area requirements, but the teams have the freedom to choose their own site location and other aspects of their design proposal. Each collegiate institution can submit one proposal per division (or six in total for 2018/2019). There are a limited number of institutions each year that submit more than one proposal. Proposals are evaluated and awarded within each typology division and there is a grand prize among the divisions. For 2018/2019, there were also undergraduate-only team and several specialized prizes.

Preliminary competition information is generally available in late August and registration ends in early November. A Progress Report is due in February and the Final Report is due in late March/early April. A juried event is held at the National Renewable Energy Laboratory in Colorado in April where teams present and prizes are awarded. Depending upon individual academic circumstances, some teams may begin the competition in the fall and have upwards of six months of worktime. However, many teams appear to run the competition in the spring semester only, which limits their worktime to 11-12 weeks.

Training is an integral aspect of RTZ/SDDC. Team members are required to complete 12 online building science training modules taught by building science experts Jon Straube and Joe Lstiburek. Teams are also given access to a number of informational webinars throughout the competition as well as software resources to assist in their project development (an important example was student access to REM/Rate software to generate a HERS rating). Many teams rely on freely accessible DOE tools as well such as BEopt (NREL 1, 2019) and PVWatts Calculator (NREL 2, 2019).

RTZ/SDDC AT BALL STATE

The Ball State University Department of Architecture is part of the R. Wayne Estopinal College of Architecture and Planning (CAP). CAP includes programs in architecture, landscape architecture, urban planning, urban design, historic preservation, and, since 2018, construction management/interior design. Ball State University does not have a college or department of engineering. The Department of Architecture has the largest enrollment of the departments housed within CAP and offers undergraduate and graduate degrees programs.

The National Architectural Accrediting Board (NAAB) requires accredited architecture programs to demonstrate that graduates can "synthesize a wide range of variables into an integrated design solution." (NAAB, 2014) At Ball State, this requirement is addressed in a graduate-level Comprehensive Design Studio (ARCH 501). As the design studio course name suggests, this studio challenges students to conceive, develop, and execute projects that address a wide variety of design considerations including, but not limited to: site design and orientation; programming; cost analysis; occupancy and human context; interior design and indoor environmental quality; structure and environmental systems integration; material selection; energy and environmental impact; etc.

A significant challenge of the Arch 501 studio is creating a project through which students can attain a high level of detail in a short period of time (each semester is 16-weeks in duration). RTZ/SDDC provides an ideal project to meet and exceed course objectives for at least four reasons. First, the competition focuses on smaller buildings (mostly housing), which means that the studio projects can be small-scale and manageable for students to develop in a short period of time. Second, the competition focuses on collaboration and teamwork, which means that students can contribute individual expertise to the projects and that members can learn from, and lean on, each other for help and skills development. This makes it possible to reach outside the studio course to other courses and disciplines for assistance as well. Third, the competition schedule and the typical spring semester schedule align relatively well (albeit not perfectly). And, lastly, the competition encourages involvement of community partners and industry professionals to assist students with limited technical skills or knowledge develop more detailed and technically sophisticated proposals. For the past three consecutive years, beginning in spring semester 2017, Ball State has entered the RTZ/SDDC competition with the ARCH 501 design studio course.

Team Structure. The typical Ball State RTZ/SDDC team structure is illustrated in Figure 2 below. Over the three years we have entered the competition, there have been slight changes to the way we organize the teams, but the basic structure remains the same. The core design teams were situated in the Arch 501 design studio, which is led by Assistant Professor Tom Collins. The enrollment of the studio and the student preferences for team size determine the number of core teams each year. For example, in 2017 we had four teams with a mix of two and three members per team; in 2018 we had two teams with four members each; and in 2019 we had two teams with four or five members each. Anecdotal evidence and student feedback suggest that 3-4 members per core team is an effective number. Each core team works collaboratively with students in architecture elective courses led by Professor Walter Grondzik that are designed to support the studio. The mainstay elective course has been Arch 632 High-Performance Buildings, a course focused on energy modeling. Over the years we experimented with other support courses with limited success in terms of improving our standing in RTZ/SDDC. In 2017 we offered a LEED for Homes course that ran the proposals through the LEED for Homes framework and developed a LEED score as a way of distinguishing the proposals. In 2018 we offered a course on embodied energy and carbon that ran the proposals through Tally software to determine the carbon footprint of the materials used. These courses have been useful to some extent, but nowhere near as essential as the energy modeling course, which ties into the competition requirements directly. The core teams also work with an independent study course on cost estimating led by Associate Professor Tarek Mahfouz in the Department of Construction Management and Interior Design (CMID). CMID's curriculum makes it difficult to involve subject area courses in the competition and relying on independent study students each year has been a challenge we hope to resolve in the coming years. See Figure 2.

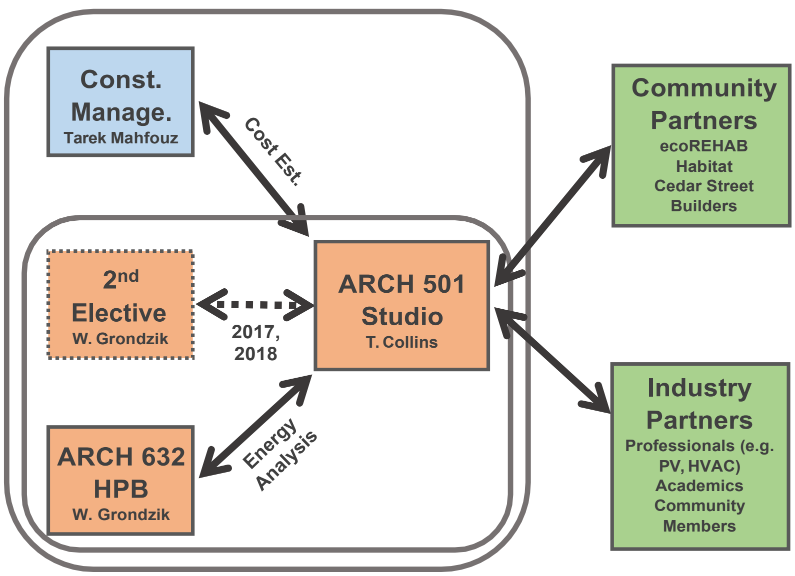

Figure 2. Diagram illustrating the course and collaborative structure of the Ball State RTZ/SDDC teams (by authors)

The competition highly encourages teams to work with industry partners "who can provide a market-ready perspective for proposed design solutions." (USDOE 3, 2019) Internally, we divide these "outside the university" partners into two categories: community partners and industry partners. Community partners are organizations that are in the business of building the kinds of buildings the student teams are proposing. In 2018 we worked with a custom home builder who designed the first Passive House Certified home in Indiana. In 2018 and 2019, we worked with a local non-profit called ecoREHAB that specializes in rehabilitating existing (often historic) housing for low to moderate income families. In 2019 we also worked with Habitat for Humanity, which specializes in low-cost new construction. Each of these partners meets with student teams 2-3 times throughout the semester, attends design reviews, and sometimes meets students out at site visits to look at properties. Industry partners are professionals and/or academics working in specialty areas. In 2017 we worked with Indianapolis-based Heapy Engineering on mechanical systems and Jefferson Electric on PV systems. In 2019 we greatly expanded our partnerships through a series of Friday afternoon workshops that included a housing design expert, a realtor, community development officials, a mechanical engineer, and faculty with expertise in high performance/net-zero energy buildings. See Figure 3.

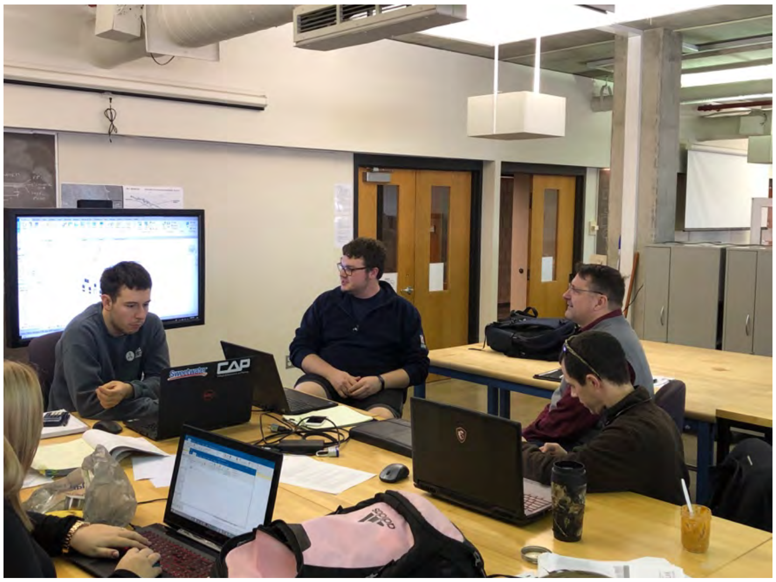

Figure 3. Photo of a 2019 core design team meeting with mechanical engineer Steve Ehrman in the design studio at Ball State (by authors)

Design studio (Arch 501). The Arch 501 Comprehensive Studio course typically has 8-9 students, which is a rather small size studio course comparatively. The instructor divides the course schedule into four stages corresponding with the RTZ/SDDC schedule. In 2017 and 2018, teams self-selected their members and division (type) on day one of the semester. In 2019, the team selection occurred in late fall semester before the students arrived back to campus for the spring term, which helped the teams get started with their projects quicker than in previous years. Design pin-ups or reviews are scheduled ahead for about every 2-3 weeks to provide timely feedback to the teams. See Figure 4.

Stage 1 includes the first several weeks of the semester and involves preparatory work such as completing the required building science training (students have to do this on their own), establishing a workflow for the team, meeting the outside partners, completely digesting the lengthy competition guide, developing project goals/objectives, and reviewing past winning proposals.

Stage 2 runs about four weeks and leads up to the submission of the Progress Report in mid-February. The report is 11 pages maximum and asks students to provide some baseline metrics for their scheme, a description of their site, and their initial design goals or intentions. No technical design is required at this stage. However, in the studio, the students are expected to have a schematic design of their project complete by the Progress Report submission. We find that the DOEs requirements for the Progress Report are not a good indicator of where the teams should be in the design process at that point in the competition schedule. The teams submit a limited amount of information, but they really need to be much further along in their design development to make the Final Report deadline 5-6 weeks ahead. One aspect of the competition that differs markedly from a typical design studio is the fast pace. Decisions that design students often have weeks to deliberate over need to be made very quickly for RTZ/SDDC. Eliminating some decision-making from the students has allowed the projects to develop more quickly. For example, in 2017 we allowed the teams to choose their own location, parcel, division (type), and building program. In 2019 we gave the teams this information up-front, which gave the teams additional time for detailed development. At this stage, the teams have developed the designs enough that initial energy and financial analysis work can commence, which necessitates opening lines of communication with team members outside the core studio team. DOE states in the guide that Progress Reports will be reviewed and finalists chosen. This procedure always worries the teams. From a course perspective, we operate under the assumption that we will continue the project whether or not each team advances to the finalist round. However, in three years or participation, every one of our studio teams has advanced to the finalist round.

Stage 3 is the six-week or so period after the Progress Reports are submitted and before the Final Reports are due. For Ball State, this includes our Spring Break, which reduces some of the motivation of the teams having a week break in the middle of an intensive period of studio work development. During this stage, the teams have to finalize their designs and begin detailed technical development and documentation. For example, the competition guide says that teams must meet the DOEs Zero Energy Ready Home (ZERH) standard for the housing divisions. The ZERH standard requires compliance with the EPA's Indoor Air Plus program, which requires students to go through the requirements and demonstrate in the materials that, for instance, the proposal has a radon mitigation strategy in place. These kinds considerations are very detailed and go far above and beyond the kinds of design considerations typically addressed in an architecture studio—the teams are forced to think about a wide range of considerations that are important aspects of high-performance built environments.

Figure 4. 2019 Core design teams in a design review with invited partners and Ball State faculty (by authors)

The RTZ/SDDC Final Report is limited to about 40-45 pages for Volume 1, but can be supplemented by a Volume 2 with appendices that include drawings, cut-sheets, etc. We focus on solidly addressing the ten contest areas aforementioned in this Final Report. The size of the report may seem ample, but teams often struggle to include all the necessary information within the page limit. Again, this constraint is an excellent opportunity for design students to gain valuable skills related to presenting their ideas succinctly, concisely, and in written/graphic form. We face two challenges every year during the run up to the Final Report. First, the instructors want to provide detailed edits to the reports before submission. This means that the reports have to be finalized more than a week ahead to allow time for edits to be made and picked-up by the teams, which cuts into development time. We solved this problem with 2-3 rounds of edits as the reports become more developed. The first review picks up major things (e.g. formatting, headers, basic information) and later review picks-up more detailed things since the edits from the first review are then complete. Second, the core teams want as much worktime as possible, which means that they sometimes wait to give the necessary information to the other team members outside the studio for their contributions (e.g. the energy modeling and final HERS score).

Stage 4 is the six weeks between when the Final Report is submitted and the end of the semester at Ball State. All teams that submit a Final Report are invited to a 2-3 day juried event at the National Renewable Energy Laboratory in Golden, Colorado. The several weeks immediately after the report submission, the core teams develop 25-minute and 10-minute abbreviated PowerPoint presentations, rehearse those presentation, develop a project poster, and build a physical presentation model (not a requirement, but we find to be an asset for the teams). Instructors focus on securing funding for this trip throughout the semester from the college and university special travel and immersive learning programs. Traveling with 10+ students to Colorado can cost upwards of $4000.00. Our students always buy their airline ticket to keep the costs for the university as low as possible.

The Colorado event is a highlight of the semester and a defining feature of the RTZ/SDDC competition. Students are excited to be at a national research laboratory to present their work and represent their university. Annually, 35+ universities are present at the event, which involves keynote presentations by well-known figures in the industry, meals, presentations, a poster session, lab tours, etc. The event is student-focused and raises the bar considerably for the students in terms of how they present their work to a jury. The kind of preparation necessary for the jury presentations, in our experience, far exceeds what most architecture students are expected to do for standard design studio final review presentations. See Figure 5. After returning to Indiana, the teams repeat their presentations for department faculty as a final academic review for the semester. This review has an architectural rather than a building science and constructability focus, and allows the teams to share their process and experience with the academic community at the college.

Figure 5. 2017 Core design team at the NREL event in Colorado (by authors)

Graduate "energy" elective (Arch 632). Arch 632, High-Performance Buildings, is a graduate course in the Masters of Architecture curriculum. It is offered on a regular basis and fulfills a role as a NAAB Realm B: Building Practices, Technical Skills and Knowledge elective. (NAAB, 2014) The specific content of this course varies from semester to semester (having, in the past, dealt with net-zero energy office design, energy simulations, carbon-neutral building design, for example). When offered in support of the RTZ/SDDC, students in this class learn how to use (at least at a rudimentary level) REM/Rate, Climate Consultant, HEED, BEopt, and WuFi (almost learn is more accurate for this one). A major focus was on the use of REM/Rate to obtain and improve a HERS rating—a requirement of the competition. An important secondary focus was the use of BEopt to select a rational mix of design strategies. HEED has been used to explore passive survivability.

Graduate "green" elective (Arch 633). Arch 633, Advanced Technologies for Green Building, is also a graduate course in the Masters of Architecture curriculum. It is offered on a regular basis and it too fulfills a role as a NAAB Realm B: Building Practices, Technical Skills and Knowledge elective. (NAAB, 2014) The specific content of this course varies from semester to semester (having, in the past, dealt with the LEED BD&C rating system, LEED EBOM, and the Well Building Standard, for example). As mentioned above, recently this course has been employed to explore LEED certification and embodied energy in the RTZ/SDDC projects.

Construction management students. From the onset, we felt it was important for the teams to be multi-disciplinary to harness the full range of skills from our students and to satisfy requirements that would be difficult for architecture students—namely cost estimating. The Construction Management/Interior Design department has been an eager partner. However, they engage students through volunteering or independent studies, which proves to be less reliable than students enrolled in a required class for course credit. In 2017 we had several CMID students work with us. In 2018, we had a larger number thanks to efforts by a graduate assistant in CMID connected to the studio. In 2019 no CMID offered to participate. Faculty in CMID stepped in and acted as "industry partners," but a more sustainable solution is necessary. Efforts to engage other disciplines have been less successful. Anecdotal evidence suggests that course content does not always align well with the competition in other areas (e.g. urban planning). However, our struggles with facilitating multi-disciplinary collaboration are, perhaps, emblematic of the siloed natures of academic departments, which are simply unaccustomed to students working together across academic units on projects with tight schedules.

CONCLUSIONS

Outcomes. 2017 was Ball State's first experience with RTZ, and we entered not knowing quite what to expect. All four teams advanced to the finalist round to present at NREL. Our Suburban Single-family team received first-place prize in its division—interestingly this was the only team that worked semi-independently from the design studio. In 2018, we entered RTZ with two larger-sized studio teams (per feedback from the previous year) and two independent teams. The studio teams worked closely with dedicated community partners for the first time. Both studio teams advanced to the finalist round to present at NREL, but not the independent teams. Our Urban Single-family team received the second-place prize in their division—interestingly this team took a risk submitting an adaptive reuse project instead of new construction. In 2019, we again had two larger-sized teams. Both teams advanced to the finalist round to present at NREL. Unfortunately, neither team received a division prize at the event. This was, in part due, to the elimination of second-place prizes altogether. However, over three years, eight teams out of ten advanced to the finalist round (an 80% success rate) and two teams out of ten won prizes at the competition (20% success rate). Given that the finalist pool is typically reduced from 80+ teams to 40 teams and that 40 teams compete for 8-12 prizes per year, we feel good about our performance in the competition thus far.

Each year, we have students submit reflections on the experience and suggestions for the future. Some responses are similar each year. In general, students feel that the pace is very fast, that they wish they had more worktime, and that they wish the teams could get started earlier (e.g. the fall semester before). Time constraints are a major stress. One 2019 student commented "the competition requirements challenge you to use your time effectively." However, students also feel that the experience is worthwhile, a good use of their skills, and helps expand their skills especially related to energy modeling and renewable energy systems. One 2019 student commented "The project was a lot of fun and a lot of hard work, but I learned a lot during the entire process."

Challenges. There are several challenges with our RTZ/SDDC experience. First, it was challenging to come up with the money for the entry fees ($200 per team in 2017 and $100 per team in 2018 and 2019). This may be one reason that few schools enter multiple divisions. The RTZ/SDDC event in Colorado is fantastic for the students and shows strong commitment to quality on the part of DOE and NREL, but it was also difficult to fund 10 students and several faculty to travel out of state. We have been able to resolve some of these issues through university travel grants, college-level funding, and students self-funding part of the trip. However, we struggle to ensure that all core team members can travel with us and have been lucky to not have to leave anyone behind in the last three years. Finally, the competition schedule technically begins in late summer, but this does not align with many academic calendars, particularly if you only have one semester in which to run the competition through a course. The result for us is an 11-12-week sprint when some teams spend 6-7 months.

Lessons learned. Overall, Ball State's participation in RTZ/SDDC has been a positive experience for faculty, students, and associated partners. Each year, we closely track the strengths and weaknesses of our process, schedule, and outcomes, and we use this information to inform our process in subsequent years. It is useful, however, to highlight a number of overarching lessons learned from our three year involvement, which may help ensure future success for Ball State and other university teams.

Ball State runs the competition through a design studio and associated elective courses. Discussions with faculty at other participating institutions suggest that there exist a wide variety of ways students enter the competition including student clubs/organizations, independent studies, etc. In these cases, the participants choose to participate in the competition., which differs from a design studio where students must participate as part of a course required for graduation. This distinction is important and likely impacts the motivation and engagement of participants in important ways. We cannot rely on having only students who really want to participate or who feel they possess the kinds of technical skills necessary for the competition success. We have found over the years that acknowledging this limitation up-front helps with team morale and engagement.

As mentioned, the competition requires the proposals to exhibit high levels of technical development and detail. A substantial amount of our time in the design studio is spent on these technical aspects, which leaves less time for typical architectural considerations such as concept development, site analysis, programming, form/massing development, precedent analysis, facades design, etc. Since “Architecture” is only one of ten contest areas, it makes sense that teams would focus on the technical aspects to ensure success in the competition. However, the course objectives for a design studio demand that teams develop architecturally compelling solutions whether or not those aspects are valued to the same degree as energy and engineering considerations in RTZ/SDDC. Therefore, there is a slight misalignment between the goals of the competition and the goals of a studio. We continue to work through these issues, but they remain a challenge of participation and can make for a harder sell to departmental administrators.

Design professionals often understand the importance of good communication among team members. Design students, who all-to-often work independently in design studios and other courses, do not have clear communication protocols or habits in place to facilitate work with partners, especially across class lines and with industry and community professionals. Since our experience thus far has been exclusively with graduate students who have completed a professional internship before taking the course, many teams already have group collaboration skills that they bring to the experience. However, there have been several teams for whom group collaboration has been a major strain on their process and outcomes. Perhaps unsurprisingly, our experience has been that the teams with the best group dynamics and communication skills tend to be most successful in the competition. Going forward, we intend to do more coaching with the teams. We implemented a weekly team report in 2018 and 2019 to help us track individual and team progress. We also have teams complete peer evaluations at the conclusion of the semester to assess team dynamics and output.

Our core teams vary from two to five students with a larger group of consulting students and professional partners. Student feedback in 2017 suggested that 2-3 person teams were too small for the work necessary. In 2018, we enlarged the groups to four members each. Feedback from 2018 suggested that smaller groups might have been better. In 2019, our four person group demonstrated that fewer members may, in fact, be better since a four person group tends to break into subgroups that can interfere with dynamics and cohesion. However, in the same semester, our five person team worked very well together and leveraged the manpower of all members to produce an excellent project. Therefore, the ideal size of a team remains inconclusive and seems to depend heavily on the personalities within those teams rather than on sheer numbers alone.

The students do not know the exact make-up of the Race to Zero juries until after the finalists were announced. However, the juries are diverse including engineers, building products reps/manufacturers, builders, code officials, architects, etc. Once the jurors are announced each year, it can be stressful for the students to determine how to effectively anticipate what the jurors will focus on or whether their schemes will pass muster from the juror's perspectives. Our experience suggests that, despite the diversity, the juries use the contest area criteria to evaluate the project and that it is unnecessary to tailor project features to specific jurors. However, the juror score sheets are not available to the teams after the NREL event, which would help to make the jury process more transparent.

RTZ/SDDC attracts students from engineering, construction management, architecture, and other disciplines. Some team projects are highly resolved in their systems design, some projects are highly resolved in terms of their construction costs, and some projects are highly resolved spatially and aesthetically. Juries tend to recognize that every team brings a different approach to the problem of net-zero-energy buildings. There is no silver bullet that will ensure success every time. However, successful projects seem to be the ones that satisfy all the requirements and, at the same time, present something compelling or unique that transcends them. No team will win at RTZ/SDDC by having a net-zero building or by having a low EUI or HERS score—every successful team has these elements. One frustration, however, is when these "extra" elements of the schemes receive so much interest from juries that basic requirements are not met or well resolved. The challenge is knowing how much time and effort teams should put into the "extras" and which of these will resonate with DOE and jurors each year.

Finally, there is an adage that a "need to know" something can enhance learning outcomes. RTZ/SDDC certainly requires and demands that students learn a great deal about aspects of net-zero energy building design that they didn't previously know or understand well. This is one of the many things that RTZ/SDDC does well and it keeps the competition relevant and challenging year after year.

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High Performance for Habitat for Humanity: Penn State's 2018-2019 Solar Decathlon Design Competition Entry

Puja Bhagat[1] and Jonathan Wong[2]

[1]Undergraduate Student, Bachelors of Architecture, Penn State, phb5043@psu.edu
[2]Undergraduate Student, Bachelors of Architecture, Penn State, jrw5857@psu.edu

Introduction

Since 2014, members of the Pennsylvania Housing Research Center have collaborated with the Energy Housing Research Group at Penn State to support student design teams to compete in the Department of Energy (DOE) Race to Zero and Solar Decathlon competitions. This annual design competition challenges interdisciplinary undergraduate and graduate student teams to design an affordable and marketable net zero-energy ready home. At a minimum, these homes must meet the DOE Zero Energy-Ready Home standard and incorporate sound building science principles. Each year, Penn State students have gone beyond the baseline competition requirements through their partnership with a Pennsylvania-based housing organization. These partnerships provide a real site, context, and practical design constraints for the students' submission and have opened opportunities for greater community impact and industry collaboration.

In 2019, Penn State's team partnered with Habitat for Humanity of Greater Centre County (HFHGCC) in order to develop an affordable, net zero-energy ready housing design strategy that adapted to any site and family. This design strategy would allow HFHGCC to provide families with houses that were tailored to their needs, while still being environmentally responsible. This case study paper will describe the Penn State team's overall organizational approach and integrative design process, as well as the technical design of the housing system created for the 2018-2019 Penn State Solar Decathlon submission.

Solar Decathlon Build Challenge (2007-2009)

Students and faculty at Penn State have been researching and implementing energy design for more than a decade. The 2007 and 2009 Penn State Solar Decathlon entries were two projects that catalyzed and institutionalized energy housing design at Penn State, each of which were utilized as precedent for the Race to Zero competition structures. During each two-year competition period, students from across the university designed and constructed an energy showcase home with the help of the Penn State faculty. For each respective competition, the competition administration structure was tailored to the needs of the university, students, and faculty. To build student, faculty, and university capacity, the 2007 'MorningStar' home project began with a university-wide design competition, which ultimately integrated with several classes and design studios. The knowledge gained from these classes and studios fueled the design for the 'Morning Star' home.

The 2009 competition project, the 'Natural Fusion' home, furthered the student and university knowledge and capacity built during the 2007 competition. This increased capacity allowed the team to primarily work through an extracurricular club with independent study credits offered when needed, rather than being embedded and administered through classes and studios. The 2007 and 2009 Solar Decathlon build competitions expanded and research pertaining to innovation, energy , and building science related to residential design at Penn State University.

Figure 1: History of Race to Zero and Solar Decathlon Projects at Penn State (image credits, left to right: 2005-2007 Morning Star Home, 2007-2009 Natural Fusion Home, 2103-2014 Challenge Home team, 2014-2015 Race to Zero team, 2015-2016 Race to Zero team, 2016-2107 Race to Zero team, 2018-2019 Race to Zero team)

Race to Zero Challenge (2014-2018)

In early 2014, the Race to Zero competition, called the Challenge Home competition in 2014 and 2015, was developed by the DOE as the Solar Decathlon competition's counterpart. While the goal of designing highly energy homes remained consistent between the two competitions, the Race to Zero competition had an increased focus on building science and market-ready housing solutions. Additionally, the Race to Zero competition was developed as a yearly, paper-based competition where teams were not required to physically build their home designs. This lowered any associated costs with the competition and allowed more students and universities to participate. Successful home designed for the Race to Zero competition must comply with the DOE's Zero Energy-Ready Home standard, where projects must:

- Qualify for ENERGY STAR
- Ensure ceiling, wall, , and slab insulation shall meet or exceed 2015 IECC levels
- Locate HVAC and all duct systems within the thermal boundary
- Include hot water delivery systems
- Qualify for EPA Indoor airPLUS
- Reach a HERS score of approximately 50, depending on home size
- Comply with the DOE Zero Energy Ready Home PV-Ready Checklist

In addition to these technical requirements, homes must also be affordable for the location's Median Family Income (MFI), which is by the competition as a monthly payment of 38% of the MFI including, not only the mortgage, taxes, and insurance, but also the predicted average monthly utility cost. Finally, the competition encourages student teams to work with industry partners in their area as they develop their project, in order to learn sustainable design through real-world practices. This will better prepare them for becoming future professionals in the design and construction industry.

Since the competition's creation in 2014, Penn State has been implementing this strategy by partnering with one Pennsylvania-based affordable housing organization each year. This works to enhance the experiential learning opportunity for the students, as well as to create a local impact in improving Pennsylvania's housing stock. At a baseline, the partnership is composed of a single point of contact at the organization for context, questions, and feedback, as well as a site or development for the proposed home design. Several partnerships have gone beyond this minimum, where project partners have provided the team with explicit expectations for the design, one or more site visits to the location, and direct feedback in one or more design charrettes.

A notable Penn State Race to Zero competition entry was the 2014-15 Heritage Homes project. During this year, the team partnered with the State College Community Land Trust (SCCLT) to design a net zero-energy ready duplex in the State College Borough. In order to integrate their project with the project partner and surrounding community, the student team led three design charrettes with members of the SCCLT board, SCCLT homeowners, students, faculty, staff at Penn State, and community members from around the State College area. After the competition, the SCCLT continued to work with the Energy Housing Research group, an outreach arm of the Hamer Center for Community Design in the Penn State Stuckeman School for Architecture and Landscape Architecture, and a co-facilitator of the Race to Zero competition at Penn State to see the homes through design and construction. The duplex home just recently construction in 2018 at 1394 and 1396 University Drive, where the design was primarily based on the work from the 2014-2015 student team.

Following the success of that project, the Centre County Housing & Land Trust (CCHLT) approached the Penn State Race to Zero team to design a case study home for a new development close to Penn State's campus. The Turnberry Development, a Traditional Town Development (TTD) located in Ferguson Township, is designed to include 891 dwelling units throughout 154 acres, built over the duration of 16 years. Beyond that, Ferguson Township has a Workforce Housing Ordinance in place for this zoning designation that requires ten percent of the homes constructed be affordable to owner-occupied families earning between 80% and 120% of the area median income (AMI). Once constructed, CCHLT would sell and administer these homes as permanently affordable housing.

In 2018, the team continued the framework of working closely with local housing organizations. During this design competition year, the team partnered with S&A Homes, a local production builder in the State College area. During this competition year, the team continued to push the envelope of design by going beyond the level of a single home. Since S&A Homes is a production builder, the team created a home that was reproducible and in design. As a result, this project became a guideline for future Penn State teams in terms of thinking on a larger scale of

Solar Decathlon Design Challenge

During the 2018-2019 competition year, the Solar Decathlon build challenge combined with the Race to Zero design challenge. This new approach consists of Solar Decathlon's existing two-year build competition and integrates a one-year design competition with several subdivisions of building categories inspired by the Race to Zero competition.

Penn State's team participated in the design challenge for 2018-2019 competition year, competing in the Suburban Single Family Home subdivision and partnering with Habitat for Humanity of Greater Centre County (HFHGCC). HFHGCC is the local chapter of Habitat for Humanity International, and aims to provide 'decent' homes to income families. In order to be considered for a Habitat home families must complete an application and show apparent need for a new home. Additionally, families must complete 350 sweat-equity hours, pay for their home and all upkeep, and maintain current payments on their properties.

Due to HFHGCC's lack of staff and time resources, the team aimed to optimize the current family process by developing a design matrix that allows for a greater consideration for site and family needs, while still meeting the Department of Energy's Solar Decathlon competition requirements. This new design strategy allowed the local Habitat for Humanity chapter to provide quality, housing to families in need, while also creating a home that the site and family requirements. In doing so, the team was able to improve upon HFHGCC's of a 'decent' home. Additionally, the team went above and beyond the design of a single home, and instead, created a system of homes that is and reproducible, while still meeting the net zero-energy ready home requirements.

Organizational Approach

Education Structure

Although the Solar Decathlon is a competition, the Penn State team places a heavy emphasis on educating students about Net Zero-Energy Ready design in order to train the next generation of sustainable engineers and designers. Each year, the Penn State Solar Decathlon team builds off the work and lessons learned from past Solar Decathlon competitions and Race to Zero competitions. Team members who worked on past projects act as mentors and share their knowledge of sustainable design with new team members. Penn State tailors the educational component of the Solar Competition based upon the student capacity, the project partner expectations, and the faculty/staff capacity.

During the fall semester, the 2018-2019 Penn State team operated independently as a student organization under the guidance of a faculty advisor as opposed to an embedded part of an class. This structure allowed for a high level of . The team could work on the project throughout the entire academic year as opposed to being restricted by a semester course. Yet, the informalness of a student organization made it to retain team membership and ensure students continued through the completion of the project.

During the spring semester, the 2018-2019 Penn State team transitions to operate through a one-credit class, CE411, where the team builds upon the team's fall semester work and works to complete the project and complete the competition deliverables. The class is a requirement of Penn State's Residential Construction minor, which invites new team members to join the team. The added formality of the class provides the appropriate amount of structure to keep the team on track to complete the project. During the class, the team participates in design charrettes throughout the semester with Penn State professors, industry professionals, and project partners to review the progress of the project and receive constructive criticism for improving the design.

Team Structure

The 2019 Penn State Solar Decathlon team was an interdisciplinary group of students made up of various academic backgrounds ranging from the College of Arts & Architecture, College of Engineering, Eberly College of Science, and the College of Earth and Mineral Sciences. The team was primarily comprised of undergraduate students and one graduate student. The team had seven returning members from Penn State's 2018 Race to Zero team, of whom acted as the team's leaders, and sixteen new students, who all had little to no experience in high performance and net zero-energy design. Having seven team members with prior knowledge of net zero-energy design afforded the perfect opportunity not only to have a mentorship-style sharing of knowledge, but also explore new areas of residential construction and energy performance.

Throughout the entire 2018-2019 academic year, the Penn State team heeded the principles of an integrated design process by continuously engaging all team members and parties as to create a cohesive and impactful design. In order to streamline the design process, the team divides into sub-teams: Architecture, MEP, Construction Management, Energy, and Building Envelope. In understanding the competition as an opportunity to train and educate the next generation of sustainable engineers and designers, team members are encouraged to join sub-teams that mirrored their future career goals and interests without any limits. Within each of these sub-teams, team members focused on the research, design, and analysis of their respective concentrations and would meet regularly to complete their work.

During biweekly meetings, all sub-teams would come together to collectively develop and discuss higher-level design goals and objectives to drive various design decisions in each sub-team. Typically, one meeting was held during the weekday, where the team would present the progress of their work through informal charrettes to professors, industry professionals, and our project partner. Through these design charrettes, the team was able to gain valuable insight and direction on their work as they progressed through the design process. Typically, another meeting was held during the weekend, where the team and individual sub-teams focused heavily on designing and documenting These weekend workshops were an critical part of our integrated design process, as team members and sub-teams were able to easily discuss, collaborate, and review portions of the design which overlapped multiple sub-teams.

Figure 2: Design Charrettes with the 2018-2019 Solar Decathlon team (image credit: Sarah Klinetob-Lowe)

2019 Penn State Solar Decathlon Project

Project Partner and Community Engagement

For the 2019 Solar Decathlon competition, the Penn State team worked closely with Habitat for Humanity of Greater Centre County (HFHGCC) to integrate their unique constraints into the design in a way that would simplify their current design process while still maintaining their methodology of deliverance and architectural language. As one of 1,500 independent of Habitat for Humanity International (HFHI), HFHGCC has built, renovated, or repaired over 60 homes in partnership with families throughout the last 35 years. HFHGCC has maintained a strong connection with the students at Penn State and Centre County community. They aim to build simple, decent, affordable houses for those who lack adequate housing conditions through constructing quality houses and selling them to families through zero-interest loans. In order to be considered for a Habitat home, families must complete an application and go through a selection process. Families selected based on apparent need for a new home must complete 350 sweat-equity hours, pay for their home and all upkeep, and maintain current payments on their properties.

Through direct collaboration with HFHGCC staff and the Penn State student chapter, the team gained unique insight for their typical design and build process. The team was able to identify numerous points of constraint within their design process, which restricted HFHGCC from making a major impact on affordable housing within Centre County through sustainable design. The team that HFHGCC often lacked the capacity to develop unique designs for each home they built or simply designed building systems to meet code minimums. Beyond that, HFHGCC is often forced to build on unfavorable sites due to the extremely high land costs in State College. Much of their labor force consists of volunteers, and the on-site construction relies heavily on their construction manager, which adds additional in terms of constructibility. Their designs are also often not enough to adapt to changes in families or circumstances either. A recent project at 351 Reynolds showcases this well, where an initial family of three became a family of seven. As a result, several bedrooms were placed in the basement due to a lack of in design.

By working closely with representatives of Habitat for Humanity, along with experienced industry advisors and Penn State professors, the team was able to develop a system of houses that relieves the strain on HFHGCC's staff and create a home that is tailored to the site, orientation, and family characteristics. In this way, the home is enough to adapt to any site and family need, both in current and future circumstances. Beyond that, HFHGCC's main goal is to create "decent homes" for families in need. This matrix system of homes updates and the meaning of a "decent home" by inserting a level of and individuality into each design that is tailored to the family's circumstance.

Figure 3: 2018-2019 team visiting a HFHGCC construction site (image credits: Sarah Klinetob-Lowe)

Design Goals

In understanding HFHGCC's core values and goals, including their capacity to achieve them, the team aimed to devise an optimized design and delivery methodology which seamlessly works within their existing framework. The team balanced the innovative solutions of sustainable design and the traditional construction practices of HFHGCC. Before starting to design, the team set forth design goals and criteria that would assist in guiding the design process in order to ensure a practical and cohesive design solution that exceeded the wants needs of HFHGCC. The team aimed to:

1. Create a family timeline of 1 week that considers the selected site's conditions, the current needs of the family and the future adaptability of the house
2. Create a matrix of plans that takes into account site slope, orientation, and the family's needs for members and ability
3. Install a modular design process that creates houses which are in dialogue with HFHGCC's Central PA vernacular designs
4. Design rectangular footprint with regular dimensions to allow for ease of volunteer construction & material sizing.
5. Maintain HFHGCC's core values of affordability, visitability, ADA accessibility, and future

Project Data
- Centre County, Pennsylvania
- IECC Climate Zone 5A
- 1320 Sq Ft on a 0.2 Acre lot
- Singele Story, 3 Bedroom, 1.5 Bath
- $2.33/month typical utility cost with PV
- $105,499 Completed Home Cost (Case S

Technical
- R-32 Wall Insulation
- R-49 Roof Insulation
- R-10 Continuous Foundation Insulation
- 0.23 Window U-Factor

Architectural Design

Modular Design Process

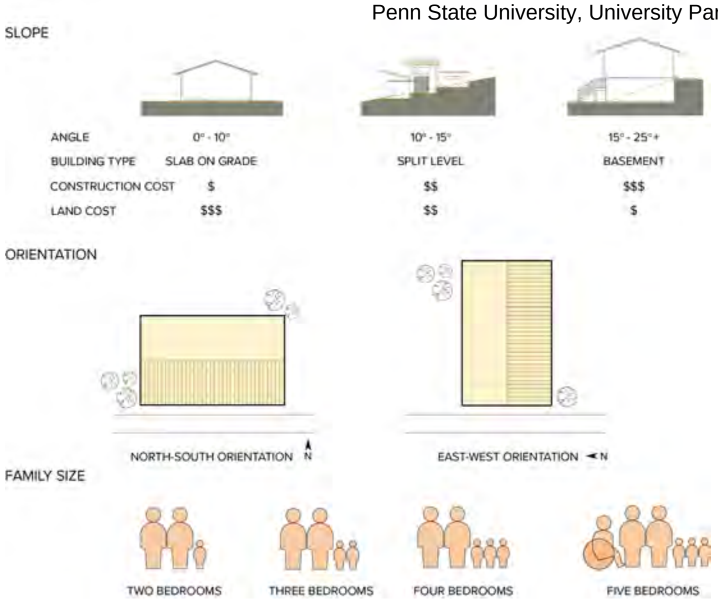
To design the matrix system, our team's goal was to right size all of the standard rooms in a house based off of a two foot module, in order to resolve any wasted space in the rooms. We designed each room size around the furniture placements and adjusted the new room boundaries in a way that comfortably the needs of that space, while increasing the of the given square footage. We then adjusted the rooms to a two-foot grid, which will make construction easier, especially for volunteers. The gridded dimensions also alleviate waste during construction, since most materials come in denominations of two feet.

Figure 4: Modular Design Process using Right Sized Rooms
(image credits: 2018-2019 Solar Decathlon team)

The Matrix System

After right-sizing rooms, the team determined three major characteristics that affect the home design: site orientation, site slope, and family size. The team utilized the right-sized rooms in conjunction with our three design conditions in order to design a matrix system that utilizes inputs from the site and family, and creates an optimized base plan. Each design characteristic has several options that determine an output for a home. For example, the slope angle has three categories pertaining to the overall home construction: slab on grade, split level, or basement home, and the family size determines the number of bedrooms and basic amenities. As a result, one ideal home layout is created based on inputs from any unique site or family HFHGCC encounters.

After determining the plan that matches the family's needs and the given site, additional customizations are presented to the family to choose from. Our Add-On system is more comprehensive than Habitat's current options, which only included choice of color and appliance selection. This new design strategy allows the family to design a home that meets all of their individual needs. Customizations include the addition of a porch, room, additional ADA bedroom, color, and energy appliances. These allow the family to tailor the home to their unique needs, while still creating a net zero-energy ready home.



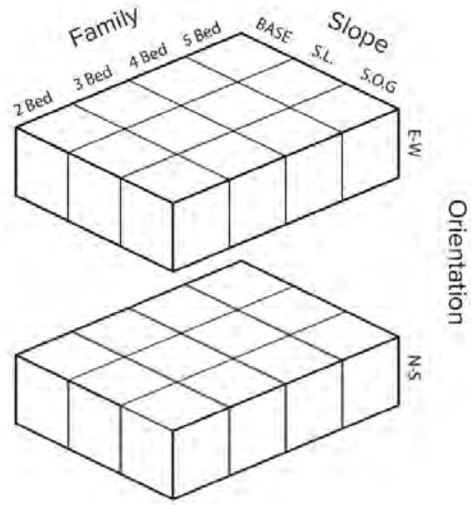
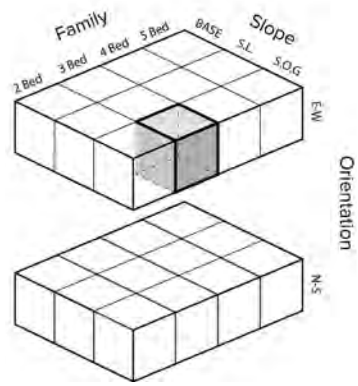


Figure 5: Matrix Design (image credits: 2018-2019 Solar Decathlon team)

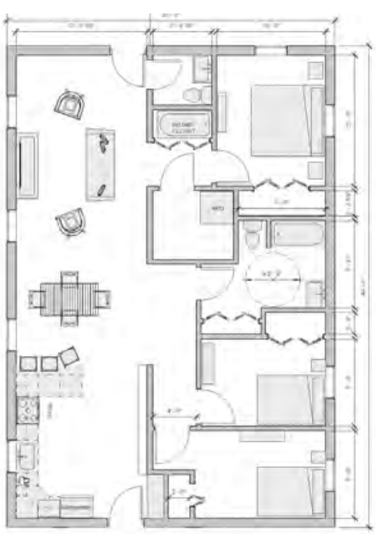
Case Study Family

In order to test the proposed design guide, the team applied the matrix system to a theoretical family in Port Matilda, PA. The chosen case study site is a twenty minute drive west of State College, PA and Habitat theoretically intends to subdivide this land into six equal lots that will each have a home placed on them. To be more easily managed, one theoretical home was designed at a time and site one was used for this case study.



The case study family approved for site one is a family of four, John Doe, his wife Jane, and their two young children, Jack and Carol. This family wanted their home to be comfortable, affordable, and net-zero energy ready. Within the next few years, it is expected that the family's grandmother will be permanently in a wheelchair and move into the home with her family for care. From this family and site description, our team determined that the home would be a slab on grade construction with a vertical orientation. The family will need three bedrooms initially, but will require a fourth bedroom addition at a later time.

To customize their home further, the Doe family chose add-ons that most accurately met their needs, both current and future. They chose to include a porch to their base design in order to create a more inviting space in the community. There is also the ability to add a fourth bedroom and convert the half-bath into a full bathroom. In terms of appliances, the Doe family chose to adopt the team's energy appliance recommendations. All of the family's design decisions led them to create a home that they are proud to own and are able to prosper in for years to come.



Base Home Model from Matrix Design

Additional Customizations Added

Final Home Design

Figure 6: Case Study Design
(image credits: 2018-2019 Solar Decathlon team)

Building Envelope Design

Design Priorities

To drive all of the design decisions for the enclosure of the home, the building envelope sub-team worked through developing a concept that focused on its constructibility and embodied energy. Since the team was working with Habitat for Humanity, it was crucial to understand the fact that a majority of HFHCCC's construction labor comes from unskilled, inexperienced volunteers. Therefore, it was important to keep in mind the ease of constructing the building envelope. Additionally, the sub-team, questioned designing a net-zero energy home where more energy is required to produce the materials than the house will offset in its lifetime seem contradictory. Keeping these priorities of constructibility and embodied energy in mind, the sub-team began exploring various options for the building envelope.

Research

When looking to design the building envelope, the team analyzed the typical building materials which HFHGCC uses, such as glass batt and XPS. Maintaining a commitment to low embodied energy materials, the team decided not to use materials like XPS, EPS, and closed-cell spray foam due to the high amounts of energy required to create them. Alternative materials, such as cellulose, rockwool, and glass batt would provide a similar thermal control, while requiring a lower amount of energy to be created.

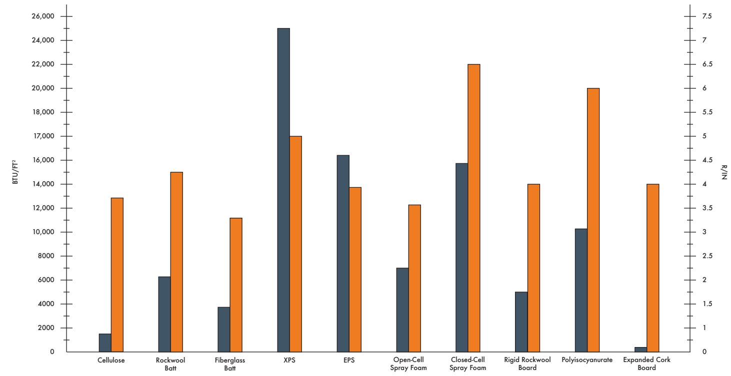


Figure 7: Embodied Energy and R-Value Material Comparison
(Image Credits: "Avoiding the Global Warming Impact of Insulation" by Alex Wilson)

Utilizing XPS would have reduced the cost of the home, since HFHGCC receives donations of it from DOW Chemical, but keeping with a commitment towards low embodied energy materials, they chose to work with rigid rockwool insulation board on the exterior. In comparing the hydrothermal performances of the two materials, rockwool is able to control moisture relatively similarly to XPS and provide a similar level of thermal control without requiring as much energy to produce.

The sub-team looked at utilizing structural insulated panel (SIP) wall construction and double stud wall construction. The prefabricated SIP panels would minimize the construction time, and the double wall construction would minimize the thermal bridging. Through research, it became apparent that the cost of these wall construction types was higher than that of standard stud wall construction. The higher cost of these walls would have placed a heavy burden on both Habitat for Humanity as well as the family for whom the home is being built. Additionally, SIP panels utilized EPS insulation, which has a high embodied energy content, and the double stud wall consistently fails to control moisture in the winter when installed improperly. After understanding these unfavorable characteristics, the team decided that SIP walls and double stud walls would not be the ideal choices for the design.

Building Envelope Matrix

In keeping with the concept of designing a matrix to streamline HFHGCC's design process, the building envelope subteam decided to develop a building envelope matrix, which HFHGCC could use to guide their design decisions on different projects. While the architecture design matrix is geared towards the family, the building envelope matrix is geared toward Habitat for Humanity. It allows HFHGCC to choose a high performance building envelope that meets the changing needs of each new project. In understanding unique elements each new project, the building envelope matrix addresses four major design factors: Cost, Constructibility, Sustainability, and Material Availability.

ENVELOPE DEISGN FOCUS	EXTERIOR ←					→ INTERIOR	
BALANCED	VINYL SIDING	N/A	2" RIGID ROCKWOOL INSULATION	1/2" ZIP PANEL	BLOWN CELLULOSE INSULATION	1/2" GYPSUM WALL BOARD	R-28
COST	VINYL SIDING	N/A	2" XPS	1/2" ZIP PANEL	BLOWN FIBERGLASS INSULATION	1/2" GYPSUM WALL BOARD	R-32
CONSTRUCTABILITY	VINYL SIDING	N/A	2" RIGID ROCKWOOL INSULATION	1/2" ZIP PANEL	FIBERGLASS BATT INSULATION	1/2" GYPSUM WALL BOARD	R-28
SUSTSAINABILITY	TRUE WOOD SIDING	1/2" AIR GAP WITH FURRING STRIPS AND RAIN SCREEN	2" RIGID ROCKWOOL INSULATION	1/2" ZIP PANEL	BLOWN CELLULOSE INSULATION	1/2" GYPSUM WALL BOARD	R-28
MATERIAL AVAILABILITY	TRUE WOOD SIDING OR FIBER CEMENT SIDING	1/2" AIR GAP WITH FURRING STRIPS AND RAIN SCREEN	2" RIGID ROCKWOOL INSULATION OR 2" XPS	1/2" ZIP PANEL	BLOWN CELLULOSE OR BLOWN FIBERGLASS OR FIBERGLASS BATT	1/2" GYPSUM WALL BOARD	R-28 R-32 R-28
					2X6 WOOD STUD 24" O.C.		

NOTE

MATERIAL AVAILABILITY REFERS TO NON-STANDARD CONTRUCTION MATERIALS OR SERVICES WHICH MAY BE DONATED BY A COMPANY OR AN INDIVDUAL FOR A SINGLE PROJECT AND CAN BE INCORPORATED INTO THE WALL ASSEMBLY, BUT THEY ARE NOT RECCOMMENDED FOR USE

Figure 8: Building Envelope Matrix (Image Credits: 2018-2019 Solar Decathlon team)

Building Envelope Design

For the roof, the team decided to utilize a vented roof assembly with a 2" air space in conjunction with a 10.5" raised heel truss. By maintaining a complete separation between the exterior and conditioned space through sealing the attic , the roof maintains a cold temperature and prevents ice dams from by venting any moisture that moves from the conditioned living space to the attic. Additionally, a vented attic assembly is the same regardless of the architecture of the roof and its construction technique is relatively simple. Therefore, it is the ideal roof assembly to work with the architecture matrix and can be utilized by Habitat for Humanity no matter which plan they decided to build.

For the wall, the team decided to utilize 2x6 advanced framing with R-20 blown cellulose insulation and 3" of R-12 rigid rockwool insulation on the exterior. 2x6 advanced framing is a relatively simple construction technique, which both minimizes the thermal bridging and lowers the cost of the wall assembly. The team decided to use blown cellulose insulation and rigid rockwool insulation instead of glass batt and XPS, which Habitat for Humanity typically uses, in order to keep with our concept of low embodied energy. By using the 3" rigid rockwool insulation on the exterior, in combination with the blown cellulose insulation cavity, we are able to achieve a R-32 wall system.

For the foundation, the team decided to utilize a frost protected shallow foundation wrapped in 3" rigid rockwool insulation continuing from the above-grade wall. This reduces the necessary excavation and site work as compared to a typical slab-on-grade house, which minimizes the costs and time associated with Habitat for Humanity hiring a company to excavate a new site.

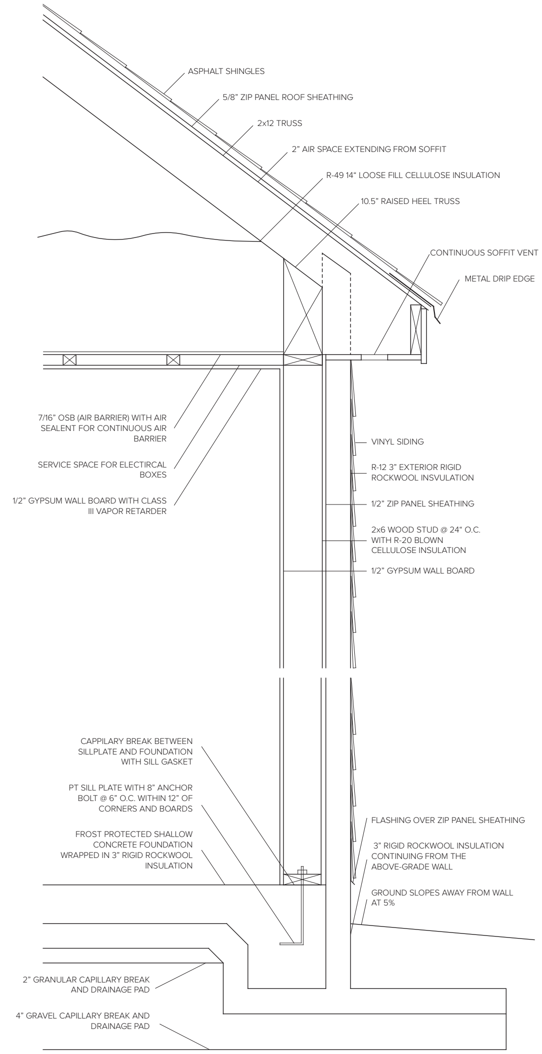


Figure 9: Building Envelope (Image Credits: 2018-2019 Solar Decathlon team)

Building Envelope Analysis

The ability of a building envelope to control moisture is critical in order to protect the building and the occupants from adverse health effects. In order to control moisture in our building envelope, it was not necessary to keep the assembly completely dry. Instead, the team focused on controlling where vapor would condense within the wall, ensuring the wall could dry to both the interior and exterior. In the wall system, the vapor control layer is the ZIP panel sheathing behind the rigid rockwool insulation. The dew point temperature is designed to occur within the rockwool such that vapor condensation occurs on the exterior of the ZIP panel sheathing and drains down and away from the wall.

When using 2x6 advanced framing with exterior insulation, the team had to balance the thickness of the exterior insulation such that it would properly control moisture, maintain a high thermal performance, and be simple for volunteers to install. According to WUFI® Pro, models the hydrothermal performance of a wall system, the moisture content of the ZIP sheathing exceeded 16% with 2" of exterior, rigid rockwool insulation, which would allow for the growth of mold. Therefore, the team decided to utilize 3" exterior, rigid rockwool insulation in order to properly control the moisture within the wall system.

According to the Weather 2050 project, that the annual summer high will raise 5.5 degrees Fahrenheit and the annual winter low will raise 4.3 degrees Fahrenheit over the course of the next 30 years. Therefore, in order to understand the resilience of the building enclosure and analyze how the building envelope design will perform in 2050, the team used WUFI® Pro to analyze its hydrothermal performance in those new conditions. The WUFI® Pro model shows that even with the elevated annual temperatures, the building envelope is still able to properly control moisture within the wall system.

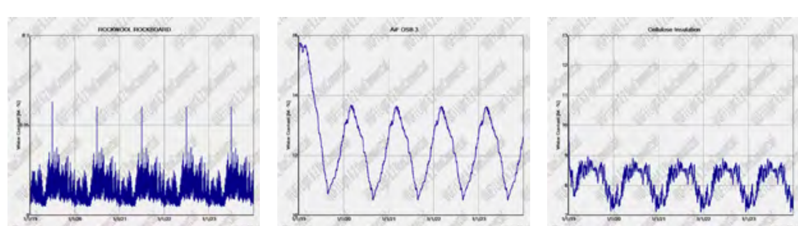
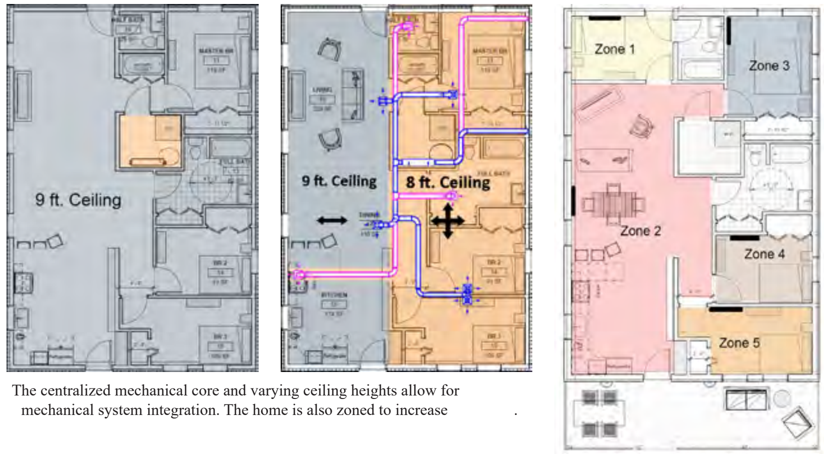


Figure 10: WUFI Hydrothermal Model with 3" Rigid Rockwool Insulation (image credits: 2018-2019 Solar Decathlon team)

Building Systems Design

The team's mechanical, electrical, and plumbing systems were designed to allow seamless integration into future HFHGCC homes without any need for a design professional. The chosen systems are also affordable, and easily understandable in order to lower costs and ensure simple maintenance. Additionally, families will be given a guide on proper programming and usage of these systems, which allows for maximum .

The selection of mechanical systems was majorly by a system's ability to adapt to any of the base model plans. In order to accomplish this, the team right-sized the mechanical room and designed a centralized mechanical design so the system could accommodate a variety of plans. Beyond that, the team utilized varying ceiling heights in order to create a bulkhead for mechanical systems. These spaces also architecturally improved the spaces, where more public rooms like the kitchen and living room had nine foot ceilings, but private bedrooms and bathrooms had eight foot ceiling heights with a plenum for any necessary ductwork.

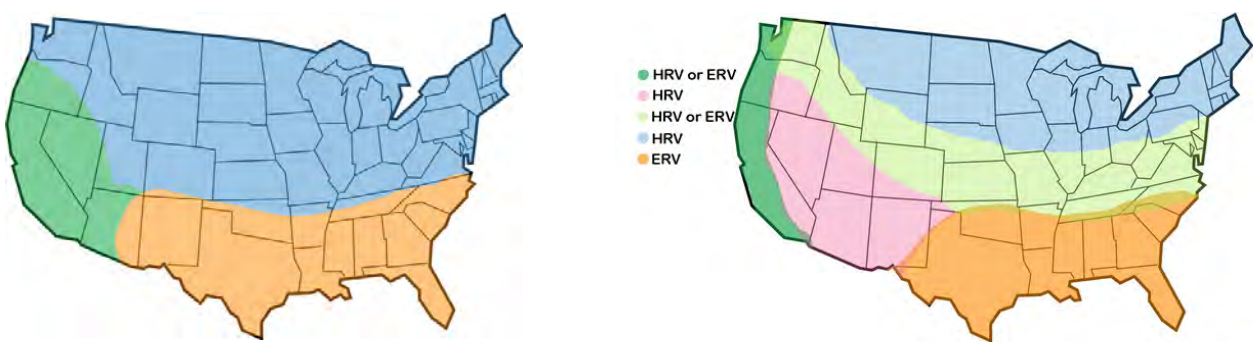


The centralized mechanical core and varying ceiling heights allow for mechanical system integration. The home is also zoned to increase .

Figure 11: Mechanical Centralization and Zoning (image credits: 2018-2019 Solar Decathlon team)

Ventilation

Since the selected envelope is extremely tight, the ventilation system becomes important to maintain acceptable indoor air quality. As a result, the team placed emphasis on selecting a ventilation that exceeded code minimums in order to provide a healthy home for both current and future homeowners. An analysis of systems with the team's goals showed two viable ventilation options: an Energy Recovery Ventilator (ERV) and a Heat Recovery Ventilator (HRV). In the end, an ERV became the optimal choice because it provided continuous balanced ventilation, transfers both heat and moisture, and meets the Zero Energy-Ready Home Standard. Additionally, recommendations for ventilation systems in the State College area show opportunities for utilizing both an ERV or HRV, but future climate data suggests that State College will soon shift to an ERV zone. Thus, the team chose an ERV to account for future climatic conditions to ensure a resilient design.



Recommended Ventilation Choice for Climate in 2003

Recommended Ventilation Choice for Climate in 2018

Figure 12: Mechanical Centralization and Zoning (image credits: Fresh Air Ventilation Systems, LLC)

Radon Mitigation

The area for which the team designed in was located in Radon Zone 1, which contains the highest concentrations of Radon. To bring Radon concentrations in the units down to safe levels, a common mitigation technique will be implemented. A hole will be made in the foundation of the unit, and a PVC pipe will be routed from the hole, through interior walls, to the roof. At the roof outlet, under the exterior roof, a fan will vent the gas running through the pipe into the air outside. This will take the majority of the Radon gas existing in the soil surrounding the unit's foundation, and vent it out into the air. This mitigation system will prevent most of the Radon from seeping into the home, lowering Radon concentrations for our units. In addition to this mitigation system, the vapor barrier the team chose that will be placed beneath the foundation slab prevents migration of Radon gas from the soil into the home.

Mechanical Systems Selection

Mechanical systems selected for the design matrix balanced price, lifespan, ncy, and constructibility. The team aimed to go beyond HFHGCC's standard of solely meeting code, where their standard systems included electric baseboard and a natural gas furnace. The team instead focused on utilizing renewable energy sources and creating a mechanical system that was highly and easily adaptable to any base model. Thus, viable options included using a ducted or ductless minisplit heat pump system, a high-velocity system, or geothermal system. Upon further analysis, the low heating and cooling loads in the home determined that a high-velocity and geothermal system were not feasible due to high costs. As a result, the minisplit heat pump system was chosen. , the chosen system was a ductless minisplit in order to increase volunteer constructibility and in the home.

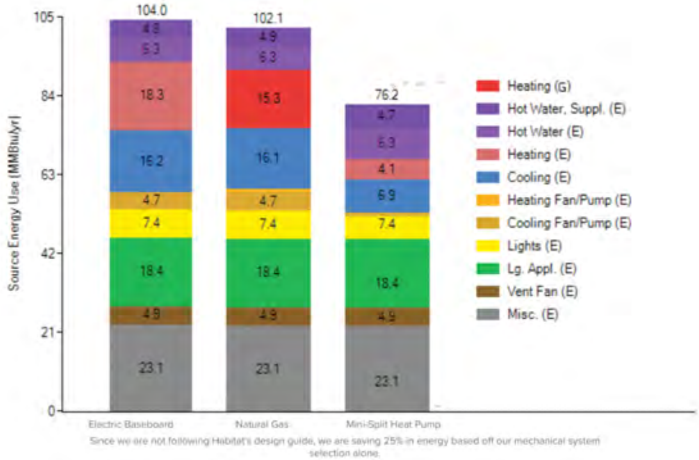


Figure 13: Mechanical System Comparison. Minisplit Heat Pump Chosen (image credit: 2018-2019 Solar Decathlon team)

Plumbing Systems Selection

In terms of plumbing systems, the team chose an 83-gallon Sanden 3rd Generation heat pump water heater. The outdoor unit for this system uses carbon dioxide as the refrigerant to supply heat to the indoor unit. The inverter compressor in this unit saves 70% on electricity and it is four times more than traditional electric units. While this system was expensive, it aligned with the team goals of utilizing solely renewable resources in terms of energy and refrigerants. In addition, the team saved money by utilizing a ductless mechanical system, which helped offset the higher cost of the plumbing system. Beyond that, the team used a homerun layout with pre-insulated Pex pipes that include a horizontal drain water heat recovery system. This reduces the amount of heating required to warm up cold incoming water. The mechanical team worked closely with the architecture team to ensure a centralized mechanical room to reduce the length of piping.

Systems Integration

In order to easily utilize the mechanical systems in the home, the team decided to use an Ecobee Thermostat. The Ecobee Thermostat will be able to control systems when the family is away, which involves tasks like lowering motor speeds or completely shutting down to save on energy. The Ecobee Thermostat is also capable of utilizing local weather to maximize systems, reacting to the occupants' comfort level, and changing temperature setpoints as well. This thermostat was the optimal selection for our team, because of the great energy savings, payback period of 1.5 years, and ability for smart home integration.

Energy Analysis

Habitat for Humanity of Greater Centre County provided a unique challenge for the team in that their current approach involved no consideration for lot orientation. As a result, homes were and expensive to operate. The energy team incorporated this into their design strategy as one of the three matrix considerations, in order to provide HFHGCC with the greatest and ensure that each Habitat family can continue to afford living in their home, especially because there is a higher energy burden on lower income families. The team used softwares such as BEopt and REM/Rate to better inform matrix design decisions. Additionally, programs like PVWatts and SketchUp aided the team in designing an appropriate photovoltaic system to offset the home's energy usage.

The goal in terms of energy was to determine design decisions that were both energy and cost effective for future families. It was important that none of the sustainable aspects in the home added cost, both in terms of upfront cost as well as long-term affordability, since lower income families would be unable to maintain these high expenses. The team utilized BEopt to determine which factors had the greatest impact on energy and cost reduction. Based on this research, the team focused on reducing the impact of major building features like envelope, insulation and, heating and cooling systems.

One of the things the energy team optimized was the envelope . One strategy used to accomplish this was integrating a raised-heel truss into the envelope design. As a result, the roof has more space for insulation in the attic and the continuity of the insulation is improved. BEopt models showed that an R60 ceiling was most but the cost savings would not offset the extra costs required for the additional insulation, so the team found that an R49 attic insulation was the best choice. In terms of the wall construction, REM/Rate models showed that using an R30 wall is the most cost-effective option.

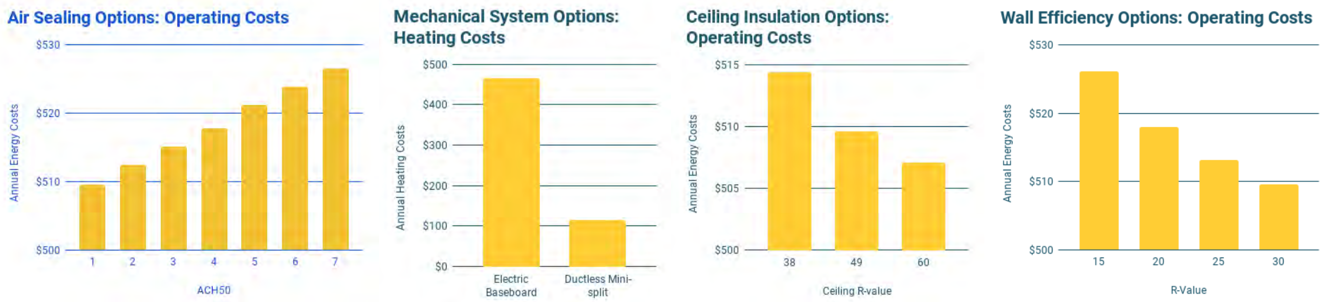


Figure 14: Analysis of Mechanical and Wall System Options (image credit: 2018-2019 Solar Decathlon team)

This higher R-value recommendation coincided with the wall system recommended by the envelope team, which included 3" of exterior insulation to keep moisture out of the wall, that an R-30 wall was optimal for this project.

Alongside the MEP team, the energy team looked into optimizing mechanical systems as well. HFHGCC typically uses electric baseboard heating as a standard for their homes because of its low upfront costs. However, this is a highly way to heat a home. REM/Rate models comparing electric baseboard heating and ductless minisplits showed that electric baseboard heating is more expensive over time even though the upfront cost is cheaper. Thus, using a ductless mini split would save the Habitat family hundreds of dollars annually in energy costs.

The team also explored integrating passive solar design into the home. Using BEopt, the team modeled homes with varying glazing amounts and orientations. As a result, the team saw that having more windows on the south side of the home would maximize solar heat gain and limiting the number and size of windows on the north side would minimize heat loss. This strategy aligns with the spaces in the home as well, since the living room and kitchen are oriented south in the all base plans. These spaces require more natural light to improve the indoor environmental quality of the space, which coincides with the team's results.

Resiliency

Our team three main options for the home: solar PV panels, an electric vehicle charger, and battery packs. While the solar PV array will be part of the initial construction, the homes will all be designed to easily accommodate the other two features at a later date.

Utilizing batteries provides the home with greater resiliency in the event of a weather emergency. The team recommends either the Tesla Powerwall or the LG Chem RESU, both of which are available off-the-shelf. They are also both ANSI rated, so they can be mounted outside the house without any issues. Our industry expert, Envinity, recommended that one battery pack would be to power the home's critical loads, such as the refrigerator and a few lights, in the event of a power outage

The addition of an EV charger would make the home adaptable for future technologies. Although the charger will not be part of the original construction, the conduit will be in place so that it can easily be installed later. In order to remain net zero with the extra energy utilized by the electric car, the homeowner would only have to add three additional panels to the initial eighteen panel array.

Financial Feasibility

While designing the home, the team carefully considered the intended occupants by a target market which worked with HFHGCC. In creating a house with highly sustainable characteristics, a lower monthly operational cost, and a high degree of customization, the design matrix exceeds the existing market expectations. The house properly controls moisture, utilizes low VOC materials, and provides the appropriate amount of fresh air, which increases the quality of life for the homeowners as compared to the homeowner of a traditional Habitat for Humanity house. Due to the high performance building enclosure in combination with highly mechanical systems, the homeowner would save $42 per month on utilities. The design matrix outputs a home that ensures the selected family will receive a high performance, individualized home that exceeds their wants and needs, making it highly sought after design on the market.

As the team as one of HFHGCC's restraints, it is for them to affordable and buildable land. Most buildable land in State College is quite expensive, and what land remains at an affordable price is often to build upon due to steep slope conditions or large obstructions. Eligible families for a Habitat for Humanity home are within the income range of $21,000 - $43,000, which is 40%-80% the Median Family Income of Centre County. Habitat for Humanity of Greater Centre County operates under the preconceived notion that the initial cost of the house is the main priority when designing and choosing systems, which typically results in code minimum homes. The team carefully selected the best options to include in the new home, which provides long term affordability and resilience for the family while keeping in mind the initial cost of the home.

	Typical Construction Costs		Habitat For Humanity Cost	
	w/o PV	w/ PV	w/o PV	w/ PV
Construction Cost	$114,932.48	$131,129.48	$82,499.61	$98,696.61
Overhead & Profit (15%)	$17,239.87	$19,669.42	$0.00	$0.00
Lot Costs (0.3 acres)	$23,000.00	$23,000.00	$23,000.00	$23,000.00
Total Project Cost	$155,172.36	$173,798.91	**$105,499.61**	**$121,696.61**
Cost Per Square Foot	$117.55	$131.67	**$79.92**	**$92.19**

Figure 15: Cost Analysis (image credit: 2018-2019 Solar Decathlon team)

The team focused not only on the two incentives that Habitat for Humanity offers homeowners, but also incentives offered by other institutions in order to reduce the overall cost of the house and provide a high-performance, affordable housing option. The incentive is the volunteer workforce Habitat for Humanity employs to construct all of their buildings, which decreases the overall construction cost by eliminating the cost of labor. In addition, Habitat for Humanity offers homeowners an interest-free mortgage to the purchase and construction of the house. The federal government offers a 30% tax credit to homeowners who utilize a solar energy system, but this program is planned to be phased out by 2022, where the tax credit will reduce to 26% by 2020 and 22% by 2021. Pennsylvania offers a rebate program for ENERGY STAR rated appliances and solar renewable energy credits (SRECs), which buys back solar energy that is sold to the grid.

A standard house built by HFHGCC has an average total cost of $90,000 including the price of the land. Using RSMeans 2019 and 2018 with adjusted factors, quotes from suppliers, and online research for associated costs, the team determined that the total cost of a house output by the design matrix was $121,697 including the price of land and a solar PV system. Without a solar PV system, the house would cost $105,500. The difference in price is mainly due to more mechanical systems and appliances, as well as the high-performance building enclosure. There is no associated labor cost in most cases, because Habitat for Humanity typically utilizes a volunteer workforce. When a contractor or specialized equipment is required, the added costs are calculated into the material costs. Taking these factors into account, the team selected elements and details which are labor intensive, yet simple to construct.

Conclusion

Looking back on the 2018-2019 Solar Decathlon project, the team found several improvement areas that could be implemented in future years. The issue the team faced was not having a consistent baseline knowledge of sustainable design across the entire team. Many team members are brand new to Solar Decathlon and are not comfortable with building science practices. As a result, these member often fall behind and are not as involved in the design process. In order to combat this, the team is looking to utilize the fall semester to implement a building science lecture series. In this case, returning team members will create mini lectures based on various topics of sustainability and building science principles to teach the newer members. This both serves to educate incoming team members and to provide an opportunity for returning members to practice leading and presenting.

The team also faced issues in terms of subteam communication. Often times, each subteam is unaware of the other work being prodiced by the remaining subteams. This leads to misalignment of overall team values, as well as work done by subteams. As a result, there is confusion relating to the overall concept and the details of the project. A solution the team found was to include more full team design charrettes and internal team presentations. This allows all team memebrs to be engaged in the project, help determine overall team values, and provide feedback in relation to their respective subteam. As a result, each subteam can design with the team's overall values and goals in mind, thus creating a more and cohesive design.

While some aspects of the 2018-2019 project could be improved, the team found other areas of the project that were successfully implemented strategies. Having a real-world project partner greatly enhances the design, because it provides authentic constraints and goals to the project. The team works very closely with these companies to understand their wants and needs, which adds a level of realism and purpose to the design. The team also engages with many industry professionals and Penn State professionals to gain insights and feedback from experts in the In doing so, the team is able to create a more feasible project. Beyond that, the team utilizes an integrative design process to produce a more cohesive design. Integrating all subteams and memebrs allows the project to gain more goals and values that are seen throughout the entire design.

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Hempcrete for as Residential Construction Material: State-of-the-art and Challenges

H. Yi[1], C. Griffin[2], A. Memari[3], David Lanning[4], and J. H. Dooley[5]

[1]Assistant Research Professor, Agricultural and Biological Engineering Department, The Pennsylvania State University, 228 Agricultural Engineering Building, University Park, PA. 16802. 814-865-2807, huy1@psu.edu.

[2]Associate Dean Associate Dean for Research and Associate Professor of Architecture of the Division of Arts + Humanities, Architecture, Penn State Altoona College, W110C Smith Building, 3000 Ivyside Park, Altoona, PA, 16601, 814-949-5746, corey@psu.edu.

[3]Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA, 16802. 814-863-9788, amm7@psu.edu.

[5]Senior Mechanical Engineer, Forest Concepts, LLC. 3320 W Valley Hwy N d110, Auburn, WA 98001. 253-333-9663, dlanning@forestconcepts.com.

[4]Chief Technology Officer, Forest Concepts, LLC. 3320 W Valley Hwy N d110, Auburn, WA 98001. 253-333-9663, jdooley@forestconcepts.com.

ABSTRACT

Given that over 95% of buildings are residential dwellings, for any meaningful global impact on CO_2 reduction, locally sourced materials, and easy to construct methods are needed for energy-efficient and low-carbon residential buildings. One such promising material is industrial hemp (Cannabis sativa L.). Hemp stalks from fiber varieties and crop residues from CBD oil varieties contain long, high-strength fibers, which enable processing into industrial biomaterials such as additives for hempcrete. The hempcrete mixture may be made up of bio-fiber hemp hurd as aggregate and mineral binder hydrated lime to adhere hemp hurd pieces together. Hempcrete has been shown to have potential in residential construction applications to improve insulation of masonry walls, reduce consumption of carbon-intensive concrete, and reduce the weight of cement-based structures. Considering that the cultivation of industrial hemp is newly reinstated, hempcrete and related construction materials should be developed as a market-ready product that considers the supply chains, processes, and manufacturing facilities that are to be established in the United States. This paper highlights a state-of-the-art review of hempcrete for affordable and sustainable home building and describes key research needed for this composite material to be a successful alternative to conventional wood-frame residential building construction.

INTRODUCTION

The UN Climate Change Conference of 2015 in Paris agreed to limit the global temperature increase to 1.5°C above the pre-industrial level, which requires a significant reduction of CO_2 emission into the atmosphere. Given that building construction is responsible for about 39% of CO_2 emissions (9×109 ton CO_2), and that according to the 2017 UN Global Status Report, it is anticipated that over 230,000 km^2 of new construction would be needed to accommodate the developments for the next 40 years, there is urgent need for overhaul of construction materials and processes to reduce greenhouse gas emissions.

In particular, because most of the building construction worldwide uses a significant amount of masonry, concrete, and steel, which have contributed to 1% increase in CO_2 emission since 2010 due to increasing demand for buildings, new low-carbon or carbon-capturing construction materials and methods must be developed. Few alternatives are available for traditional loadbearing structural systems. On the other hand, the market increasingly leans toward factory-built and assembled panelized and modular systems, including a large variety of transparent and opaque factory-built façades and building envelope systems. However, most new materials and systems require advanced technology and skilled labor in the fabrication and construction process, whereas hempcrete represents a change that does not require significant investments or training.

Given that residential buildings constitute over 95% of buildings, for any meaningful global impact on CO_2 reduction, locally sourced materials and easy to construct methods are preferred for home building. In developing countries, masonry and concrete buildings are the typical choices of construction materials and systems. Unfortunately, much of the construction is with unreinforced masonry and concrete. Wood- or plant-based reinforced concrete and hempcrete may improve the strength of residential buildings in developing countries. The US could lead in providing new materials, methods, and products for resilient, low-carbon residential construction, which can then encourage many other countries to adopt such construction system and have a significant impact on sustainable global house construction. Research has shown that the structures of these unreinforced concrete buildings are both unreliable and ineffective when natural disasters occur, due to compromised construction in the quality or quantity of materials (McWilliams and Griffin 2013). For example, it is noted that the Haitian construction of recent buildings and particularly those that collapsed in the 2010 earthquake were all built with poor concrete mixes. When mixing the concrete, builders would use the poorest quality of sand for concrete and save the more valuable sand for the exterior stucco of buildings.

This also holds true for the amount of rebar used in the concrete as well. Continuing to build with structural systems that: (1) have a high environmental cost in terms of CO_2 emissions, (2) require imported materials, and (3) can be easily compromised during construction due to economic hardship or societal inaction is not sustainable. Consequently, carbon-sequestering alternatives to steel-reinforced conventional concrete are needed globally.

Bio-integrated concretes and blocks with wood-based (stud) reinforcement offer a viable alternative to imported steel rebar that could be tailored to specific regions depending on the plants available. Therefore, this study reviews the state-of-the-art of bio-integrated concretes and blocks with load carrying wood stud that is used in residential buildings. This review highlights the advantages and challenges to aid future researches toward adoptation of hempcrete in the residential building industry.

WHAT IS INDUSTRIAL HEMP?

Hemp is an industrial non-load bearing variant of cannabis that is grown mainly for its fiber, hurd, and seeds (Figure 1). Because of the long-time ban on growing and doing research related to industrial hemp, hemp has not been considered as a viable renewable resource for U.S. building products. Recently, such bans are being lifted globally because of the increase in the needs and interests in renewable resources. In the United States, the Senate Bill S.2667 by the 115th Congress makes the hemp producers eligible for the Federal Crop Insurance Program and some USDA research grants (https://www.congress.gov/bill/115th-congress/senate-bill/2667). Subsequently, there are substantial needs for research on its processing and utilization to support increased acreage planted. However, according to Popescu (2018), out of 30 countries that now grow industrial hemp, currently, only about 10,000 acres in the US grow this crop, half of the acreage in Canada. However, with the passage of the 2018 Farm Bill, it is expected that the US acreage grows significantly. At the same time, there exists a great need to figure out the usage of industrial hemp to expand markets.

Figure 1 Pictures of hemp plant (left), hemp fiber (center), and vertical section of hemp stock. (Photos courtesy of Forest Concepts Inc.)

From an agricultural crop perspective, the yield of hemp is reported to be quite high (2.5 to 8.7 tons of dry straw per acre), which makes it hard to match by any other plants to provide this volume of biomass (Green Home Gnome 2017). Also, the growth rate is fast (about four months), and without the need of much fertilizer for growth and without the need for pesticides, it makes the crop highly profitable for farmers (Popescu 2018).

As far as carbon sequestering is concerned, according to GreenSpec (2019) (also in Tradical 2019), hempcrete sequesters 110 kg of CO_2 per 1 m^3 of hempcrete, taking into account the carbon emission due to producing the lime binder. Based on another report (Green Home Gnome 2019), on average, a 2000 ft^2 home would sequester about 5 tons of CO_2 if built using hempcrete. This can be compared with the emission of 1 ton of CO_2 in the production of batt insulation for the same home.

HEMPCRETE

In hemp, the fibers that make up the exterior surface of stalk have tensile capacity comparable to steel are the premium part. The woody core hurd can be chopped as shiv and used as a construction aggregate material to create a wall system with high thermal insulation and thermal mass properties. As hemp grows (as tall as 4.5 m and 25 mm dia.), it absorbs a significant amount of CO_2, (e.g., 716 lb. (325 kg) of CO2 in one tonne of dried hemp) (Green Home Gnome 2017). Other estimates mention that the hemp used in 1 m^3 of hempcrete has sequestered 165-180 kg CO_2.

From environmental and sustainability perspective, hemp hurd (Figure 2) can be considered a by-product of hemp fiber producers essentially, as they strip the valuable fibers from the hemp stalk leaving the hurd with no value-added use. In particular, since the use of hemp hurd in hempcrete provides thermal insulation, it offers another important advantage over conventional construction materials. Other advantages include being renewable, low-impact on the environment, and obtained from the waste stream as a by-product.

Besides the insulation property, the hemp hurd has a large capacity to absorb moisture on the internal surfaces of the plant fibers and absorb moisture in the voids of the cellular structure of the hemp. This is a desirable attribute for construction material, as it can store vapor that is driven by the interior-exterior vapor pressure difference and release it to dry when conditions change. Such a vapor storage capacity is very important in areas with high humidity, as it will not adversely affect the wall performance and durability.

Figure 2 Hemp hurd is chopped for use as aggregate (Photo courtesy of Forest Concepts Inc.)

LIME

Natural hydraulic lime can be considered an alternative to Portland cement, in particular when reduced carbon footprint is of interest. An example use of lime to make concrete is when it is used as the binder with lightweight aggregates, which results in a "breathable" concrete, i.e., allows vapor to pass through (Abbott 2014, Pullen 2017). However, while increasing the lime content increases the strength, it reduces the breathability, which is of interest for slab on grade floors.

In hempcrete, bio-fiber hemp hurd is used as an aggregate replacing gravels. In addition, hydrated lime can be used as a mineral binder to adhere hemp hurd (mulch-like shape) pieces together. Just as limecrete uses lime as the binder and lightweight aggregates to make lightweight concrete, hempcrete uses lime as the binder, but hemp hurd (shiv) as the aggregate, where lime basically coats the hemp shiv. The reaction between lime and water during the mixing process creates a binding property that adheres hurd particles together. Some additives can also be added to lime to control setting time, durability, and strength. One difference between hempcrete and conventional concrete is that the voids between shiv aggregates are not necessarily filled with lime binder, thus providing enhanced thermal insulation property (Green Home Gnome 2019).

While the presence of stored moisture in construction material is detrimental to its durability, in the case of hempcrete, because lime with high pH coats each hemp hurd aggregate, it enhances its antimicrobial and antifungal properties, thus protects the hurd from mold development under humidity and temperature conditions that can adversely affect other insulation materials. Therefore, having both high thermal insulation property and high moisture storage capacity lends this material suitable for use in home construction in both cold climates and hot and humid climates (Green Home Gnome 2017).

Lime used as such cures more slowly than Portland cement, but unlike Portland cement, it absorbs CO_2 as it sets and dries. The breathability property of concrete made with lime is consistent with timber construction (Abbott 2014); therefore, if used for walls, it allows vapor to pass through, thus avoiding moisture accumulation that can cause many issues in walls including mold growth. To make concrete with lime, a volumetric mixer can measure the proportions of lime, aggregate, and water, and then an auger is used to mix the ingredients and prepare the concrete (Abbott 2014). Test cubes can be made at the site to test for strength. With respect to CO_2 generation and absorption, it should be noted that CO_2 is generated and released through the process of making hydraulic lime. While CO_2 is generated during calcining limestone to make quick lime, once water is added to make hydrated lime, it re-absorbs 20-75% of the original CO_2 from the atmosphere as the concrete cures, a process known as "lime cycle."

Combining these facts, hempcrete is net carbon negative, *i.e.*, the construction of a 300 mm thick hempcrete wall can be a net negative of 40 kg CO_2 per m^2 of a wall when we consider CO_2 absorbed during hemp growth, emission during hydrated lime production, and re-absorption by lime over time. In comparison, a masonry wall releases 100 kg of CO_2 emissions per m^2 of a wall.

HEMPCRETE MIXTURE

While there are some example hempcrete mixture proportions suggested by some builders/industry, some basic material mixture design is needed in order to develop a thorough understanding of various designs and choose the design that works best for the envisioned system. In general, hempcrete can be made by mixing hemp hurds, lime, sand, plaster, cement, additives, and water (Priesnitz 2006). The proportion of each ingredient should be varied until optimum properties for precast block form and cast-in-place option can be determined. Currently, a standard mixture design has not been developed.

MECHANICAL PROPERTIES OF HEMPCRETE

Figure 3 Typical example precast Hempcrete Block Building Construction (Courtesy of Wikipedia: https://en.wikipedia.org/wiki/Hempcrete)

Stevulova et al. (2013) report on their study of the impact of hemp hurd properties on the behavior of composites when the binder changes from hydrate lime with and without cement to zeolite and magnesium oxide cement. Walker et al. (2014) report on their study of hemp-lime concrete comparing the effect of two different binders, hydrated lime/pozzolan, and hydrated lime/cement, on mechanical and durability properties. The test results they provide offer some reference point for comparison. Furthermore, the strength of hemp-lime concrete increases during curing. For example, they reported the compressive strength of hemp-lime concrete to be between 0.02 and 0.04 MPa at 5 days, and between 0.29 and 0.39 after one year, but most of the strength developed between 5 and 28 days. A similar trend is observed with the flexural strength of a typical test beam.

The correlation between the properties of wood-based materials and reinforced hemp-lime concrete will be important in developing the design standard for building with hempcrete and the guidelines for quality control of plant-based materials. Such standards are still yet to be developed for the U.S. However, according to NYT (2018), in 2017, ASTM International formed a technical committee to look into possibility of developing such a needed standard. Especially, the structural properties of interest for hempcrete would depend on the form, that is block work (Figure 3) vs. cast-in-place.

For block form, the conventional masonry block properties would need to be determined (e.g., Memari et al. 2012, Kauffman and Memari 2014). Accordingly, the masonry compressive capacity would be determined using ASTM standard C1314 (Standard Test Method for Compressive Strength of Masonry Prisms, Figure 6). Masonry prism tests better describe the performance of walls since mortar modifies the capacity of single blocks.

For a cast-in-place option, however, one should determine basic properties for a concrete type material, including cylinder or cube compressive strength per ASTM C109/C109M (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2in. Cube Specimens)) or per ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens), and modulus of elasticity per ASTM C469 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression).

BIO-BASED REINFORCEMENT MATERIALS FOR HEMPCRETE

Because of the high percentage of air voids in the hempcrete that provide its insulative properties, it has a relatively low compressive strength at about 1 MPa (145 psi) or 5% of a 3000 psi concrete strength. Therefore, it is currently used as nonload-bearing poured-in-place wall material or used as infill blocks and placed between or in front of wood-frame studs, which carry the gravity loads. For home construction, hempcrete is currently used as precast blocks to fill the space between conventional 2×4 studs (Figure 3), or as a cast-in-place concrete wall with framing members (2×4 studs) embedded in the concrete as vertical reinforcement to carry the gravity loads of the floor and roof above (Figures 4 and 5).

Figure 4 Formwork for placement of cast in place hempcrete to confine studs (Courtesy of American Lime Technology http://www.americanlimetechnology.com/clayton-house/)

Figure 5 Example cast in place hempcrete wall confining studs (Courtesy of American Lime Technology http://www.americanlimetechnology.com/tradical-hemcrete/)

In particular, as a cast-in-place option, since hempcrete provides continuous confinement for constuction timber or 2×4 studs, it lends them significant vertical load-carrying capacity. Wood studs embedded in hempcrete are confined throughout their height. Embedding wood studs in hempcrete will also increase axial load capacity of timber due to full height lateral confinement by hempcrete, which prevents lateral buckling under compression. Such a compressive strength is reported to be three to four-time of that of bare unconfined wood studs (Green Home Gnome 2017). In addition, due to high pH, the lime binder will also inherently protect timber as well as hemp from fungi and termites, thus significantly enhancing durability of the hempcrete structure.

THE USE OF HEMPCRETE

Previous research has highlighted the important role of non-technical barriers to the use of sustainable structural materials in general (Griffin et al. 2010) and wood specifically (Knowles et al. 2011). These studies have shown that the desire for lowest cost and building codes requirements are the primary drivers when design teams are selecting a structural system for green buildings and not which material or system is more sustainable. Such research has also shown that the supply chain for more sustainable building materials can also be a barrier to their use. One important use of hempcrete is rigid insulation as shown in Figure 6. As an example of comparison of

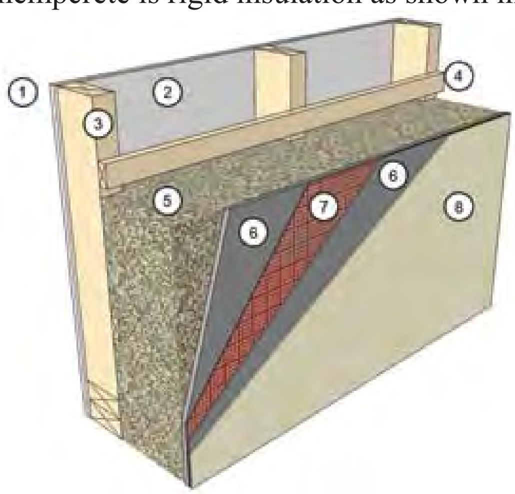

Figure 6 Example Wall System Detail with Hempcrete Rigid Insulation. Components include the following: 1) Plast skim; 2) Board that includes lime; 3) Wood studs; 4) Horizontal batten to tie hempcrete insulation to studs; 5) Hempcrete insulation; 6) Basecoat render; 7) Mesh for basecoat; and 8) Top coat render. (Courtesy of American Lime Technology (http://americanlimetechnology.com/wp-content/themes/HEMP_Aggregate/images/pdf/Hemcrete%20Brochure%202012%20-%20ALT.pdf).

the cost of hempcrete (assuming hemp is imported from Canada) as an insulation for walls with conventional insulation, according to Green Home Genome (2019), the cost per square foot of hempcrete (14 in. thick) for an R-28 wall can vary from $3.50 to $11.66, while the cost of fiberglass batt (7 in, thick) for the same R-28 is $1.20, and the cost of expanded polystyrene (7.5 in.) turns out to be $4.50. This shows that currently because of lack of a high volume sale (leading to price break), hemcrete cannot compete with batt insulation, but perhaps closer to the cost of expanded polystyrene.

Subsequent research (Schmidt and Griffin 2013; Pei et al. 2014; Mallo and Espinoza 2015) has shown that the cost and building codes are perceived barriers to the use of new, bio-based structural materials such as mass timber. In the U.S., recent attempts to construct the first high-rise mass timber building ran into these less technical barriers, the major one of which was the lack of qualified and knowledgeable sub-contractors to install the wood panels. If similar non-technical barriers are not addressed, then hempcrete, despite their favorable environmental profiles, will not be used in new construction. There is no known legal constrains in residential applications of hempcrete under current building codes in most jurisdictiosn, especially for non-structural applications. Nonetheless, research and data are needed to broaden the use of the hempcrete. This can be especially important for hempcrete considering the correlated connotation of hemp with Cannabis. Therefore, there is a need to identify the factors that constrain the adoption of highly agriculturally relevant hempcrete and allow the development of a strategy encouraging the adoption of hemp-based engineered products. Further, there should be research on how to bridge information gaps about supply chain, cost, and code compliance for agricultural professionals as well as future architects and engineers. Hempcrete building products must address architectural considerations and provide the requisite utility to ensure longevity. It is also critical to uncover potential agricultural supply chain issues that could imped the adoption of hempcrete buidling products.

CONCLUSION

Industrial hemp is a promising renewable material. Considering the mechancial properties of industrial hemp, hempcrete is a capable alternative material that provides appropriate mechanical properties required for residential construction especially when it is combined with bio-based reinforcement materials such as wood studs.

The successful adoptation of hempcrete to the residential building construction practices will create a new market demand for the hemp and hempcrete as a construction material. Furthermore, by replacing existing industrial materials in select applications for reinforced concrete structures with materials of agricultural origin, the adoption of hempcrete will contribute to promoting the sustainability of society with positive impacts on economic opportunities of farmers and the environment.

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Long-term Exposure Data Analysis of Residential High Performance Wall Assemblies Exposed to Real Climate

M. Bartko[1], T. V. Moore[2], M. Ghobadi[3], G. Ganapathy[4] and M. A. Lacasse[5]

[1] Research Officer, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada. Michal.Bartko@nrc-cnrc.gc.ca.
[2] Research Council Officer, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada. Travis.Moore@nrc-cnrc.gc.ca.
[3] Research Officer, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada. Mehdi.Ghobadi@nrc-cnrc.gc.ca.
[4] Technical Officer, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada. Gnanamurugan.Ganapathy@nrc-cnrc.gc.ca.
[5] Senior Research Officer, National Research Council Canada, 1200 Montreal Road, Ottawa, Ontario, K1A 0R6, Canada. Michael.Lacasse@nrc-cnrc.gc.ca.

Abstract

This paper presents in-situ hygrothermal test results of residential, highly insulated and zero energy ready wall assemblies. A comparison of results of freshly exposed specimens, and results after 3 years of exposure is provided.

Three wall specimens were installed and instrumented at the NRC-Construction's Field Exposure Wall Test Facility (FEWF) in 2016. The wall assemblies consist of 1) a high R-value (R-29) retrofit assembly with continuous external foam insulation (W1- XPS) and poly-ethylene vapor barrier on the interior side; 2) a Passive House (W2- PH), R-43 double stud assembly with wood based insulation; and, 3) a stud wall assembly with external insulation (R-29) and wood based oriented strand board vapor control on interior side (W3- OSB). The specimens, installed on a west facing wall of the FEWF were exposed to real climate conditions in Ottawa, Ontario, Canada for the period of 2016 to 2019. Hourly values of temperatures, pressure difference, relative humidity and moisture presence have been monitored and recorded during all four seasons. Temperature, moisture, pressure and heat flux sensors were installed on both interior and exterior sides, as well as within the assemblies at multiple locations where the potential for condensation and mold growth was considered high.

The present study reports on the behavior of all three specimens over a three year period of year-round exposure and data monitoring. Some changes in R values were observed. The R value decrease of 12% was calculated for the W1. A 5% decrease in R value was obtained for the W3. The likely reason for this decrease is a combination of material aging (which could be combination of potential off gassing of the XPS and/or settling of the glass fibre insulation) and the potential for increased moisture contents of the components. The presence of moisture was detected at the exterior sheathing board (XPS), corresponding to rain events, however, in each case, the moisture load dried to the exterior, indicating that the risk to deterioration of potentially vulnerable components in the wall assembly is minimal. Comparison of yearly runs of pressures differences, temperatures and humidity results together with dew point calculations results show that after the long-term exposure.

1. Introduction

The aim of this study is to evaluate the hygrothermal performance of highly insulated wall specimens exposed to real climatic conditions for an extended period of time by considering changes in the moisture accumulation and thermal resistance of each wall assembly. The initial behavior immediately after the installation of the specimens has been compared to the one after three years of constant exposure and monitoring.

The study has been executed with the aim to develop information on the moisture, thermal and long-term durability performance of progressively higher insulated wood-frame wall assemblies. The information is to be used to: (1) Support the evaluation of future code proposals regarding energy efficiency improvements to building envelope systems; (2) Support the development of knowledge, details and practices for advanced wall systems for voluntary residential energy efficiency programs; (3) Help the housing industry meet the 2030 net-zero energy ready targets in Canada, and; (4) Promote the deployment of highly energy efficient wall details for new and retrofitted existing wood-frame construction.

The three wall specimens were installed in the NRC-Construction's Field Exposure of Walls test Facility (FEWF) and were instrumented with temperature sensors, relative humidity, pressure, moisture and heat flux sensors. These sensors were monitored for a period of three years (2016 to 2019). This paper compares the moisture performance after three years (2016 and 2019) and the thermal resistance performance of the wall assemblies after 1 year (2017) and 3 years (2019) of exposure. This is due to unavailability of the initial heat flux sensor data for 2016.

Analysis of the moisture sensors were used to determine the potential for accumulation of moisture for the duration of the experiment, due to either condensation wind driven rain loads, or exterior relative humidity. In addition these sensors were used to determine the degree of moisture ingress to the interior wall cavity from exterior moisture loads by monitoring moisture accumulation at each layer of the wall assembly.

The temperature sensors and heat flux sensors were used to determine the in-situ thermal resistance for two periods, January-February 2017 and January – February 2019, using the summation calculation method in ASTM C1155. The results of the calculations for these two periods were compared to determine the potential for a decrease in thermal resistance of the wall assemblies over time.

In addition to the results of the moisture and thermal analysis, this paper describes the test facility, wall assembly configurations, instrumentation locations, data acquisition system (DAQ) used during the experiments, and an estimate of the uncertainty of the calculation results.

2. Experiment and calculation methods

This section describes the experiment and calculation methods used to determine the results and also an estimate of the uncertainty of the calculation results, based on the uncertainty of the experimentally derived values. The following subsections describe the test facility, wall specimens, instrumentation locations, DAQ details, thermal resistance calculation methods, and an uncertainty analysis of the thermal resistance calculation method.

2.1. FEWF Test Facility

The wall specimens were installed in a side-by-side test bay of the FEWF pictured in Figure 1. This facility is designed to determine the thermal and moisture response of up to three specimens, which are installed side by side in a west facing orientation. It measures the hygrothermal performance of specimens of the dimensions 4ft wide by 6ft tall and up to 12in. deep. All the specimens were subjected to the local climate conditions of Ottawa, Canada and conditions on the interior side of the test specimen were nominally maintained at 21°C and 35% RH as per ASHRAE Handbook of Fundamentals.

Figure 1. NRC's Field Exposure of Walls Test Facility (FEWF)

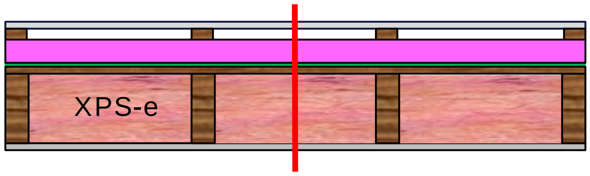
2.2. Test Specimens

Representative diagrams of the three as tested highly insulated walls are shown in Figure 2.

The theoretical thermal resistance values, neglecting the effect of studs, ranged from RSI = 5.1 m^2K/W (R29) to 7.6 m^2K/W (R43). Walls W1 and W3 contained essentially the same components, the difference being for Wall 3 in the use of an 11 mm OSB wood sheathing panel in lieu of a polyethylene membrane to act as a vapour barrier on the interior side. Wall W2 consisted of wood fibre insulation with a 24 mm wood fibre "diffusion board" as an exterior sheathing panel. For wall W2, there was interest in knowing whether wood fibre products of the type used in this wall assembly had merit for use in Canadian homes.

a)

W1

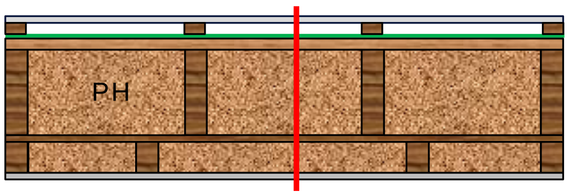


RSI 5.1 [m^2K/W]
R-value 29 [$hr\text{-}ft^2\text{-}°F/BTU$]

- Vinyl siding
- 3x0.75-in. nominal vertical furring strip
- 1-in. XPS rigid foam insulation (R5)
- Sheathing membrane
- 11 mm OSB wood-sheathing
- 1.5x5.5-in. nominal wood stud cavity
- R24 glass fiber batt insulation for 6-in. cavity
- 6 mil poly air/vapour barrier
- ½-in. painted drywall

b)

W2

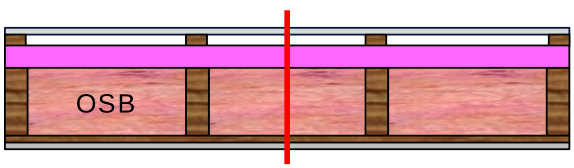


RSI 7.6 [m^2K/W]
R-value 43 [$hr\text{-}ft^2\text{-}°F/BTU$]

- Vinyl siding
- 3x0.75-in. nominal vertical furring strip
- Sheathing membrane
- 24mm Diffusion board
- 1.5x9.13-in. nominal wood stud cavity
- Wood fibre insulation for 10-in. cavity
- 11 mm OSB wood-sheathing; joints taped
- 1.5x3.5-in.studs (Service wall interior)
- Wood fibre insulation for 4-in. cavity
- ½-in. painted drywall

c)

W3



RSI 5.1 [m^2K/W]
R-value 29 [$hr\text{-}ft^2\text{-}°F/BTU$]

- Vinyl siding
- 3x0.75-in. nominal vertical furring strip
- 1-in. XPS rigid foam insulation (R5)
- 1.5x5.5-in. nominal wood stud cavity
- R24 glass fiber batt insulation for 6-in. cavity
- 11 mm OSB wood-sheathing; joints taped
- ½-in. painted drywall

Figure 2. Tested wall assemblies, used materials and calculated R values, a) Retrofit wall with external continuous XPS insulation, b) New built wood fiber based insulation for Passive house construction c) Smart vapor barrier (OSB) with external continuous XPS insulation.

Note: For the In-Situ R-value calculation, sensors located along the center (red) line were used.

2.3. Specimens' Instrumentation and DAQ sampling

An Agilent 34890a multifunction measure unit was used as the data acquisition system (DAQ). The DAQ reads values from all sensors every minute and records the average values over 15 minutes period.

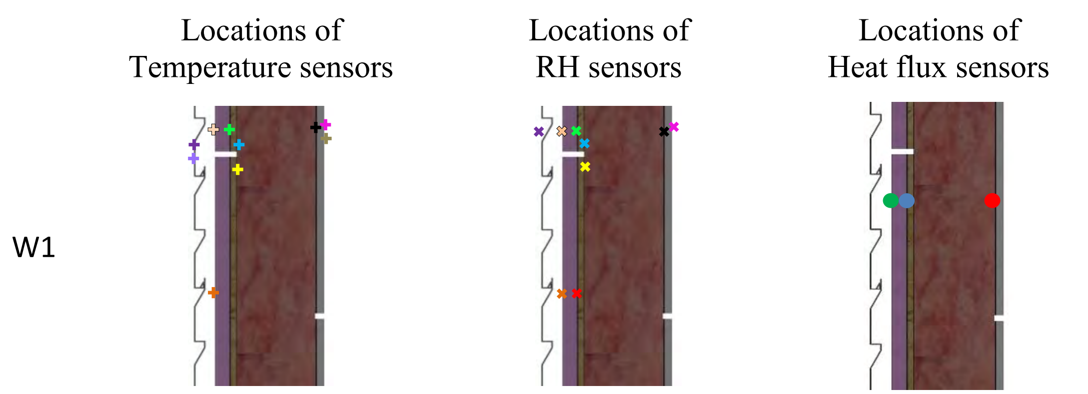
The types and characteristics of all sensors used in this study are listed in Table 1.

Table 1. List of sensors used to determine hygrothermal response of test specimens to changing local exterior and interior conditions

Sensors	**Manufacturer Supplier**	**Model**	**Range**	**Accuracy**
Thermocouple	Omega	TT-T-24-SLE	-100ºC to +200ºC	0.5ºC or 0.4% FS
Relative Humidity &Temperature	Vaisala	HMP-60	RH: 0 to 100%; Temp.: - 40ºC to +60ºC	RH : ± 5% Temp.: ± 0.6ºC
Heat flux sensors	Hukseflux	PU11T & PU32T	-20ºC to + 60ºC	± 5% at 20ºC
Moisture tapes	Detec & SMT	N/A	Up to 40% moisture content	

The specimens were instrumented with the listed sensors in various locations throughout the assembly. The highest concentration of sensors was generally located on the interface between the exterior side of glass fiber insulation and the respective sheathing board (OSB, XPS, wood fiber diffusion boards), as shown in Figure 3.

Detec moisture sensors were also used to determine the presence of liquid moisture as might have arisen due to condensation of moisture on the surface of wall components within the wall assembly, or due to rain intrusion from the exterior. An example of the location of the Detec moisture tapes in each wall assembly is presented in Figure 4. The principle of the Detec moisture tape relates to the electric conductivity of water. Instrumentation measures the electrical resistance (kΩ) between two metal bands separated by non-conductive tape. The presence of moisture is detected on the tapes because it connects a circuit between two metal bands, causing a measured decrease in the resistance between the metal bands.



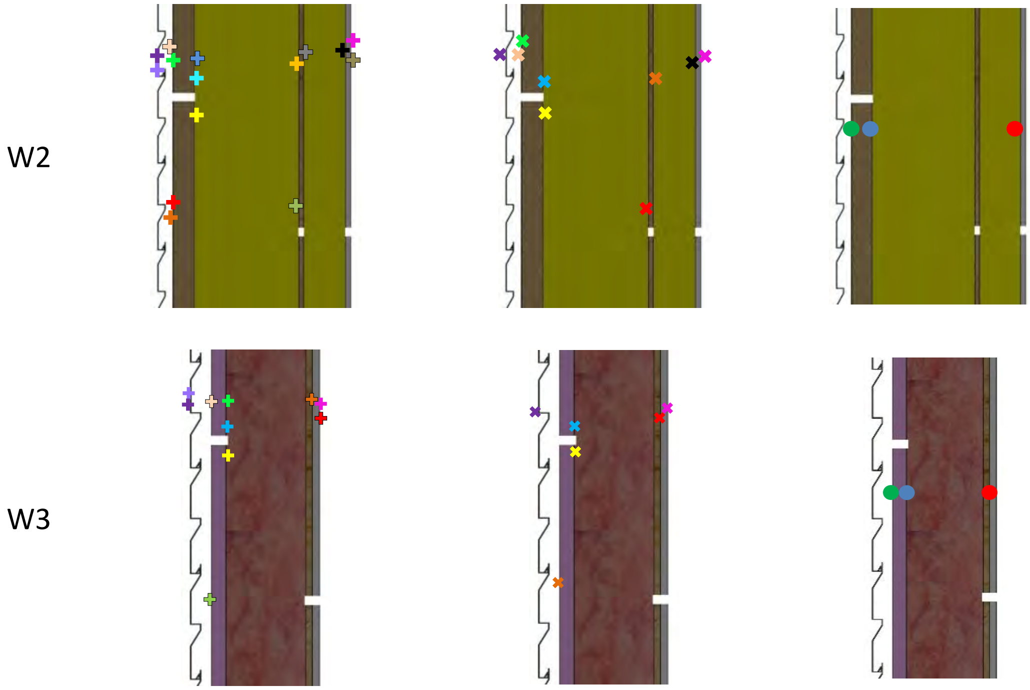


Figure 3. Instrumentation of specimens and locations of sensors in wall assemblies

Figure 4. Example of wall specimen assembly construction showing locations of moisture detection tapes, temperature sensors and RH sensors

3. Long term performance assessment methodology: Thermal resistance

As mentioned previously, the purpose of these experiments was to determine the long term performance of the highly insulated wall assemblies when subjected to real exterior climate of Ottawa, ON for a two (2) year period; from 2017 to 2019. The long term performance of the wall assemblies was characterized by determining the change in performance of the wall for two metrics: 1. the thermal resistance of the wall assembly, and 2. the long term moisture accumulation. This section describes the methods by which the in situ thermal resistance was determined, and the uncertainty associated with the calculation method.

3.1. Thermal resistance calculation method (ASTM C1155)

The in situ experimental thermal resistance for each wall assembly was determined from the experimental results, following the summation method described in ASTM C1155. This method determines the thermal resistance by determining the summated average hourly temperature difference across the wall assembly divided by the summated average hourly heat flux measured for each wall assembly. The equation of this summated approach is given in (1.

$$RSI = \frac{\sum \Delta T}{\sum q} \tag{1}$$

Where:

RSI – is the thermal resistance in SI units [m^2K/W]
ΔT – is the temperature difference across the wall assembly [°K]
q – is the heat flux [W/m^2]

In addition this method also specifies a convergence factor, to determine over how many values the summation should occur. The convergence criteria equation is given in (3. It is also noted that the calculation method should occur for no less than 24 hours of data.

$$CR_n = \frac{RSI(t) - RSI(t-n)}{RSI(t)} \tag{2}$$

Where:

CR_n – is the convergence value for each hour (CR_n<0.10 to meet convergence criteria)
$RSI(t)$ – is the thermal resistance at the current time step
$RSI(t-n)$ – is the thermal resistance at the previous n time step (n=12 hours)

As discussed previously, the purpose of this analysis was to determine the potential decrease in thermal resistance of the wall assembly by comparing calculated values from 2017 to those in 2019. To do this, the thermal resistance was calculated for two (2) cold months (to ensure larger heat flux and temperature difference values), specifically January and February, in both 2017 and 2019. The corresponding calculated values, accounting for uncertainty are described in the results section.

It should be noted that the ASTM C1155 method describes the use of ASTM C1046 for instrumentation locations in the in situ experiments, which ensures that heat flux is accounted for in all components of the wall assembly, thereby the thermal resistance calculated using ASTM C1155 accounts for heat transfer through various components of differing heat transfer properties (i.e. thermal bridges, centre of stud cavity, etc.). However, characterization of these various components was not captured in these experiments, due to lack of instrumentation availability in the DAQ units. As described in the Instrumentation location section, the heat flux transducers were installed in the centre of the wall assembly, far away from thermal bridges. As such, the values calculated in this paper represent the ideal thermal resistance values, and likely overestimate the true thermal resistance of wall assemblies.

3.2. Uncertainty Analysis

The uncertainty analysis for the experiments was determined as the uncertainty in the calculated experimental thermal resistance, as given in (1, using the uncertainty analysis method by Kline and McClintock, given in (3.

$$W_{RSI} = \left[\left(\frac{1}{q}\right)^2 (\Delta T_{\text{unc}})^2 + \left(-\frac{\Delta T}{q^2}\right)^2 (q_{\text{unc}})^2\right]^{0.5} \quad (3)$$

Where:

W_{RSI} – is the thermal resistance uncertainty in RSI units (+/-), [m^2K/W]
ΔT_{unc} – is the uncertainty value for temperature difference [K]
q_{unc} – is the uncertainty value for the heat flux [W/m^2]

The uncertainty was determined using the uncertainty values associated with the thermocouples and heat flow sensors, which were used to determine the temperature difference and heat flux respectively, during the experiments.

The uncertainty of the thermocouples was +/-0.5 °C. Hence, the measurement uncertainty in the temperature difference (ΔT_{unc}) was 1 °C. The heat flow sensors (HFS) were calibrated before being used in the wall assemblies. The sensors were inserted between two medium density glass fiber specimens and characterized in a heat flow meter. An average uncertainty of 2.5 percent of the reading data was observed for the HFSs. Therefore the uncertainty in the heat flow sensors was determined as the average measured heat flux, multiplied by the heat flow sensor uncertainty ($q_{\text{unc}} = q * 0.0025$).

Using these values the experimental uncertainty for the calculated thermal resistance was determined as an average of +/-3.9% for the experiments.

4. Comparison of Original vs. Long Term Exposure Results

The experiment data was analyzed to determine the effects of long term exposure of the wall assemblies for both long term moisture accumulation, a thermal resistance. Changes in these values could indicate risk to durability (moisture) or risk to increased energy costs (thermal resistance) of the building envelope during its service life. The results analysis for the thermal resistance calculations, and the moisture performance are presented in the following sections.

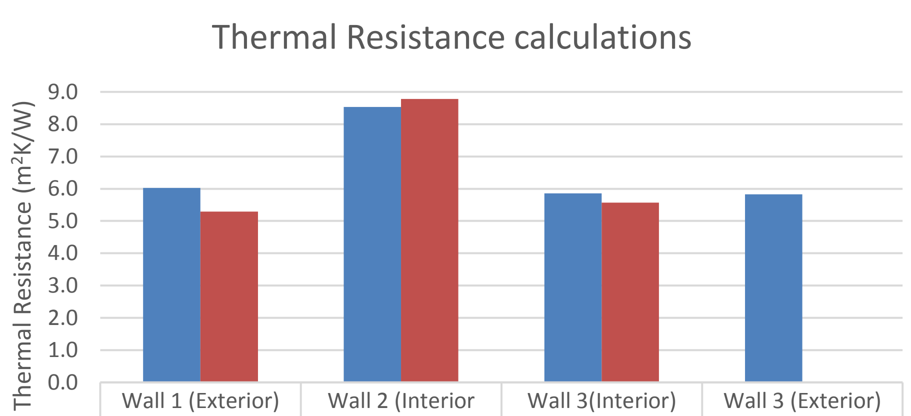
4.1. Thermal resistance comparison: 2017 to 2019

As discussed previously, the long term field experiment results were used to determine the thermal resistance of the wall assembly for 2017 and 2019. The analysis was completed over two (2) months in each year, January and February, following the summation calculation procedure detailed in ASTM C1155 previously described in this paper.

To complete the thermal resistance calculation method requires data from a heat flux transducer located in a shielded location of the wall assembly, and two temperature sensors, one located on the interior surface of the wall assembly, and one located on the exterior of the wall assembly. For Wall 2 and Wall 3, the interior most heat flux sensor was used in the calculation method, located on the exterior surface of the gypsum sheathing board. For Wall 1 2017 results, the exterior heat flux transducer was used in the calculation method for comparison because the interior heat flux sensor malfunctioned during the analysis period.

The interior temperature was taken from the interior surface of the gypsum sheathing board, located at the centre line of the stud cavity at the mid-height of the wall (i.e. equidistant from both stud locations). The exterior temperature was taken from the interface surface between the wall assembly and the furred airspace. For Wall 1 and Wall 3, the exterior temperature used in the calculations was the exterior surface of the XPS, at the centre of the stud cavity. For Wall 2, the exterior temperature used in the calculations was the exterior surface of the sheathing membrane. The reason the exterior temperature was taken as the surface in contact with the furred airspace, instead of the most exterior surface (exterior surface of the vinyl cladding) was to remove the effect of solar and night time radiation on the exterior temperature measurement in the calculations.

The comparison results of the calculated thermal resistance from 2017 and 2019 for each wall assembly is presented in Figure 5.



	Wall 1 (Exterior)	Wall 2 (Interior	Wall 3(Interior)	Wall 3 (Exterior)
2017	6.0	8.5	5.9	5.8
2019	5.3	8.8	5.6	

Figure 5: Thermal resistance comparison for each wall assembly from 2017 to 2019.

The results presented in Figure 5 show comparison results for: Wall 1, using the exterior heat flux transducer; Wall 2, using the interior heat flux transducer; and, Wall 3, using both the interior and exterior heat flux transducers. The reason the results for Wall 3 include both the results for both the interior and the exterior heat flux transducers is to determine the validity of having to use the exterior heat flux transducers for Wall 1.

To check the validity of using the exterior heat flux sensor in the Wall 1 calculations, the thermal resistance values for the exterior heat flux sensor location are compared for 2017 between Wall 1 and Wall 3, to the thermal resistance values of the interior sensor for Wall 3. The reason these two walls are compared is due to their similarity in construction, which should lead to extremely similar thermal resistance results between walls; additionally, if there are aging effect differences between both wall assemblies, these should be minimal in 2017 values.

Comparing the results indicates that in 2017, the thermal resistance of Wall 1 and Wall 3 using the exterior heat flux sensors was 6.0 and 5.8, respectively, compared to the interior heat flux sensor in Wall 3, which resulted in a thermal resistance of 5.9. The difference in these results is negligible, indicating that using the exterior heat flux sensor to characterize Wall 1 is valid.

Further analyzing the results presented in Figure 5 also demonstrates the performance of the wall assemblies over time. Wall 1 shows the most significant change in the thermal resistance, with a decrease from 6.0 in 2017 to 5.3 in 2019, a reduction of ~12%. Following that, Wall 3 results indicate a slight decrease in thermal resistance from 5.9 to 5.3, a reduction of ~5%.

Wall 2 results indicate that the wall increases in thermal resistance from 2017 to 2019, from 8.5 to 8.8, respectively. However, this increase is attributable to the uncertainty in the measurements and calculation method, as the increase is less than less than 3%.

The results for Wall 1 indicate that a significant decrease (i.e a decrease in excess of the uncertainty in the experiment results) in the thermal resistance has occurred. The likely reason for this decrease is a combination of material aging (which could be combination of potential off gassing of the XPS and/or settling of the glass fibre insulation) and the potential for increased moisture contents of the components.

The results for Wall 3 indicate that a slight decrease in thermal resistance has occurred, however the decrease is just within the uncertainty of the experiments. If this decrease is significant, it is again most likely due to the same reasons as Wall 1. Due to the similarity of Wall 1 and Wall 3, one might expect that the decrease in thermal resistance would be similar in the two walls. However, there is one significant difference between the constructions, which is that the OSB sheathing board is located in an exterior layer in Wall 1 (between the studs and the XPS) and interior location in Wall 3 (between the gypsum sheathing board and the studs). Having the OSB located in an interior location in Wall 3 means it should be subject to less moisture and temperature cycling effects vs. the OSB in Wall 1, which could explain the difference in thermal resistance decrease between Wall 1 and Wall 3.

4.2. Water Vapor Condensation Comparison: 2016 to 2019

Temperature and relative humidity for walls 1, 2 and 3 for years 2016 and 2019 are shown in Figure 6, Figure 7 and Figure 8, respectively. The location of the temperature and relative humidity sensors for which values are provided in the figures are shown in the diagram adjacent to the plots.

For both years, 2016 and 2019, the daily fluctuations in temperature of both the exterior surface of the thermal insulation as well as the interior dew point temperature are superimposed on the seasonal variations.

For 2016 period, it can be generalized for all three types of walls tested, that the temperature at the interior surface of the respective sheathing panels gradually rises from below -10°C in winter to upwards of 35°C in summer. The temperature runs in 2019, reach similar values; however, the increase in temperatures was gradual as compared to the immediate rise in 2016.

The relative humidity (RH) at the interior surface of the respective sheathing panels varies between 30% and 60% RH for all specimens for both years. The corresponding temperatures at this same location were quite low, reaching -10°. As such, the risk to the formation of condensation in winter conditions was high. On the other hand, the potential for condensation to evaporate in summer is also significant.

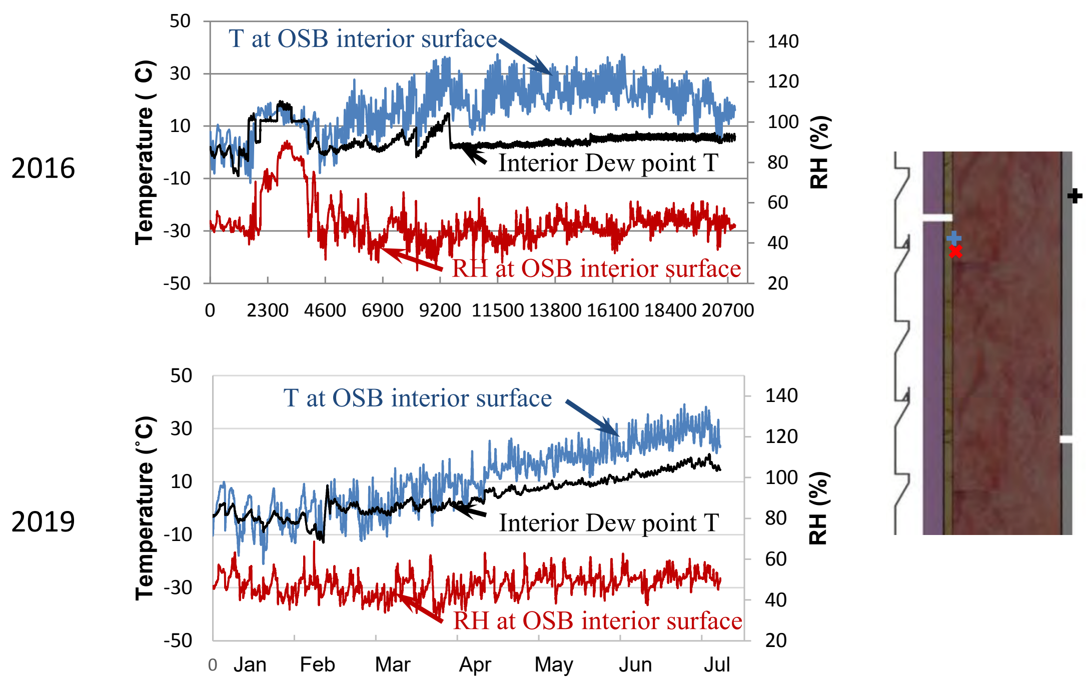


Figure 6. Comparison of 2016 and 2019 responses of the Wall 1 (temperature and RH on interior side of the OSB and internal surface temperature)

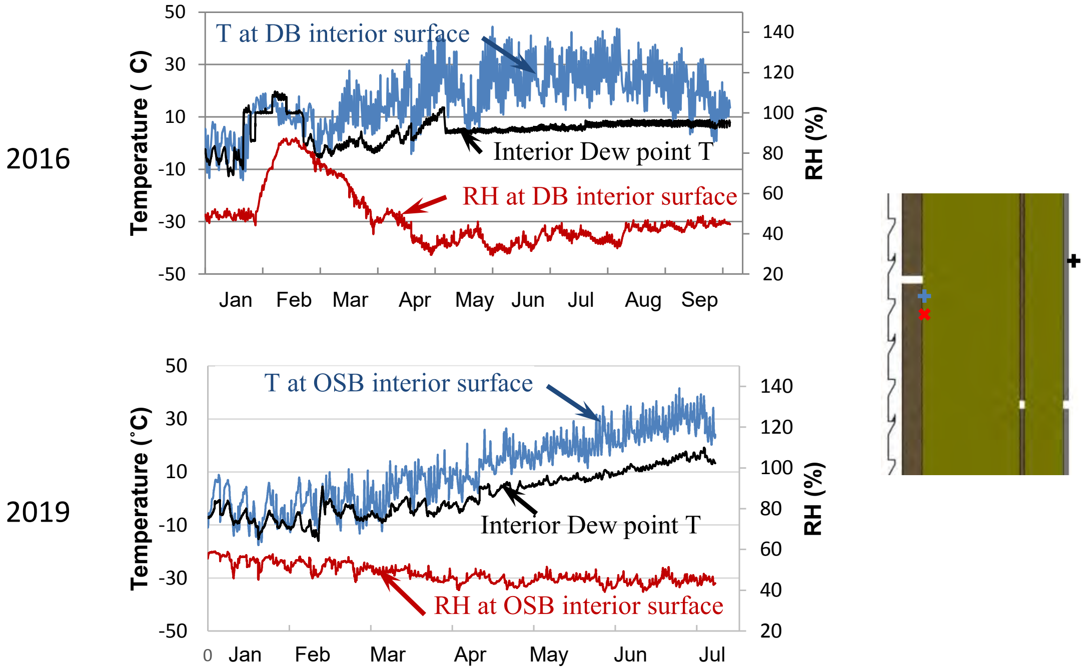


Figure 7. Comparison of 2016 and 2019 responses of the Wall 2 (temperature and RH on interior side of the wood fiber based diffusion board and internal surface temperature)

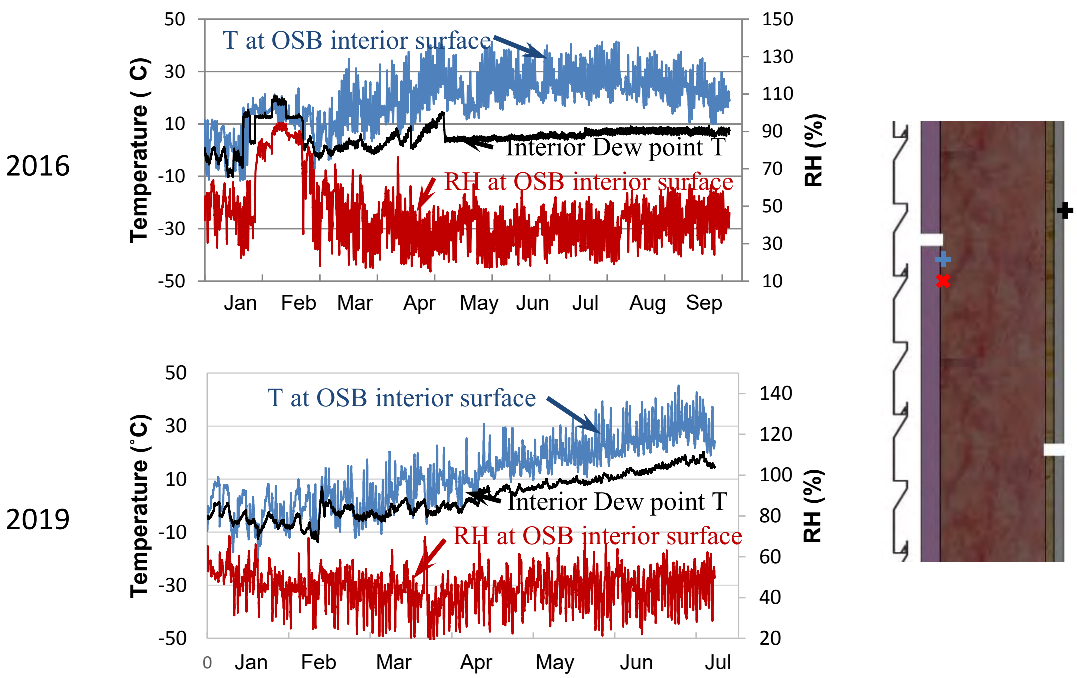


Figure 8. Comparison of 2016 and 2019 responses of the Wall 3 (temperature and RH on interior side of the XPS insulation and internal surface temperature)

4.3. Moisture content comparison: 2016 to 2019

Figure 9 shows the moisture content results for one of the adhered tapes located in the air cavity behind the exterior cladding. Both diagrams, 7a) summer 2016 and 7b) summer 2019 show intermittent moisture presence presented by electrical resistance decrease depicted by the red line.

There is one more tape sensor that recorded a presence of moisture. Both sensors were located towards exterior side, inside the air cavity behind the vinyl cladding. The moisture presence corresponds to the rain events in Ottawa. The surface dries out within several hours after each rain event. This indicates that there is a local imperfection in the vinyl cladding causing slight rain water breach, however moisture does not penetrate inside the assemblies. All remaining tape sensors showed no decrease in electrical resistance, hence no liquid moisture presence inside the assemblies of all three specimens.

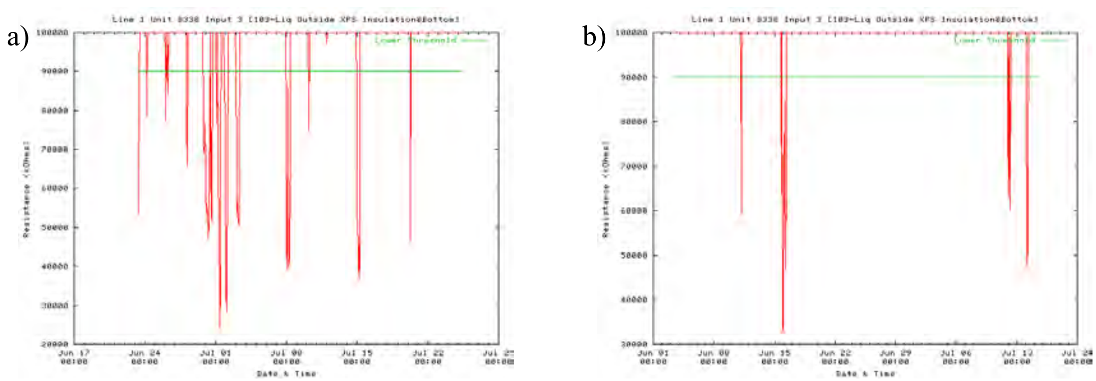


Figure 9. Example of data for moisture detecting tape inside air cavity showing intermittent moisture presence corresponding to the rain events in Ottawa, ON a) July 2016, b) July 2019

5. Conclusions and Future Work

The R values of all three specimens after 3 years of exposure remain reasonably high. The two specimens containing the XPS insulation layer (W1 and W3) registered 12% and 5% R-value decrease respectively. However, based on the analysis completed in this report, it is not possible to determine the cause of this decrease in thermal resistance. The most likely conclusion is that the change is due to increased moisture in the OSB sheathing board. The R value of the W2 specimen increased slightly.

Moisture performance of all three walls showed slight possibility of the moisture condensation within assemblies in winters but large capacity to dry out in warmer conditions. Moreover, the moisture detection tapes did not record any moisture content at any locations within the all three assemblies.

The only location where the presence of water was detected was inside the air cavity behind exterior cladding. These moisture occurrences were corresponding to rain events in Ottawa and the moisture evaporated promptly.

At this date, the data is still being collected. In the future, when the specimens will be decommissioned:

1) All new data will be processed in similar fashion.
2) An air leakage test will be carried out to verify changes in the airtightness performance.
3) Subsequently, the specimens will be visually reviewed for moisture presence, mold growth and overall material integrity status to determine if any long term durability effects have taken place.

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Panelized Multifamily Passive House: Less Cost & More Profit Than Code

Paul Grahovac, Vice President Business Development & General Counsel
Build SMART, LLC, 3701 Greenway Circle, Lawrence, KS 66046, 785-830-7355,
paul.grahovac@BuildSMARTna.com

ABSTRACT

Passive House panelized multifamily whole-building air tightness case study. Passive House certified wall panels with factory-installed Passive House certified windows have been causing houses and apartment buildings constructed with them to surpass Passive House air tightness requirements on the very first blower-door effort with no leak chasing. For one of these instances, a single blower door unit with a single fan was used to pressurize and test an apartment building of 52,781sqft in a single whole-building test. The architect-contractor design-build developers of the system attribute the air tightness performance to the fluid-applied detailing materials that are used to line the rough opening and secure the window to the lined rough opening as well as to the fluid-applied material used to seal the panels at the floor, the top, and to each other. No tapes or self-adhered membranes are used. The Passive House energy performance on the Affordable Housing project resulted in a $300,000 increase in mortgage funding and a $300,000 increase in developer fees – the non-profit developer says this allows them to build more Affordable Housing. Financial projections hypothesizing the same structure built for the unsubsidized market to code-only standards and for comparison to Passive House show private-sector developers can increase their cash flow (income after debt service which includes the added cost of Passive House construction) significantly by building to Passive House and paying tenant utilities. The payback period is less than a third than for blue-chip stocks and occurs without stock-market risk. If the speed of panelized construction is accounted for along with avoiding the customary 20-year window replacement because of the high quality of Passive House windows, the payback goes to 4.92 years.

INTRODUCTION

THE AS-BUILT PROJECT

The Whitehall is a 49-unit three-story apartment building in Spring City, PA near Philadelphia.[1] See Figure 1.

Figure 1 The Whitehall apartment building (Mission First, 2018)

At the 2017 New Gravity Housing Conference of the Philadelphia area US Green Building Council (Delaware Valley), the Whitehall project developer, architect, Passive House consultant and the external wall-panel vendor gave a presentation called "The Whitehall" which disclosed the "Final Drywall Blower Door Test" result of 0.42ACH50. See Figure 2.

Figure 2 Disclosure of blower-door test results
Passive House consultant Tim McDonald displaying test results

This result is below the Passive House Institute maximum allowable of 0.6ACH50 (Air Changes Per Hour at 50 Pascals of pressure). (Passive House Institute US, 2018.) The building was tested at shell completion, post-MEP penetrations, and final. In all three instances a single blower-door unit with a single fan was used to test the entire building at once, and in each instance, the result was lower than the maximum allowed for Passive House. There was no leak-chasing to achieve any of the results.

THE PANELIZED WALL ASSEMBLY DESIGN

The exterior walls were provided by prefabricated 2x6" Passive House certified stud-wall panels featuring:

- Oriented Strand Board (OSB) sheathing (within-panel seams, panel-to-panel connections, and panel-to-floor / panel-to-top plate connections sealed with Silyl-Terminated Polymer (STP) joint and seam filler),
- 3.5" Expanded Polystyrene (EPS) rigid foam insulation laminated to the OSB,
- OSB (with OSB manufacturer-laminated water-resistive barrier) laminated to outer face of the EPS,
- Rough openings lined with fluid-applied STP flashing, and
- Passive House certified windows factory installed and air-tightened using STP sealant.

The complete plans and specifications are available online. (Caldwell, Heckles & Egan. 2018.)

DEVELOPER SATISFACTION

At the environmental conference in Philadelphia (Delaware Valley Green Building Council 2017 New Gravity Housing Conference), the Whitehall non-profit developer provided slides relating to increased net income and fees on their project stating:

- "Passive House Makes us Money!!"
- "Passive House lets you borrow/leverage more money to build more housing"

  [Increase from $800,000 to $1,100,000]

- "Higher net fees mean we can house more people"

  [Increase from $1,000,000 to $1,300,000]

ENERGY MODELING

Passive House energy modeling and consulting for the project was performed by Certified Passive House Consultant Tim McDonald RA, CPHC, LEED AP. The Excel file containing the Passive House Planning Package modeling was provided to Paul Grahovac (co-author of this paper) who in turn provided it to Certified Passive House Consultant Skylar Swinford, energy and enclosure consultant at Energy Systems Consultants, who modeled The Whitehall project as if it were built to Passive House performance standards in Kansas City, and, alternatively, built merely to code standards there. Mr. Swinford estimated the code air changes per hour at 7.0ACH50 based on his field experience.

The Kansas City modeling showed that the HVAC kilowatt hours (kWh) for the code case to be 617,760 kWh with the Passive House case at 41,098 kWh.

PASSIVE HOUSE PANELIZED CONSTRUCTION COST

The company providing the exterior wall panels for Whitehall estimated that the additional cost of Passive House construction versus stick-building to code at approximately $292,297 which includes these costs:

- wall panels and windows,
- slab and footing insulation,
- energy heel truss,
- additional attic insulation,
- exterior insulation panels for energy heel truss, and
- OSB ceiling lid for long-term durable ceiling air barrier performance.

This was estimated to be an approximately 3.76% increase in overall construction costs.

CALCULATIONS

The wall-panel company interviewed three high-energy performance multifamily real estate developers who said they paid or planned to pay their tenants' utilities. One of them indicated they determined their rental charge by adding the market value of the space to an amount the tenant would pay for utilities if they lived in energy-inefficient premises rather than the energy-efficient structure.

The calculations below compare the net income of hypothetical owner A (who stick-builds to code and does not pay tenant utilities) to hypothetical owner B who builds to Passive House, pays tenant utilities, and determines their rental charge by adding the market value of the space to an amount the tenant would pay for utilities if they lived in energy-inefficient premises rather than the energy-efficient structure.

TABLE 1 A REVENUE COMPARISON OF PASSIVE HOUSE VS. CODE CONSTRUCTION FOR A KANSAS CITY MARKET-RATE MULTIFAMILY PROJECT

Code-compliant building cost: $7,783,196
Passive House building cost: $8,075,493
Cost difference (investment): $292,297
Percent cost increase: 3.76%

49-UNIT APARTMENT BUILDING: ANNUAL REVENUE

	Builds to code	Builds to Passive House & pays tenant power bill	HVAC electricity use common areas	HVAC electricity use living units	Tenant rent	Tenant total cost	Owner net revenue	Passive House net revenue increase
Apt. Bldng. Owner A	x		113,250 kWH $12,344	299,685 kWh $32,666	$588,000	$620,666	$575,656	0.00
Apt. Bldng. Owner B		x	9,513kWh $1,037	25,225 kWh $2,750	$620,666	$620,666	$616,879	$41,223

Assumes all-electric Heating, Ventilation, and Air Conditioning (HVAC). kWh cost is KCK average $0.109/kWh. (Electricity Local, 2018.)
Total conditioned area: 41,259sqft. Common area: 11,325sqft.

THE SENIOR LIVING CASE (SAME RESULT AS MULTIFAMILY ABOVE)

	Builds to code	Builds to Passive House	HVAC electricity use common areas	HVAC electricity use living units	Tenant rent	Tenant total cost	Owner net revenue	Passive House net revenue increase
Senior Living Bldng. Owner A	x		113,250 kWH $12,344	299,685 kWh $32,666	$620,666	$620,666	$575,656	0.00
Senior Living. Bldng. Owner B		x	9,513kWh $1,037	25,225 kWh $2,750	$620,666	$620,666	$616,879	$41,223

Assumes all-electric Heating, Ventilation, and Air Conditioning (HVAC). kWh cost is KCK average $0.109/kWh.
Total conditioned area: 41,259sqft.

TABLE 2 49-UNIT APARTMENT BUILDING: PASSIVE HOUSE ANNUAL NET CASH FLOW

Moving from left to right, each case assumes the previous case is adopted.

Case→	Base case. See previous chart.	HVAC capital expense savings $120,000	Fixed windows[1] $34,250	Construction loan interest decrease $42,400	Contractor overhead[2] $161,510	Rents start sooner $102,814	20-year window replacement avoided[3] $456,500 Present Value $208,340
Net annual cash flow	$27,190	$32,951	$34,596	$36,631	$44,385	$49,321	$59,323
Years to Payback	10.75	8.80	8.44	7.97	6.59	5.92	4.92

[1] Operable windows in bedrooms retained. Fixed windows lower maintenance costs and reduce falling risks.
[2] Owner captures in contract negotiations or bidding process.
[3] State affordable housing manuals and most experts maintain windows should be replaced every 20 years. Passive House certified windows are of exceptional quality, have a 20-year warranty, and are expected to last the life of the building.

FINAL FINANCIAL CONCLUSIONS.

1. $100 per month per unit cash flow increase during 5-year payback

2. $120 per month per unit cash flow increase after 5-year payback

3. $73,356 total annual cash flow increase after 5-year payback

4. Panelized Passive House reduces building cost by $377,017 compared to code (4.8% decrease)

5. If the overall building construction cost reduction rather than the cash flow increase is used to offset the Passive House upgrade cost, the payback is completed when the construction is completed. The portion solely due to accelerated construction is sufficient for this purpose. The reduced HVAC capital expense and the present value of avoiding the 20-year window replacement cycle further reduce project cost.

TABLE 2 BACKGROUND INFORMATION

Table 2 shows the increased income after consideration of the additional revenue from energy savings and the additional cost of the mortgage payment attributable to the additional cost of the Passive House energy efficient construction. The "Net annual cash flow" attributable to Passive House construction and energy savings was calculated using an Excel spreadsheet created by a bank multifamily housing lending manager. Various construction cost savings amounts are used to reduce the construction cost in the calculation.

HVAC FIRST-COST SAVINGS

"Some developers even report a negative cost premium for passive building since the high-performance enclosure allows for the reduction in mechanical system size and equipment, thereby reducing both first costs and operational expenses for the life of the building." (Passive House Institute US, 2018.) For this 49-unit case study example, the first-cost savings have been estimated at 30% after accounting both for the reduction in heating and cooling equipment cost and the addition of energy recovery ventilation cost. Our thanks for this go to Barry Dicker of Decent Energy, Inc.

SPEED MATTERS

Bruce Anderson, the owner of Insulated Concrete Form company Polycrete USA, who is also an accountant, wrote a guest editorial entitled "Speed Matters" in a leading ICF publication. (Anderson, 2016 Bruce.) In that piece, Anderson explains that accelerated construction reduces construction loan interest, brings in rent sooner, reduces overhead, and increases profits.

Applying that to the Whitehall case study, we assume a projected ten-month construction schedule based on conventional stick-building rather than use of prefabricated panels.

Based on the reduction in field wall assembly construction hours, we have calculated a two-month reduction in the construction schedule from ten months to eight months. The National Association of Home Builders reports prefabrication acceleration of 2.5 homes to 1 which proportion supports a two-month reduction in a ten-month schedule. (National Association of Home Builders, 2016.)

Further support on accelerated construction comes from the National Conference of State Housing Agencies: "Breakthroughs in modular and prefabrication techniques can now cut construction times in half and shave up to 20 percent from development costs, according to research from the Terner Center for Housing Innovation."
(National Conference of State Housing Agencies, 2018.)

The two-month reduction does not take into account the time saved by avoiding weather delays and reduced waste management. In the report cited above, the National Association of Home Builders calculates that prefabrication results in 30 times less waste.

The faster comparative speed of wall assembly erection after the foundation is prepared and which is discussed above is only one of two elements of construction acceleration provided by panelization. The other is the concurrent construction of the wall assembly while the site is prepared and the foundation constructed. Normally, construction of the wall assembly cannot begin until the foundation is laid. So, not only do the walls go up quicker after the foundation work, but also the time necessary for mobilizations and transitions relating to field construction of the wall assembly layers and the window installations is saved. This time savings is not quantified in this paper.

SPEED -- CONSTRUCTION LOAN

The interest on the construction loan of $8,075,493 is calculated to be $212,000. With a ten-month duration, the monthly interest is $21,200. Ten months is reduced to eight months, so project cost is reduced by $42,400.

SPEED -- SOONER RENTS

The estimated annual revenue after paying HVAC utilities is $616,879 which yields a monthly revenue of $51,407. The project cost is accordingly reduced by the amount of two months' rent which is $102,814.

Steve Bliss is the Founding Editor of BuildingAdvisor.com, and he was Editorial Director of The Journal of Light Construction for 16 years. In a BuildingAdvisor.com article, he addressed contractor accounting. (Bliss, Steve, 2018.) Bliss explained that "10 and 10" for 10% overhead and 10% profit is sometimes referenced in the industry and has been borne out by a National Association of Home Builders study.[9]

SPEED – REDUCED OVERHEAD

Starting with $8,075,493 in contractor revenue, a 10% overhead of $807,549 is calculated. Dividing this by 10 months yields a monthly overhead of $80,755.
Two months overhead saved is $161,510, so the project cost is reduced by that amount. (We depart from the financial concepts provided by the Anderson and Bliss articles here by not including a project cost reduction of $161,510 corresponding to profit that would be a windfall to the contractor, so that we present a worst-case scenario where the owner is not able to negotiate the profit away from the contractor.)

WINDOW REPLACEMENT AVOIDANCE.

The original formulations of the fluid-applied window rough opening flashing, joint and seam filler, and window installation sealant used in the panel prefabrication and installation were developed by Tatley-Grund Building Repair Specialists, Inc. of Seattle, Washington. Company President Stacey Grund has evaluated the Passive House Certified windows used in the wall panels and opined that because of their high quality, buildings using them will be able to save $456,500 by avoiding the customary 20-year window replacement that is also typically referenced in the architectural manuals of State Affordable Housing agencies. After present-value adjustment, the project cost is reduced by $208,159.

TENANT AMENITIES

Passive House tenants enjoy a 50% reduction in urban noise exposure (Tree Hugger, 2018), and their living space is continuously infused with abundant, fresh, virtually allergen-free air. (Herron, David, 2018.)

CONCLUSION

Cost-effective panelized Passive House building shell construction has been demonstrated along with operational profitability. Specific outcomes include: panelization of a Passive House wall assembly, a successful blower-door test without leak chasing, a satisfied developer who increased their income and ability to provide housing, code versus Passive House energy modeling, identification of Passive House upgrade costs, identification of accelerated construction and building cost reductions, and increased operating income and cash flow.

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The Mycorrho-grid: A Blockchain-based Mycorrhizal Model for Smart Solar Microgrids

Z.M.I. Gould[1], S.D. Day[2], G. Reichard[3], I. Dimobi[4], and A. Choudhry[5]

[1] Graduate Research Assistant, Building Construction, Virginia Tech, Bishop-Favrao Hall - 1345 Perry St, Blacksburg, VA 24061. +1 (860) 944-6829, gould@vt.edu.
[2] Professor, Faculty of Forestry, The University of British Columbia, Forest Sciences Centre, 2424 Main Mall, British Columbia, Vancouver, V6T 1Z4, Canada. +1 (604) 822-6652, susan.day@ubc.ca
[3] Associate Professor, Department of Building Construction, Virginia Tech, Bishop-Favrao Hall - 1345 Perry St, Blacksburg, VA 24061. +1 (540) 818-4603, reichard@vt.edu.
[4] Graduate Student, Electrical and Computer Engineering, Virginia Tech, Whittemore Hall -1185 Perry St, Blacksburg, VA 24061. +1 (678) 328-9501, ikdimobi@vt.edu.
[5] Graduate Research Assistant, Computer Science, Virginia Tech, McBryde Hall - 295 Stanger St, Blacksburg, VA 24061. +1 (540) 630-2222, aj07lfc@vt.edu.

ABSTRACT

The Mycorrho-grid is a blockchain-based microgrid inspired by the way trees collect and distribute resources through mycorrhizal networks in the forest. It was first developed in conjunction with Virginia Tech's grand-prize winning TreeHAUS entry in the 2019 Solar Decathlon Design Challenge and is expanded upon here with a focus on further potential for biologically inspired functionality. The baseline case as simulated in the competition is a 12-unit multi-family microgrid with a shared 50kW rooftop solar array and fixed price return from the grid. A framework derived from literature in mycorrhizal networks and the mathematical modeling of mycelial growth is developed to help transition the Mycorrho-grid from phyto-centric operation, where resources are exchanged based on the needs of the trees (energy producing and consuming households), to myco-centric operation, where resources are exchanged based on the needs of the fungal energy storage and distribution mechanism (local battery and centralized grid) with a larger environmental awareness. This transition helps introduce an element of altruism into the larger grid network that the authors believe could improve overall reliability in response to regular outages and resilience in response to major outages. Degrees of decentralization and their implications for the security and fault tolerance of critical infrastructure are discussed along with strategies for simulating the efficacy of a mycorrhizal dynamic pricing algorithm moving forward.

INTRODUCTION

With the proliferation of distributed energy resources (DERs), it is becoming critical to manage many different energy generators with intermittent power production on a connected network. This distributed generation not only allows for the integration of more sustainable power production through wind and solar, it also encourages energy self-sufficiency and awareness instead of dependence on centralized power from an unknown source. The simultaneous decentralization of computational architectures with distributed ledger technologies like blockchain presents an opportunity to assemble groups of prosumers (producers and consumers of electricity) into dynamic, self-sufficient networks. Implicit in this arrangement is an improved sense of autonomy on the local level, where communities can generate and control their own energy on smaller scales (Morstyn et al. 2018). In an increasingly connected world, it is also critical that the security of such networks is robust enough to stand up to bad actors attempting to hack critical infrastructure. The novelty and appeal of blockchain as it was initially conceived in the Bitcoin white paper (Nakamoto 2008) was in reaching consensus in a truly decentralized manner. Thus, blockchain protects against attacks on central hubs where taking out one node on the network could cripple an entire community's access to infrastructure, whether it be energy, water, or food. Many recent innovations and proposals have focused on semi-centralized approaches that hybridize the blockchain approach, privatize it, and impose a centralized hub or traditional database onto the platform (Wu et al. 2017). Volareo, a brand of smart speakers, has created a private blockchain-based alternative to products like Google Home and Amazon Alexa, but it still serves as a middleman in controlling devices in the Internet of Things (IoT). While this has its merits for practical implementation and economic gain, it threatens many of the benefits of the truly distributed information architecture initially proposed by Satoshi Nakamoto in 2008 (Lin et al. 2017).

Through millions of years of evolution, nature has already developed solutions to manage distributed energy generation and distribution. Trees and plants in the forest can be seen as the forest's equivalent of DERs, but they do not operate in isolation. Fungal mycorrhizal networks connect these biological DERs and facilitate the distribution of energy, water, and nutrients amongst themselves (Beiler et al. 2009). Some of the largest known organisms in the world, these networks connect autotrophic organisms such as trees and other photosynthetic plants in a forest and enable widespread resource exchange (Simard et al. 2012). The flow of energy resources through natural ecosystems have been studied and quantified by scientists such as Howard Odum since the middle of the 20th century. In his systems ecology framework, Odum defined information, not electricity, as the purest form of naturally occurring energy (Odum 2007). The proposed work seeks to integrate energy and information systems by applying a mycorrhizal model to inform the flow of electricity through decentralized collections of solar powered homes. Evolution solved this particular distributed energy problem through many iterations over time and through the introduction of symbiotic organisms acting as a fungal distribution grid. The authors believe that a learning algorithm with proper feedback parameters will allow microgrid smart contracts to derive an optimized solution to this same problem, but in the domain of electrical infrastructure.

BACKGROUND

The Brooklyn Microgrid (BMG) is one of the most well-known examples of blockchain applied to peer to peer (P2P) energy exchange in a microgrid (Mengelkamp 2018). LO3, the company behind BMG was one of the first groups to implement a transactive energy grid, where participant prosumers can actively sell energy amongst themselves (LO3 Energy 2017). Other projects in the blockchain-based energy domain include Austin, TX based Grid+ that recently released a hardware wallet with physical cards containing private keys that enable users to automate their energy purchasing decisions on a distributed ledger (Grid Plus, Inc. 2018). Both companies have faced extensive hurdles in tackling policy issues pertaining to legal interaction with their respective local utilities.

The main contribution of this paper is the application of a biological model to the distribution of power in a blockchain-based microgrid. This will enable the introduction of altruism to market-based mechanisms where individual agents may sacrifice their optimal performance for the long-term reliability and resilience of the network as a whole. Though many attempts have been made to apply lessons from nature to critical infrastructure such as wireless networks, none to the authors knowledge have taken inspiration directly from the formation of mycorrhizal networks, and none have dealt specifically with electrical microgrids. Mobile ad-hoc wireless networks have drawn upon trends in biomimicry to apply swarm theory in creating dynamic routing algorithms that minimize the number of nodes traveled in relaying messages and increasing the reliability of transportation and other network-based infrastructures (Harrabi et al. 2018). A basic principle in these networks is that any given node is only aware of its neighboring nodes (within feasible communication range) and not the entire system state which can span much larger distances. The more complex behavior and capabilities of the larger network is made up of relatively simple, repeated actions on the scale of individual nodes. This type of thinking has inspired wireless routing algorithms that derive function from termite swarm intelligence (Roth and Wicker 2003), beehive behavior (Çelik and Zengen 2018), ant colony pheromone exchange (Chandana and Thakur 2016), and fungal mycelial growth patterns (Hao et al. 2009).

Hao et al.'s FUNNet is of particular interest here and used as a starting point because the hyphae in fungal mycorrhizae also display similar patterns of growth. Also of direct interest is an example in the transportation domain, where researchers in Japan retraced optimally efficient transportation networks by letting a slime mold grow between bits of food placed on the map at locations of major Japanese cities (Tero et al. 2010). This work resulted in general guidelines for adaptive, bio-inspired networks including algorithms that allow for the reallocation of resources to areas of higher energy input. In general constructal theory and other biologically-inspired frameworks help determine form by optimizing the flow of some resource through space and time, whether it is cars through highway corridors, packets of information through wireless networks, blood through the veins and arteries of our bodies, or energy through distributed electrical networks (Bejan and Lorente 2008).

Mycorrhizal networks have been studied and modelled in various ways, both analytically and experimentally. The measurement of mycorrhizal transfer of carbon between different tree species using tracer ions was featured in Nature in 1997 (Simard et al. 1997). Beiler et al. made one of the most comprehensive attempts at identifying the network structure of mycorrhizal networks by tracing genotypes of fungi at different trees in a forested plot. They determined that mycorrhizal networks follow a highly interconnected small-world typology meaning that most nodes can be reached in a relatively small number of hops (Beiler et al. 2009). Other researchers have also used graph theory to define mycorrhizal network structure (Montesinos-Navarro et al. 2012). Further attempts have been made to model the growth patterns of mycelia in general (Falconer et al. 2005) and mycorrhizae specifically (Schnepf at el. 2008). Falconer et al.'s mycelial model directly inspired the work of FUNNet and will be examined further in this paper to inform environmentally-aware dynamic pricing algorithms in the Mycorrho-grid.

This paper is a further development of Virginia Tech's grand-prize winning TreeHAUS entry in the U.S. Department of Energy's 2019 Solar Decathlon Design Challenge. TreeHAUS as presented in the competition was a multi-family residential building consisting of three repeating clusters of four units. Each cluster included a diverse array of one-, two-, three-, and four-bedroom modular, prefabricated apartments that were designed to be joined on-site. The projected building location of the twelve collective units is in Blacksburg, Virginia, located in ASHRAE's mixed-humid Climate Zone 4A. The biologically inspired framework for energy exchange presented here would allow for the Mycorrho-grid to evolve to better reflect its initial mycorrhizal inspiration. Within this paper the authors demonstrate how a 'fungi-first', myco-centric perspective could create electrical symbiosis with integrated dynamic pricing that protects local battery life and encourages mitigation of peak demand events on the central grid. A presentation of various states of decentralization and the proposed value of reflecting the network structure of mycorrhizal networks in the energy domain is then discussed in further detail.

BASELINE MYCORRHO-GRID

Each of the twelve TreeHAUS units from the baseline case participate in sharing the power generated from a 50kW rooftop array. The energy is distributed amongst the units based on normalized heating and cooling loads. For example, the four-bedroom unit with more floor area and more exterior wall area will receive a higher percentage of generated energy compared to the two-bedroom unit with lower passive energy consumption to maintain standard temperature and humidity levels. At each timestep, starting with hourly intervals, a given unit's energy consumption is subtracted from their fair proportion of the solar energy produced by the rooftop array to arrive at a delta factor. This factor is distributed or charged as credit to each of the TreeHAUS tenants depending on whether they were net-producers or net-consumers during the previous hour. The credit or charge is recorded on a blockchain at each timestep and distributed as USD fiat-stable tokens (fixed one to one value with USD) worth the equivalent price of the electricity consumed or produced at that time.

Energy exchange is facilitated with the automated exchange of these tokens using smart contracts and a ranking algorithm. All tenants in the TreeHAUS are participants in an automated, hourly contest. Energy efficiency is incentivized by giving the highest net-producers the first chance to sell to their consuming neighbors at a rate just below retail, and the lowest net-consumers the first chance to buy this energy at the same lower rate. In the baseline case, the retail rate from the grid and the discounted rate for local energy exchange are fixed at 12 cents and six cents per kWh. respectively. When simulated in this manner using the EOSIO blockchain platform, the annual net energy distributed within the community was projected to be

18,894 kWh plus an additional 3802 kWh sold to the grid corresponding to a financial savings of $2789 (Choudhry et al. 2019). These simulations were completed using simulated data from the National Renewable Energy Lab's PVWatts tool for PV production, and the U.S. Department of Energy's OpenEI database for energy consumption. A mixture of high, low, and baseline energy values for the adjacent weather station at Blacksburg's airport (TMY3-724113) was adjusted for square footage and corrected for the appropriate electrical versus gas appliances to approximate consumption at the proposed TreeHAUS complex.

An important aspect of this design became the user interface. One of the main appeals of using a blockchain platform is to be able to implement smart contracts to automate the trading of ECOT tokens (the Mycorrho-grid's native cryptocurrency). No forecasting is required for a single or double auction process and can thus avoid the cognitive overload and inconvenience of tenants needing to constantly monitor their energy status. Instead, all functionality is integrated into multi-family residential web portals, which are commonly utilized for setting up autopayment of rent and logging of maintenance requests. Through this same interface it is projected that tenants could utilize their earned tokens to directly pay their monthly rent and other utility costs. See Figure 1 for an overview of the proposed Mycorrho-grid user experience. Its functionality includes paying rent directly with credit earned from solar energy, comparing unit by unit energy consumption, and displaying transparent breakdowns of hourly delta values and token distributions for each tenant. The image in Figure 1 was reproduced with permission from Arjun Choudhry et al. 2019, pending publication in the upcoming 2019 Cryptocurrency and Blockchain Technologies (CBT) conference proceedings in Luxembourg.

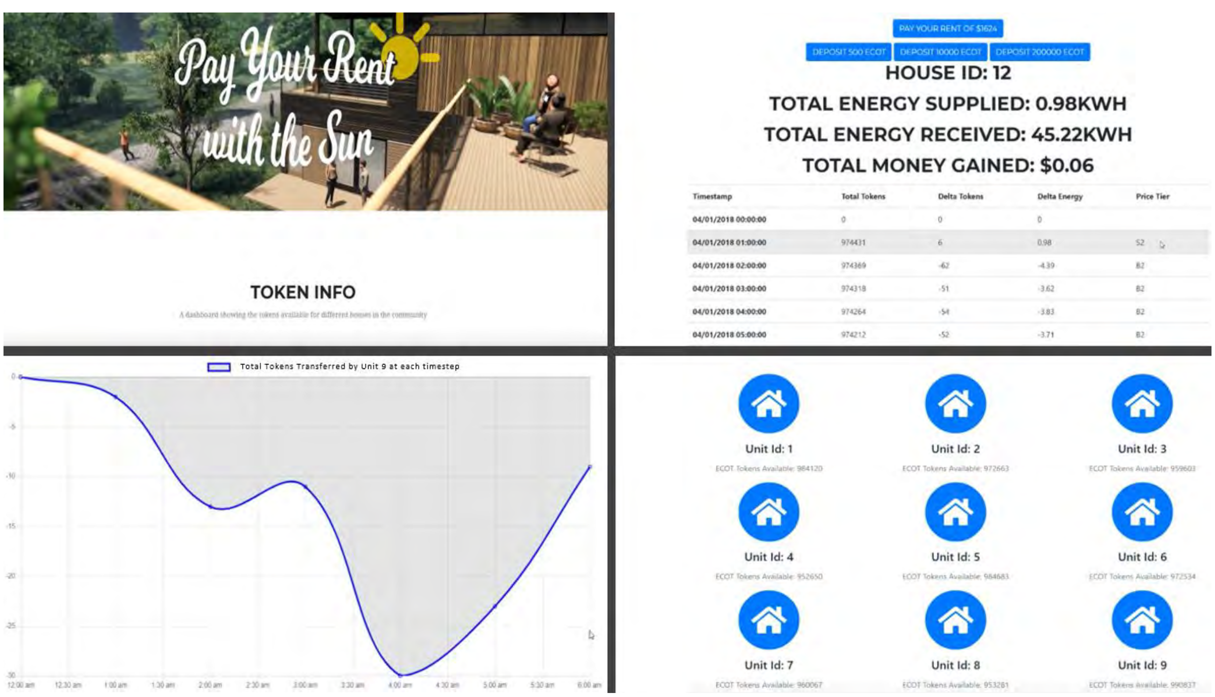

Figure 1. Web-based User Interface for the Mycorrho-grid designed to integrate into existing multi-family residential housing online portals.

PROPOSED MYCO-CENTRIC FRAMEWORK

Though the proposed baseline operation of the Mycorrho-grid performed quite well in simulations, it remained a static price model that did not encourage awareness of the surrounding environment in incentivizing certain energy behaviors. More specifically, incentives on the blockchain trading platform remain the same if the grid is experiencing a peak demand event, or if it has plenty of surplus energy available during a given time step. Additionally, the local battery reserve that stores on-site energy was not included in initial simulations which can be essential for reliability during outages. Part of the benefit of applying a mycorrhizal approach to the existing platform is to help increase this environmental awareness, as fungal networks actively respond and adapt to their environmental context to distribute energy and resources most efficiently.

One of the main divergences in the literature on mycorrhizal networks is the phyto-centric versus myco-centric perspective. In a phyto-centric perspective, autotrophs like trees and plants that produce their own energy and trade it through the fungal network control the flow of energy, nutrients and water in their own self-interest or that of their fellow plants. In a myco-centric perspective, the connected fungal organism is thought to dictate the terms of these resource flows. The baseline Mycorrho-grid model, with energy exchange dictated by energy production (photosynthesis) and consumption of the units (autotrophic metabolism) is decidedly phyto-centric in nature. The well-being of the 'living' conduit of fungal connections is not considered. The following is a proposed framework that could be implemented in the context of the Mycorrho-grid to increase contextual awareness of central grid-status and local battery health and to promote a more sustainable and symbiotic operation of the energy system.

Table 1. Network components mapped between fungal and electrical domains.

Fungal Network	**Electrical Network**
Insulated Biomass (Hyphae)	Connection between nodes i.e., wires/conduit
Mycorrhizal network	Entire connective network including central grid, microgrid, TreeHAUS building with PV production and local battery storage.
Non-insulated Biomass (Hyphal Tips)	battery interface with both resource (PV) and network connections (hyphae)
Mobile biomass	Energy in transit
Immobile biomass	Energy stored in batteries
Canopy (leaves)	Solar panels (PV)
Trees/plants (autotrophic organisms)	Households/units
Forest	Whole TreeHAUS multifamily building

To elucidate the biological analogy, different elements of the fungal and electrical networks have been correlated in Table 1. The foundation of these comparisons come from translating the established fungal infrastructure connections in FUNNet from wireless communications to energy domains (Hao et al. 2009). Additional elements come from the specific mycorrhizal growth model (Schnepf et al. 2008) and general terms from mycorrhizal physiology and forest ecology. A fundamental element of Falconer et al.'s fungal growth model is biomass recycling, or the reallocation of biomass from one part of the organism to another based on the surrounding environmental conditions (Falconer et al. 2005). In the presented mycorrhizal correlation, the biomass is energy, either stored locally, or in transit (being transacted). Insulated biomass is sheathed hyphae that serve mainly as conduit, and do not acquire additional nutrients or lose nutrients to the surrounding soil. Uninsulated biomass, on the other hand is correlated to the fungal interface with the autotrophic participants on the network, or the battery charge controller that decides how much energy from the PV gets stored locally (primary storage) versus sent to the larger grid (secondary storage).

Local Battery Life Consideration: In the initial Mycorrho-grid simulation, local battery storage has not been considered. For some of the energy to not be transacted with the local grid, at least one on-site battery would be required to hold energy within the network and meet local loads without triggering net-metering rates from the central grid. This battery's well-being is not considered in the current model, though it is of considerable importance in terms of operational sustainability and maintenance. In the myco-centric perspective, the longevity of the storage mechanism is prioritized over meeting the energy and financial needs of network participants. Battery longevity is often measured by the number of charge and discharge cycles expected before the battery's energy capacity is significantly decreased. The depth of discharge, temperature, and current flow are also important contributing factors to long term battery life and would also need to be included as parameters in the proposed algorithm.

Grid State Consideration: The market dynamics of the grid can be approximated with the wholesale market locational marginal pricing (LMP) model directly obtained from the PJM Interconnection (PJM) regional transmission organization database. These real time market prices reflect the current supply and demand dynamics as well as congestion and cost concerns on the central grid. Though current policies often prevent this type of dynamic pricing from filtering down to the residential level, using wholesale prices as an input parameter to the smart contract algorithm allows for consideration of the central grid's need for extra energy during peak demand events. This factor serves as an environmental indicator of the presence or absence of energy on the larger network, with the likelihood of selling back to the grid being higher when demand is high, and supply is low. The result of these adaptations to the baseline performance of the microgrid is a biologically informed dynamic pricing algorithm with feedback for consideration of local battery health and longevity.

Mycorrhizal Structure Consideration: Beyond pricing mechanisms to facilitate altruistic P2P energy exchange and increase grid awareness, the network structure of microgrids and of the larger grids is another opportunity to investigate how the evolution of mycorrhizal networks could possibly inform more reliable Mycorrho-grid operation. The superimposition of mycorrhizal structure from Beiler et al. in 2009 onto a simulated grid of distributed prosumers could test the hypothesis that these network structures have evolved to improve performance parameters over time. The networks are not completely decentralized as the more central ‘mother tree’ nodes have higher degrees of centrality, but they are small-world networks where every node can be reached in relatively few hops from every other node. Various degrees of decentralization could be tested as displayed in Figure 2, and then compared to the performance of a mycorrhizal network structure subject to the same environmental conditions. Stress testing for fault tolerance may reveal clues as to how to design efficient P2P microgrids with improved reliability (during shorter, regular outages) and resilience (during longer, extreme outages) even when hub nodes are wiped out.

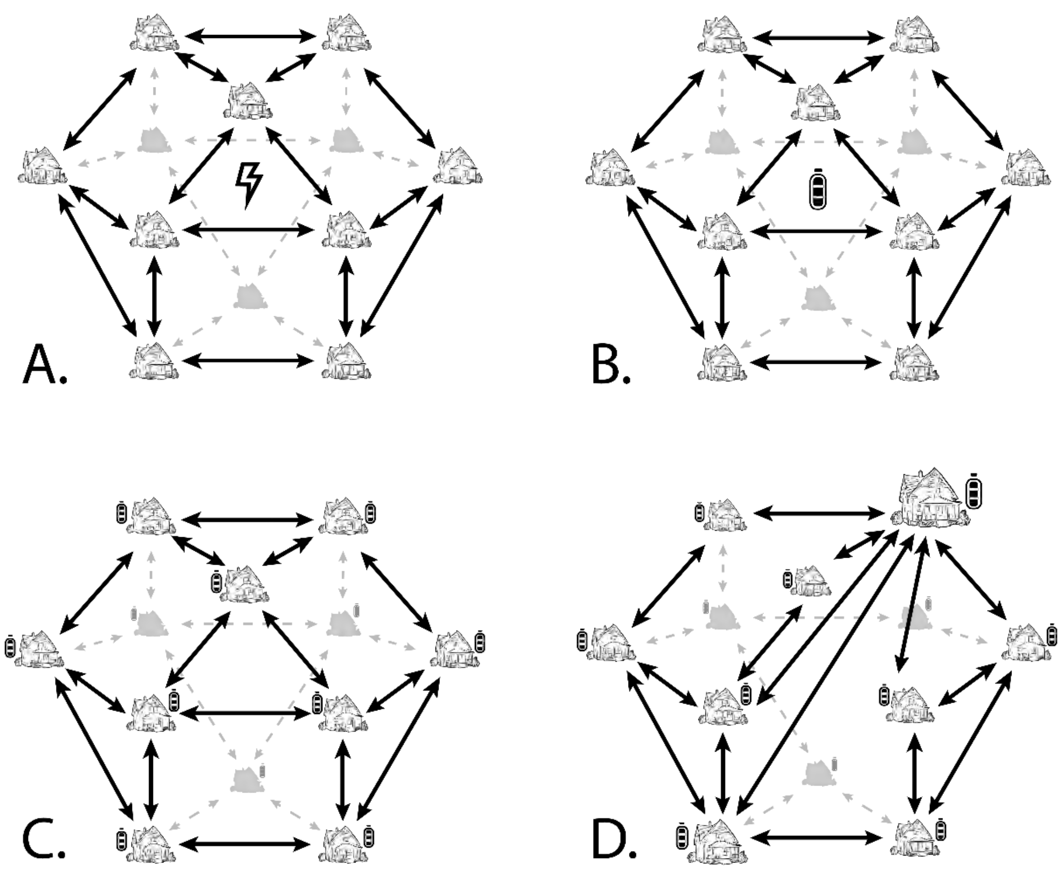

Figure 2. Degrees of decentralization for Mycorrho-grid simulation ranging from A.) Fully Centralized with each unit grid-tied and no local battery storage, B.) Locally Centralized with each unit connected directly to local battery storage, C.) Fully Decentralized with each unit having its own battery storage and an equal degree of centrality, and D.) Mycorrhizally Decentralized where each unit has its own battery storage but larger ‘mother tree’ hubs have higher degrees of centrality and reflect the small world structure of mycorrhizal networks as described in Beiler et al. 2009.

Quantifying the effect that these changes would have on the performance of a given grid are outside of the scope of this paper and will be saved for future work. The focus of this paper is to present the biological correlation as a framework and elucidate how the features of biological and ecological systems may map to electrical infrastructure in the Mycorrho-grid environment.

Discussion of Correlations

There are a couple of critical assumptions being made here related to energy flow in a physical environment. First, in order to implement the wireless routing algorithms of Hao et al. in the electricity domain it must be assumed that energy flows in a manner more like information than it does in actual, physical power systems. A second corollary to this is that batteries would charge much faster and more reliably than the current status quo, without sacrificing longevity. While physical conduit connections are not out of the question in the multi-family arrangement presented here, it becomes more questionable when houses physically further apart want to exchange actual electrons with neighbors in a Mycorrho-grid arrangement. The cost of running separate conduit in this case could outweigh the benefits of keeping transactions behind the meter, if policy in the area even allows implementation of this strategy. The prospect of safe, wireless power transfer at these higher rates and longer distances is not currently feasible but could be assumed in order to proceed with initial simulations.

In terms of testing the various degrees of decentralization presented in Figure 2, the sizes of various loads are not specified. Only the 'mother tree' hub and other nodes in the Mycorrhizally Decentralized case (D.) are shown as larger and smaller to reflect how connected they are to other units in the network. Beiler et al. group tree nodes into categories based on their diameter at breast height (DBH) and estimated age (2009). If larger, older trees are assumed to generate more energy, store more energy, and consumer more energy than their smaller, younger counterparts, then the various categories of simulated residential load profiles from the Department of Energy's OpenEI database (high, low, and baseline) could be mapped to various tree categories and assigned the same place in the network. As long as the larger load profiles also have larger solar panel arrays and larger battery banks, the analogy will hold true and will help to provide a reasonable translation between domains.

The importance of blockchain in allowing the Mycorrho-grid to run in a decentralized manner is critical to transparency and security. The use of blockchain-based distributed ledgers not only provides an immutable, accessible record and accountability for all exchanges of credit, but also prevents bad actors from easily altering systems states to steal money or manipulate critical infrastructure like the grid. Battery charging and discharging commands can be brought under the jurisdiction of the blockchain, requiring a percentage of the nodes to reach consensus before the platform sends any energy to the local battery or to the larger grid. The same can eventually be applied to toggling appliances on and off in an Internet of Things (IoT) controlled environment that could be integrated into demand side management (DSM) scenarios. Though the authors have not addressed the specific mechanisms through which this added security could be implemented in this paper, the data architecture of the Mycorrho-grid provides an important baseline in protecting more connected, critical infrastructures.

From a socio-economic perspective, decentralized solutions like blockchain could help promote energy solidarity in local economies in terms of instilling trust and incentivizing cooperation amongst neighbors (Yu 2018). Electrical utilities remain one of the most powerful and most connected industries in the modern U.S. democracy. Incredible amounts of money can get siphoned off in large government contracts, and the common people see little to no benefit (Nyang'Oro 2017). True energy reliability in many parts of the world is still unheard of, with restrictions in policy sometimes preventing small scale producers from selling excess energy back to a central grid, even when the extra power is desperately needed during peak demand events. Traditional energy distribution systems that rely on regulated utilities governing all aspects of supply and distribution exclude other participants, creating serious obstacles for experimentation in distributed models that could provide society with more energy security. The Brooklyn Microgrid and Grid+ have had to apply to become local utilities themselves just to interface with the existing entities and transact energy locally (Mengelkamp et al. 2018).

Conclusion and Future Work

In a myco-centric approach to energy management in a microgrid, the importance of battery life cannot be overlooked. Battery capacity remains a central challenge in many electronics industries, including but not limited to electric vehicles, consumer electronics, and solar energy storage. Shifting from a phyto-centric focus to a myco-centric focus helps to account for this critical limitation in system performance by considering the energy storage and distribution infrastructure as an organism with a will to survive and extend its own lifetime.

The diversification of load profiles is a critical element to the function of the Mycorrho-grid. If all units attached to the network produce and consume energy at the same time, it would be very difficult to foresee any improved performance from P2P energy trading. Just like biodiversity breeds resilience in natural ecosystems, the authors are of the opinion that load diversification in an infrastructural system will also provide for higher levels of resilience, especially in terms of providing access to stored energy during a longer, more extreme power outage. This applies not only to load type and magnitude, but also to the temporal diversity, more akin to Jane Jacobs' definition of schedule diversity from The Death and Life of Great American Cities creating safer communities in urban environments. This type of temporal diversity could be achieved by introducing a mix of industrial and commercial buildings to the initial residential units, or through automated scheduling and incentivization of load shifting coordinated through IoT.

Small-scale autonomous energy grids could pave an elegant, modular path toward full electrification and equity in energy systems, but first policy must catch up and governments must acknowledge that it is time to rethink our centralized approach to power. The next step in proving the value of this myco-centric approach and the fungal metaphor in power system policy is to simulate this adapted smart contract governed by the principals laid out in the preceding framework. The baseline static simulation including a fixed six cent return for selling energy back to the grid was imposed by local co-generation rates in Blacksburg, Virginia. In reality, the incentive is only offered to commercial entities and returns closer to three cents per kWh energy produced. In the next phase of this research, the grid will be assumed to be more progressive in addressing its own needs and incentivizing innovation in distributed generation techniques.

Future work includes testing these same ideas in different contexts and at different scales. Blacksburg, Virginia offers a unique opportunity to understand the dynamics of this type of microgrid and the benefits of a biologically inspired dynamic pricing algorithm in a rural, developed context, but there are many other areas where this model could apply. Highly developed urban areas and extremely rural developing regions are two examples of where the Mycorrho-grid could make the most difference in either providing relief to overloaded urban grids or providing a pathway to electrification of remote villages. Each of these contexts presents different challenges in terms of policies, existing infrastructure, surrounding supply and demand, and resource availability and cost. Ongoing research efforts may reveal what an operation like this could look like in Austin, Texas through the existing Pecan Street program, and in the Arusha region of Tanzania on a microgrid run by the Innovative Technology and Energy Center (iTEC) at the Nelson Mandela African Institution of Science and Technology (NM-AIST). The idea of biomass recycling for backup energy production could also be tested at different scales, from appliances in an IoT environment taking turns in demand side management to the recycling of organic waste streams through anaerobic digestion to generate back-up power.

Moving forward, new techniques and methods that have been developed and published recently present opportunities to expand upon this work, both in simulations and in real biological experiments. The max-flow complex network methodology in power systems to demonstrate security and bad-actor simulations to show the true security benefits of decentralization through distributed ledger platforms (Dwivedi and Yu 2013). Other fault tolerant energy distribution mechanisms could also be tested on the Mycorrho-grid to demonstrate how the system recovers when battery storage at a given node is suddenly wiped out (Prodan et al. 2015). The ultimate validation of this theoretical work lies in experimental measurement of resource flux at the root-mycorrhizae interface. Laser speckle contrast imaging has been utilized to visualize fluid flow in roots (Braga et al. 2009) and agricultural applications (Zdunek et al. 2014). As long as the interface of the root with the mycorrhizal fungi could be exposed, environmental conditions could be varied and corresponding flows at different connected plants could be estimated. The adaptation of mycorrhizal network topologies could be tested and compared to random network topologies, but quantification of the actual flux of carbon or other resources such as water and nutrients would enable a direct bio-inspired approach to the mycorrhizal distribution of energy, water, food, and information in the built environment.

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Message Design for Residential Energy Feedback

Wendell Grinton[1] and Frederick Paige, PhD[1]

[1]The Charles Edward Via Jr., Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 200 Patton Hall, 750 Drillfield Dr., Blacksburg, Virginia 24061, email: wgrinton@vt.edu

ABSTRACT

Humans are suboptimal components of building operations. Population growth and wasteful behavior require engineers to develop new approaches for meeting society's residential energy needs. Energy feedback messaging is an emerging socio-technological approach to improving the efficiency of energy consumption in homes. Annually, nearly $40 billion of electricity is squandered by U.S. residents on end uses, which do not improve well-being. Residents are underinformed on how their personal behavior and increased number of in-home devices have dampened the impact of efficiency gains of individual technologies. Currently, the ability for energy monitoring devices to act as two-way communicators between energy providers and consumers is being underutilized. Real-time energy use data can be leveraged to create behavior influencing messaging. Utility companies have begun to leverage standard utility meters and enhanced energy bills to provide messages, with varying levels of success. Recently, energy monitoring devices have improved to become more detailed and "smart" but feedback techniques are lagging. To identify the impacts of the design of energy feedback messages, this study measures the neural activation of participants using a functional near-infrared spectroscopy (fNIRS) device. The fNIRS device quantifies neurocognition, which describes the function of one or more specific areas of the brain. To enrich the brain activity data, a post-task survey gathers data on participants' willingness to change energy consumption behaviors after seeing messages. Lastly, study participants' suggestions for personalizing messages to evoke a behavioral response are captured via semi-structured interviews. Through understanding the cognitive and behavioral response to energy feedback messages, the effectiveness of energy feedback messaging can be enhanced to optimize energy consumption with minimal physical changes to a home. The findings from this study are transferable to a variety of energy feedback mechanisms and provide insights for meeting new residential building standards which require resident education.

INTRODUCTION

The culture of increasing energy demand is a major concern when considering population growth and finite energy resources. To aid in mitigating the misalignment between expected and monitored energy consumption, energy feedback messages are being explored for their influence on energy users. Through observing a behavioral response to feedback messages, energy consumption may be reduced with minimal physical inputs. Many current energy feedback devices can provide messages, but a better understanding of the delivery of these messages is needed. To understand the social aspects (i.e. peer competition) that impact human behavior, engineers benefit from leveraging psychology and sociology theories. Engineering systems are often oversimplified to streamline the design process prioritizing technical functionality over social adoption. Home occupants who do not receive the full benefit of the energy they consume can improve their quality of life through energy efficiency.

Altering human behavior to become more energy efficient is the key to unlocking peak energy performance of existing buildings. Multiple studies have shown that human behavior drives energy consumption and behavior can be affected by energy feedback (Wilhite and Ling 1995; Abrahamse et al. 2007; Ehrhardt-Martinez et al. 2010; Alahmad et al. 2012; Vine et al. 2013; Murtagh et al. 2014). Though human energy behavior is not fully understood, new and innovative methods must be used to optimize energy consumption.

One innovative method for understanding human energy behaviors is neuroscience. Neuroscience is the process of making sense of brain-behavior relationships by producing images of the structure and activity in the brain (Eysenck and Keane 2005). Neuroimaging techniques allow researchers to measure cognition and brain activity during mental tasks (Shealy et al 2018). Functional near-infrared spectroscopy (fNIRS) devices measure brain activity (neurological response) through blood flow. fNIRS operate by emitting near-infrared light into the human cortex and the reflected light that is not absorbed is detected by sensors. Changes in blood flow patterns are indicators of neural activation. Neuroimaging is beneficial to the civil engineering profession in the following ways: neuroimaging devices can triangulate self-reported data, can be useful in exploring brain-behavior relationships, as well as describing and predicting behavior (Shealy et al. 2018).

Figure 1 below illustrates this study's design. Due to the misalignment between perceptions and actions, this study collects multiple data points for triangulation. First energy feedback devices are evaluated for their functionality and messaging capabilities. Secondly, messages are evaluated for their "design" utilizing existing literature. Thirdly study participants will participate in an experiment to determine the impacts of message design on perception and perceived behavior.

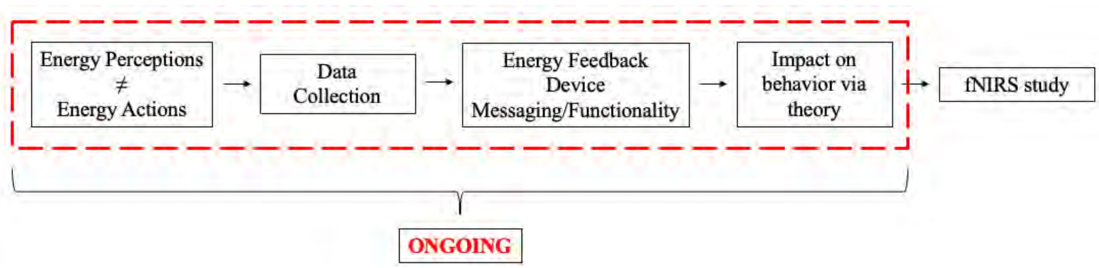


Figure 1 Research Study Design

BACKGROUND

The human brain is the most complex organ in the human body (Gannon 2012). As humans, we don't fully understand our own behavior and decision-making processes, especially regarding energy consumption. Consequently, because we don't understand human energy behaviors, there is a misalignment between the expected energy consumption our built environment is designed for and the actual energy consumption patterns of building occupants (Darby 2010). Overconsumption is a critical concern in the United States where buildings account for 40% of the total energy consumption in the United States, with residential buildings accounting for 21% of that energy (US EIA 2017; Alahmad et al. 2012). To accommodate for this ill-use of energy, the use of energy feedback technology is emerging as a socio-technical solution to utilizing behavior to reduce environmental impacts (Froehlich et al. 2010).

Prior literature on energy feedback systems backdates to the late 1970s (Froehlich et al. 2010). Energy feedback is typically given through energy feedback devices or enhanced energy bills. Energy feedback devices such as the Ambient Energy Orb, Curb, eGauge, Sense Home Energy Monitor, and TED Pro provide consumers with beneficial information on their energy consumption. The messages delivered by these devices vary widely in format and the approaches to influencing behavior are nonuniform. However, according to Delmas et al. (2013), 60% of the studies conducted on energy feedback devices only lasted for about three months, leaving the long-term results of these devices unknown.

To fully understand how to effectively deliver energy feedback to consumers through energy feedback devices, we need to know what motivates consumers and why. For example, Wallenborn et al. (2011) found that homes which were already engaged with energy savings or interested in using energy feedback were more likely to use these devices. Currently, there is no national standard to deliver detailed energy feedback messaging. This sometimes leads to the "fallback effect" (Wilhite et al. 1995), meaning as the devices continually present the same information in the same format, the users become uninterested overtime and the devices fade into the background of everyday life (Barreto et al. 2013; Hargreaves et al. 2013; Mountain 2006; Ueno et al. 2006a; Ueno et al. 2006b).

Through understanding the human brain and its decision-making processes, we can use neuroscience and neuroimaging techniques (fNIRS) to improve energy feedback message design. The fNIRS cap utilized in this study covers the prefrontal cortex (PFC) with sensors that detect brain activity. The PFC is the section of the brain that is responsible for executive functions (e.g. reflexive behaviors, decision-making, problem-solving, self-control). The PFC is in the front of the premotor cortex, which is thought to be the section of the brain that deals with movements and other functions. The PFC also makes up about 10% of the human brain (McBryde et al. 1999). Many would argue that the PFC is partly responsible for making each human individually unique.

METHODOLOGY

Our approach investigates the optimization of energy messaging by linking together the neurological responses, expected behaviors, and design suggestions for building occupants exposed to energy feedback messages. The first step is to categorize messages by various factors such as color, information, display, and timing from existing design frameworks (Sanguinetti et al. 2018).

This research study is divided into two phases. **Phase I** will consist of conducting a literature review, developing a database of energy feedback messages, and identifying gaps in current knowledge to address the needs of making homes more energy efficient. In **Phase II**, we will develop the independent and dependent variables that impact the study and assess the participant's neurological response to various types of energy feedback messages. This two-phased approach will be utilized to create a custom framework of potential energy feedback messages that can be used to promote energy efficiency.

Phase I: Literature analysis and analysis of energy feedback devices

Task 1.1 Analysis of energy feedback devices and existing literature

The energy feedback devices being investigated during this study include the Ambient Energy Orb, Curb, eGauge, the Sense Home Energy Monitor, and TED Pro. The feedback messages these devices provide will be used as a guide to creating experimental feedback messages that will be presented to participants.

Through a literature review, we will develop a list of independent and dependent variables that are critical to test and measure. These variables include choice architecture message framing (Wilhite et al. 1995), message types (Sanguinetti et al. 2018), text size, color, frequency (Wilhite et al. 1995), education level, ethnicity or cultural practice, gender, energy consumption patterns, and age.

The dependent variables observed in this empirical research were pulled directly from Shealy et al. 2018 and include expected behavioral changes from the messages, cognitive activation, required time to cognitively process the messages, short term memory of the messages, comprehension, and attitudes toward content.

By classifying energy feedback messages, we can explore differences between groups and provide a more descriptive literature review that answers which energy feedback messages are more effective (greatest neurocognitive response, most memorable, and easiest to comprehend). For instance, we will be able to provide guidelines about whether energy users respond differently to specific messages and which messages are most effective.

Phase II: Conducting empirical research to measure cognition

The purpose of Phase II is to measure the neurological response to energy feedback messages.

Task 2.1 Data collection

Task 2.1.1 Functional Near-Infrared Spectroscopy (fNIRS)

Our experimental approach will include using a computer screen to present energy feedback messages to participants. Messages gathered from the existing energy feedback devices will be used as a guide to creating example messages of what feedback these devices may display. These messages will be grouped into the following themes: messages that impact energy participants kids or close family members, monetary gains or losses, loss aversion, decision-making, and the environment. Lastly, we will use the example messages to create a series of "block tasks". The number of messages in each block will be structured based on the number of energy feedback messages gathered in Phase I. Blocks will be composed of similar messages for each type of intended behavior (Shealy et al. 2018).

Although the behavior trends can be observed and measured by asking participants interview questions, we believe the fNIRS device can provide an innovative way to quantify cognition. The fNIRS device can be useful because participant self-responses aren't always accurate, and this device also shows fundamental differences in processing. Interpreting and processing energy feedback messages produces a cognitive response in the brain. It operates by emitting near-infrared light into the human cortex and the reflected light that is not absorbed is detected by the sensors of the fNIRS. Changes in blood flow patterns are indicators of neural activation. This device captures cognitive responses by measuring an increase in oxygenated blood (HbO) in real-time. We will measure the peak level of HbO and time to reach this peak response.

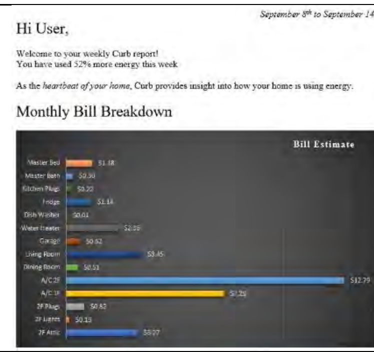
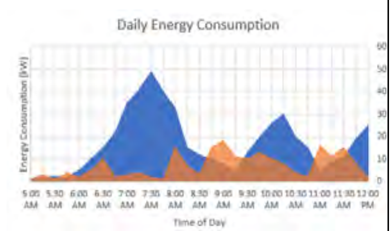
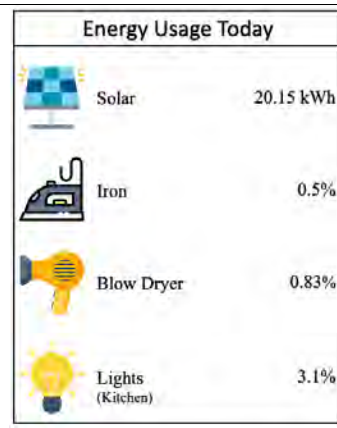
Task 2.2.2 Post-task semi-structured interview

To conclude the fNIRS study, a post-task semi-structured interview will be given. Semi-structured interviews allow the interviewer to gain an understanding of data that is not openly accessible (e.g. perceptions, attitudes) (Partington 2001). This interview will ask participants for feedback on which energy feedback messages they found to be most impactful, potential designs for new messages, and describe how the messages could change to entice them to be more efficient.

RESULTS

The data collection for this study is currently underway. Our preliminary findings show that messages can be improved upon. Relatively small increases in energy efficiency can greatly impact the lives of homeowners, as well as reduce the detrimental impacts the ill-use of energy has on the environment. Through prior research, some of the key variables found that have impacted how messages have been framed and how messages will be framed are choice architecture, message types, text size, color, energy and consumption patterns.

Table 1 Current Energy Feedback Devices

Energy Feedback Device	Function	Feedback Type	Feedback Frequency	Energy Message Examples
Curb	Monitors each circuit, allowing the device to detect abnormal energy patterns	Mobile app notifications, emails, display.	Real-time dashboard, weekly email reports, event-based alerts, user-defined	
eGauge	Measures whole-home energy and help to reduce costs, and optimizes energy production	User-definable text alerts and email alerts, online graph, user interface (UI)	Per second	
Sense Home Energy Monitor	Provides consumers insight on their energy use and home's activity, identifies energy use patterns	Mobile app notifications	60 seconds	
TED Pro	Tracks running costs, current time-of-use period, real-time power consumption	Text alerts, online interactive graph	2 – 3 seconds	

Choice Architecture

To convince consumers to alter their energy behaviors to become more efficient, choice architecture can be utilized to improve energy efficiency. Choice architecture describes the ways in which information and concepts are presented to individuals. Choice architecture is essentially a combination of the types of messages presented, the text size that is used, and the colors the message utilizes to increase contrast and effectiveness. The way the feedback messages are framed can sway consumers to draw different conclusions. For example, Wilhite et al. (1995) conducted a three-year study in Oslo, Norway on the relationship between billing information and residential energy consumption. The hypothesis the researchers used for this study was that more informative energy bills would result in increased efficiency of residential energy consumption. The variables the researchers deemed most important for feedback include frequency, a message medium that catches the consumers attention, presentation of the feedback, and a comparative framework (Wilhite et al. 1995). In the variables mentioned, the researchers concluded that for frequency, the shorter the feedback period, the overall effectiveness of the energy feedback increases.

When choosing a message medium for grasping the consumer's attention, it is important to utilize a bill, device, or an object that the consumers will pay attention to. Though energy bills are excellent mediums for portraying this information, and due to the rapid advancements in technology, most bills are automatically deducted from the consumer's bank account, removing the feedback-friendly aspect of this medium. Presentation is a vital component regarding the effectiveness of feedback information. In the presentation of energy feedback, it is important to convey the feedback information in a clear, elementary manner so that it appeals to all consumers. Some of the variables such as choice architecture, text size, color, and frequency are all key variables being investigated to effectively present energy feedback. These variables can affect how consumers perceive and utilize energy feedback information. Cost and consumption must also be delivered in a clear, straightforward manner because these two components also impact the customer's actions regarding their energy use. In the final year of the study, researchers found that more informative energy bills resulted in energy savings of at least 10%. This study shows that with more frequent and informative energy bills, energy can be conserved.

Message Types

The types of messages presented to consumers impact the choice architecture of energy feedback messages. Message types refer to the content that the presented messages give the energy consumer (Sanguinetti et al. 2018). These messages come in different forms (e.g. notifications on a mobile device, read-outs, interactive graphs). For example, Sanguinetti et al. (2018) found that presenting energy feedback information effectively can be achieved by including three components within energy feedback messages: contextual information, metrics, and valence. Contextual information is information that compares consumers energy consumption to other consumers or to their own past behaviors. Metrics provide quantitative information on energy consumption. Valence refers to the amount of energy the energy consumer used, wasted, or saved.

Text Size

Prior research on the impact that text display can have on energy feedback technology is limited. Text size is important, especially for elderly people or people with impaired vision. Larger text sizes may be needed for these underrepresented groups for readability purposes. Though larger text sizes may seem more beneficial when attempting to highlight the most important information within text-based data, this is not always the case. For example, Darroch et al. (2005) found that age, as well as the size of the text size, impacted the readability. Darroch also found that the font that is used (e.g. Microsoft Sans Serif) can also impact readability.

Color

Though larger text sizes can draw attention to the more important information, its impact can be bottlenecked by color. Specifically, Curb and the Ambient Energy Orb (Orb) leverage color. Curb sends personalized weekly energy audits to consumers that provide information on your energy consumption, as well as a color-coded bar graph that has a breakdown of each individual appliance's energy use. This color-coding approach can help users easily notice which appliances use more energy than others and can potentially catch their attention and change their behavior. The Orb uses colors to represent energy consumption (e.g. red symbolizing negative behavior, green symbolizing good behavior). It takes the network about five seconds to update the color change or pulsing effects. Energy Orbs were introduced in California residences for ten months as part of a 2004 Southern California Information Pricing Pilot. Investigators examined whether the critical peak pricing information provided by the display lighting of the Orb could encourage consumers on a time-varying rate plan to conserve energy. The 30 residential participants provided with feedback saved about 0.5–0.7 kW of energy.

Energy Consumption Patterns

We don't understand human behavior, therefore causing energy consumption in our built environment to be sporadic at the individual scale. For example, the Sense Home Energy Monitor collects energy data real-time, identifies daily, weekly, and monthly trends, and detects usage statistics of each individual device. In doing this, Sense makes it easier for consumers to see how their behavior is influencing home electricity use. With Sense, you can also set and track energy day-to-day goals to help improve energy use. Similarly, Curb directly monitors individual circuits within your home to detect energy consumption, as well as detect abnormalities over time. The resolution of the data and behavior over time are important factors in regards to energy feedback.

Murtagh et al. (2014) conducted a research study on twenty-one households that contained energy feedback devices for more than six months. Of those homes, only four of them continued to refer to the energy feedback devices. Participants in these homes also demonstrated energy-saving behaviors prior to and outside of the energy feedback devices. The researchers also grouped the homes into three energy-based categories: monitor enthusiasts, which accounted for 20% of the sample, aspiring energy savers, which accounted for 60% of the sample, and energy non-engaged, which accounted for the last 20% of the sample. Initially, the researchers assumed that, compared to the general population, the participants selected for this particular study would represent a good portion of consumers that are relatively engaged with saving energy, because these consumers either purchased an eco-friendly home, taken part in a community sustainability project, or simply purchased an energy monitoring device.

Likewise, Vine et al. (2013) found that annual energy savings decreased by 3%, the literature finds that feedback can reduce electricity consumption in homes up to 12% (Ehrhardt-Martinez et al. 2010), and it works best when delivered regularly, presented plainly and engagingly, tailored to the householder, interactive and digital, capable of providing information by appliance, accompanied by advice for reducing electricity use, and associated with a challenging goal for energy conservation.

DISCUSSION

Prior research points towards flaws in the current techniques of delivering energy feedback to consumers. In the messages that energy feedback devices present, the variables deemed most important to investigate to improve the delivery of energy feedback included choice architecture, message types, text size, color, energy consumption patterns, and age. Though choice architecture is essentially a combination of message types, text size, and color, all these factors can impact the effectiveness of choice architecture. Color can bottleneck text size because even though you have a large text, the contrast of the message can weaken the impact of the text size, therefore making the text blend in. Prior research on how text size impact energy feedback is minuscule. Once we have a better understanding of their energy behavior, we will be able to track their energy consumption patterns better, which can help us to find new, innovative ways to become more energy efficient. Age can also impact the effectiveness of energy feedback. For example, older people may have more trouble with comprehending how to use energy feedback devices as opposed to younger and some middle-aged people. Determining a way to dumb it down so that all user can easily understand how to use these devices is needed.

Data visualization is the visual representation of information that uses charts, diagrams, pictures, and messages to make information easier for the consumer to see and understand. Data visualization also makes it easier for consumers to detect patterns, trends, and other correlations that can go undetected in text-based data. Data visualization is important because it depends on the type of data being utilized, the targeted consumers this data impacts, and the type of message the data is intended to display. The data, along with the visual representation, must work cohesively to convey the most effective message. Due to advancements in technology, data visualization can play a vital role in more effective energy consumption. Energy feedback messages can potentially encourage consumers to change their behaviors and save energy. The problem with data visualization within energy feedback technology is figuring out how to effectively present energy data. Also, because of availability heuristics, consumers overestimate energy use for low-energy activities (e.g. overestimating the amount of energy a light bulb uses), as well as underestimate energy use for high-energy activities (Herrmann et al. 2018). Oftentimes when consumers are exposed to graphical data, the consumers may have a response relapse (Wilhite et al. 1995). For example, as you implement an intervention or an energy feedback message, consumers energy consumption will decrease, but with time, consumers energy behaviors will slowly relapse and go back to their original energy consumption habits until the next energy feedback message or intervention is implemented. To mitigate response relapse, determining which variables are most appropriate and the most effective way to present the information from those variables is key.

Two-way communication, in the context of energy feedback technology, is the exchange of energy feedback information between energy feedback devices and consumers. Two-way instant communication is different from one-way communication. One-way communication sends the energy consumer a read-only message, while two-way communication sends the energy consumer a message and gives the customer a chance to respond to the message. The challenge with two-way communication is keeping consumers engaged. If consumers are unable to use the devices in a degree that is comfortable with them, they will eventually stop using the energy feedback devices. Machine learning and automated messages are improving, providing great opportunity for consumers to get answers to their energy questions instantaneously at any time.

FUTURE RESEARCH

This study will not explore all the different message styles and delivery types. Therefore, to ensure this design framework is as effective as possible, the other styles and delivery types must be researched especially as feedback devices evolve.

The current scope of this study will cease after study participants are given semi-structured post-task interviews and surveys about the energy feedback messages. Future work will explore the energy demands and take the design framework that we have created and apply it in the built environment (residences) to see how effective the designs are in a longitudinal manner.

This study is constrained in regards to participant sample size given its exploratory nature. Larger and different sample populations will need to be explored to see how this impacts energy consumption. The different sample populations would need to be determined based on age, gender, ethnicity or cultural practice, environmental beliefs, education level, environmental conditions, and socioeconomic status.

CONCLUSION

This research study is currently ongoing. Preliminary findings show a wide variety of feedback messages with unique features. Though there is a plethora of prior research on energy feedback, there is no set structure for effectively delivering energy feedback information to consumers. Everyone is different in some way, shape, or form, meaning, each individual energy consumer uses energy differently, making the quest for finding a universal solution to reducing the gap between perceived and actual energy use challenging. With a better understanding of how energy feedback messages design influences behavioral responses in consumers, future messages can become more effective. The motivation of this study is to understand the impacts energy feedback messaging has on consumers and the built environment. Through this study, there is hope to create a customized energy feedback design framework that will help to fill the gap between perceived and actual energy use, as well as improve the design delivery of energy feedback messages.

Climate change is a societal problem and is looked at as a problem for engineers to solve. This study incorporates concepts from psychology and sociology to supercharge existing technologies to increasingly to mitigate climate change. A better understanding of human behavior and how the human decision-making process works is being developed in a transferrable manner. The framework that energy feedback device companies and/or utility companies use for consumers should transfer to other sectors of energy consumption which also could benefit from improved feedback processes.

Improved and more efficient energy usage is becoming of increasing concern. To accommodate for the current ill-use of energy, energy feedback messaging can be utilized to optimize consumers energy usage. To understand how consumers use energy, we must understand their motives and decision-making processes. This process can be achieved by using the fNIRS device. Consequently, the fNIRS monitoring will don't on stationary participants within a lab with minimal distractions, compared to the real world. There is no one size fits all, regarding these energy feedback devices because everyone is uniquely different, and they use energy differently. However, there is some evidence from prior literature that consumers' personal characteristics and individual differences may impact how they utilize or react to energy feedback devices (Murtagh et al. 2014). For example, Murtagh et al. (2014) found that by grouping consumers into specific energy categories, energy consumption patterns and energy conservation varied. This may be because consumers with certain behavioral traits or motives may be more willing to explore the necessary behavioral processes needed to make energy feedback devices beneficial, while other consumers may not. Energy feedback devices will appeal to groups of consumers differently, requiring customization to optimize the positive impact these devices can have on energy consumption. It is also likely that existing research on energy feedback devices has been overemphasized because existing research samples may have been created of volunteers who may have a current interest in energy savings (Hargreaves et al. 2013). Subsequently, these findings cannot be generalizable to the portion of the population that is not interested in energy savings and energy feedback because everyone is different and uses energy differently. Nevertheless, the opportunity to reach the portion of the population that is uninterested in energy savings and energy feedback is possible. Since energy feedback messaging studies typically only last for around three months, longer-term studies on energy feedback devices are needed. This research seeks to create a design framework that attempts to make energy feedback devices appeal to everyone. In targeting such consumers, improving the design delivery of energy feedback messages in energy feedback devices may aid in achieving wider scale results.

Energy feedback messaging shows potential to improve the well-being of society while reducing climate change through increasing societal consciousness of energy consumption. Energy feedback messaging can present ways in which consumers can perform small physical inputs that will, over time, positively impact the environment. At the conclusion of this study, we will have a better understanding of human energy behavior, current interactive energy feedback technologies, and how the two can be intertwined to make energy consumption more efficient. At the conclusion of the scope of this study, we will have a better understanding of human energy behavior and their decision-making processes.

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Energy Efficiency Rebate Programs: An assessment of investment behaviors by homeowners

Celso. N. Santos[1], Kristen S. Cetin[2]

[1] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA

[2] Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI; email: cetinkri@msu.edu

ABSTRACT

In recent years there has been a growing concern regarding the carbon footprint associated with buildings. In the U.S., building operations alone account for over 40% (approximately 20% for the residential sector) of CO_2 emitted, with the vast majority due to energy consumption. To encourage homeowners to invest in energy efficient technologies for their homes, many utilities have implemented residential rebate and incentive programs. However, few studies have examined homeowners' needs and their associated energy efficiency investments. The aim of this study is to describe the investment behaviors of homeowners associated with energy efficient technologies. This study focuses on data collected for homes in Cedar Falls, Iowa, which has significant seasonal climate variations, a variety of building ages, and a long-standing residential efficiency rebate program. Based on the rebate program data collected from 2013 to 2016, of the homeowners who purchased energy efficient technologies, the most common technologies invested in were efficient lights, central air conditioning systems, and insulation. Approximately 65% of investments in new, efficient cooling systems were due to inoperable or broken existing systems, while 30% were still working but less efficient; heating or cooling system replacement is also among the most common first energy efficiency technology investment that households make, potentially serving as a common gateway to interest in and knowledge by households of energy efficiency programs. Efficient lightings are financially attractive investment for homeowners when considering the total cost of investment versus the rebate received. The results of this research can be used to benefit and improve the effectiveness of energy efficiency rebate programs.

1. Introduction

The continued increase in electricity demands associated with building operations has shown to have a strong impact on the volume of carbon dioxide emitted into the atmosphere. In the U.S, the total energy consumed by commercial and residential buildings accounts for approximately 40% of the total energy delivered and is responsible for about 40% of all carbon dioxide gas emitted (U.S. Dept. of energy, 2019). The single largest contributor to this energy consumption from buildings, on average, is the cooling and heating systems. The ongoing improvements and adjustments to energy related policies and appliance energy efficiency requirements play an important role in reducing these numbers. For instance, building lighting electricity consumption, previously considered to be continually increasing, is now decreasing faster than other household appliances (U.S. Dept. of energy, 2019).

Moreover, the implementation of the Energy Independency and Security Act of 2007 and energy efficiency incentive programs have also helped to support the development of new, energy efficient products and their use.

Despite the benefits that energy efficiency technology (EET) provides, there continues to be significant differences between the capabilities and potential for energy savings of commercially available technologies, and adoption and use of such technologies, even when there are clearly demonstrated energy savings and smaller payback periods. In other words, many homeowners, overall, still display reluctance toward the purchase and use of energy efficient technologies (Attari et al, 2010; Frederiks et al, 2015; Vijayalakshmi1 and Mahalakshmi 2012; Ha, and Swinder, 2012). In some cases, it has been found that homeowners' value and view energy efficient technology as important; however, they may not necessarily implement energy efficient technologies in their homes (Ha, and Swinder, 2012; Frederiks et al, 2015). In some studies (Cetin et al. 2014; Nielsen,1993), the authors point to socio-economic status, and personal motivations and knowledge as being some of the main reasons for this behavior. The often-high required initial investment (Steg, 2008; Zhao, 2012), lack of knowledge of the energy use by the homeowner (Steg, 2008; Dietz, 2009], and low household income levels are also indicated as impediments for many homeowners to purchase EET (Steg, 2008; Zhao, 2012). These together limit the extent to which energy savings is achieved in households (Dietz, 2009). Related to motivations, recent research in the UK found that 88% of homeowners are concerned, first with financial savings, followed by environmental impacts, and finally, by the improvement in efficiency (Caird et al, 2008; Pelenur, and Heather, 2014). These motivations, nonetheless, do not always translate into actions and may be easily impacted by homeowner's behaviors, as described above.

This paper aims to study the homeowner's investment behaviors associated with the purchase of energy efficiency technology and the influence the rebate program may have on it. We consider both the investments made in efficient lighting and central heating and cooling systems, in Cedar Falls, Iowa. This town is located in the Midwest of the United States, in ASHRAE Climate Zone 5A. Cedar Falls Utilities has long-standing incentive programs from which homeowners receive a monetary rebate after a qualified EET is purchased and installed. The rebate program targets the promotion of energy conservation through the adoption of energy efficiency measures for buildings and also aimed to attract those with low income to implement these measures (U.S Dept of energy, 2010). We expect that the result of this work can contribute to providing insights associated with these programs and can help to improve these programs moving forward.

2. Literature Review

Climate change and its current and future potential impacts are widely recognized worldwide. The European Union predicts that approximately 88% and 90% of carbon dioxide emissions from buildings could be reduced from energy savings in residential and commercial buildings, respectively, by 2050 compared to 1990 levels

(European Union, 2011). In the U.S, it is estimated that by substituting less-efficient lighting with efficient lighting, changing behaviors associated with household energy use and motor vehicle operation could help to save between 11% to 30% of total energy (Vandenbergh et al, 2008; U.S. Census Bureau 2018; Gardner et al, 2008), and approximately 20% of carbon dioxide emissions (Bennear et al, 2013). However, the ability to achieve these goals is constrained by peoples' lifestyles, financial investment capabilities, misinformation, and/or lack of knowledge/awareness (Frederiks et al, 2015; Steg, 2008; Lopes et al, 2012). The 2019 Annual Energy Outlook points the continues rise of the use of energy-consuming household appliances, electronic devices, and equipment as being the main reasons for electricity consumption demand increases, as well as the continued increase in the size and number of houses and households (U.S. Dept of energy, 2019). The required monetary investment in energy efficiency technology may also become an issue for some homeowners. That is, while the return from energy efficient investment might provide good long-term savings, higher initial investments are required, which might lower the attraction for some homeowners, particularly those with lower household incomes (Zhao et al, 2012). To stimulate homeowners' interest in energy efficiency, many utility companies in the U.S have implemented incentive programs for those who purchase and install qualified EETs; nonetheless, to improve these programs' efficacy, it is necessary to understand the homeowner's needs and behaviors regarding those energy efficiency investments that may occur even without any incentive (Bennear et al, 2013; Zhao et al, 2012). For instance, research focused on high-efficiency toilets (HETs) for household's water reduction in North Carolina, concluded that those who used HETs on the rebate programs corresponded only of 37% of the total savings comparing to 63% that could be achieved without the rebate program (Bennear et al, 2013). While this research effort only includes rebate-based investments, this is an important consideration for future work in this area.

3. Methodology

3.1. Data source and collection

This research uses data from the energy efficiency rebate incentive program implemented by Cedar Falls Utilities (CFU), which generally services homes in the city of Cedar Falls, Iowa. Cedar Falls is located in ASHRAE Climate Zone 5A, and includes a total population of 41,050, and approximately 14,950 households in 2016 (U.S. Census Bureau, 2018). The research focused on data collected from 2013 to 2016, which includes a homeowner ID/address, the energy efficient technology investment(s) made, the rebate amount ($) received, new and old units' characteristics (where applicable, i.e. for HVAC systems), and the date the technology was purchased. Table 1 present the main characteristics of the investments made by householders. Cedar Falls, Iowa experiences significant variation in terms of weather conditions and has a range of household characteristics and ages. More specifically, this location experiences all four seasons throughout the year, with some extreme cold and extreme hot temperatures during the winter and summer, respectively.

Table 1: Summary of characteristics of the energy efficient technology investments in Cedar Falls, IA based on data available from 2013-2016

Technology	Energy Efficiency Investment				Rebate value			# Houses
	N	Range ($)	Average ($)	SD ($)	Range ($)	Average ($)	SD ($)	
Air Conditioning	744	928-30,000	6,278	3,332	100-900[1]	550	168	726
Furnace	739	936-17,090[3]	6,007	760	200-400[2]	347	88	723
Efficient lighting	1,238	4-2,140[4]	156	253	2-700[5]	75	121	656
Insulation	606	25-28,900	1,693	2,197	15-2,810	635	357	366

[1] The rebate includes up to $500 for 14 SEER (Seasonal Energy Efficiency Ratio), and $100 for each additional SEER value
[2] In this category, rebates were only either $200 or $400.
[3] The rebate includes up to $400 for 95% AFUE minimum.
[4] The rebate is limited to 35 units of recessed lights per year per household maximum; rebate is 50% of pre-tax price, and up to $20 per fixture
[5] This value includes only the number of times efficient lights were invested in. The total number of efficient lights units bought, however, is equal to 8,933 with an average number of lights per homeowner of approximately 7.

3.2. Data analysis

Descriptive statistics, including frequency analysis and central tendency are used in this study to analyze the regularity of which homeowners made investments in energy efficient technologies. In total, for air conditioning, furnaces, efficient lighting, and insulation (including attic, side wall, foundation/exterior wall, rim band joist, crawl space, and floor insulation), 3,327 rebate applications were submitted, processed, and documented from 2013 to 2016, based on the dataset available. Frequency analysis was used to determine the type of technology that was invested in the most per home as presented in Table 1 and Fig. 1 and 2. As such, the dataset for this research is focused on investments in efficient lighting and air conditioning (central only) technologies. The analysis is then used to investigate the frequency of which households change their central air conditioning system and the reasons for this investment (i.e. the working/non-working condition prior to the new purchase; if a unit's capacity was increased, decreased or remained the same after retrofitting). Ultimately these are used to estimate the average cost households would incur in the case they would have increased the central air conditioning efficiency by 1 SEER (i.e. instead of buying a unit with efficiency of 14 SEER, they bought a 15 SEER) and the average rebate received for this increase.

The correlation between the investment per technology and the rebate per investment are also studied. For efficient lighting, the data include the monetary investment in the lights themselves (i.e. LED light bulb, fixture, recessed light, and/or specialty bulb). Efficient lighting is the only type of technology, among those studied, where more than one item was purchased at the same time for the same address. The investment cost is calculated using the quantity purchased and the price per unit. This is then used to determine the correlation with the rebate received. For the heating and air conditioning units, households only invested once per unit and/or address across the dates studied.

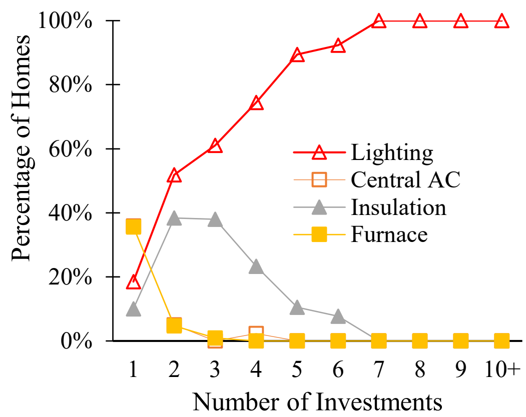
For the purpose of this research, an investment was considered as the number of times homeowner purchased and installed an EET. For example, if multiple efficient lights were purchased at the same date, this was considered one investment. This is because the rebate they received is based on the total amount invested plus the installation cost. This rule, however, has two exceptions. First, when homeowners invest in two or more different technologies, they are considered two investments, and each technology is counted separately. That is, if both efficient lighting and the air conditioning system were purchased at the same time, this is considered as two investments. This is because these are different technologies and the rebate program has different payment procedures for each technology. The second is when someone purchases a technology for two different houses or units. If they are the same technology, this is considered as a single investment; if it is two technologies, it is considered two investments.

3.3. Data quality control

Due to factors such age, fire, and conservation, there were missing some subset of data of the old units. So, we prioritized those investments which included all the information related to the unit's status before retrofitting, total expenses, and the rebate. That is, the data should show indicate whether the equipment was broken, was working, or was a new construction. We kept those investments that missed only information regarding the cooling capacity, power consumption and efficiency.

4. Results and Discussion

The frequency of investments made per home from 2013 to 2016 is shown in Fig. 1 and 2. Amongst the 3,327 investments made, over 80% of homes only purchased one energy efficient technology. That is, the majority of homeowners made only one investment during these 3 years, and the *central air* conditioning and *furnace* were the most common type of technology invested in, with approximately 36% each (72% total) of those who made one investment, and 29% each one of the total investments. This is followed by efficient lighting, which represented approximately 18% of one investment only and 27% of total investments, followed by insulation, representing approximately 10% of one investment and 15% of total investments. Efficient lighting, however, was the only technology of which we find homeowners investing in more than 7 times. Yet, in terms of price, air conditioning and furnaces represent an investment cost which is nearly 700% higher than the next most expensive technology while the efficient lighting was the cheapest technology (Table 1).



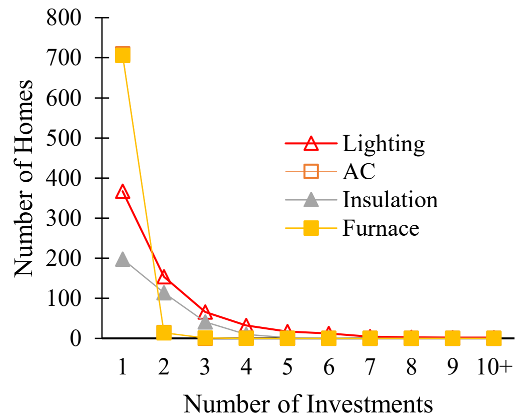


Fig. 1. Number of homes by the number of investments

Fig. 2. Percentage of homes by the number of investments

Energy Efficient lighting

As can be seen in Fig. 1 and Table 1, investment in lighting was the most frequent and the cheapest amongst all EETs considered. This finding supports the statement presented by the U.S. EIA Annual Energy Outlook (2019) that lighting has become one of the most invested in types of EET (Attari et al, 2010). In this dataset, total investment in lighting is approximately 37% of all investment made, followed by investment in air conditioning at 29%. Fig. 2, however, shows that the percentage of investments in efficient lighting reduces significantly when considering only one-time-investments (18%), meaning lighting is not typically the first energy efficient technology that households invest in. This may be because most households may consider lighting as a fairly low-cost investment, as compared to the higher costs of HVAC systems; as such, this is a relatively minor expense and not something households may need financial help in purchasing, nor an expert to install. In the case of an HVAC system, by comparison, an expert installer is needed as well as significant monetary investment. In both cases, either the installer may mention the opportunity for energy efficient technology rebates, or the homeowner may seek out opportunities for financial support.

The lighting rebate program provide a rebate of 50% of the pre-tax purchase prices. As such, it makes sense that the correlation between the investments made in lighting and the rebate received indicate a strong positive correlation for both (0.97) (Fig. 3). That is, the rebate received for the investments were highly proportional to the money invested and as much money homeowners spend on lighting higher is the rebate received. This, along with the manufacturer- claimed long operational life (Philips, 2018) and energy savings, makes efficient lighting potentially more attractive for buyers. The correlation, however, between the number of lights purchased and their cost is limited (0.22), at least based on the analyzed dataset.

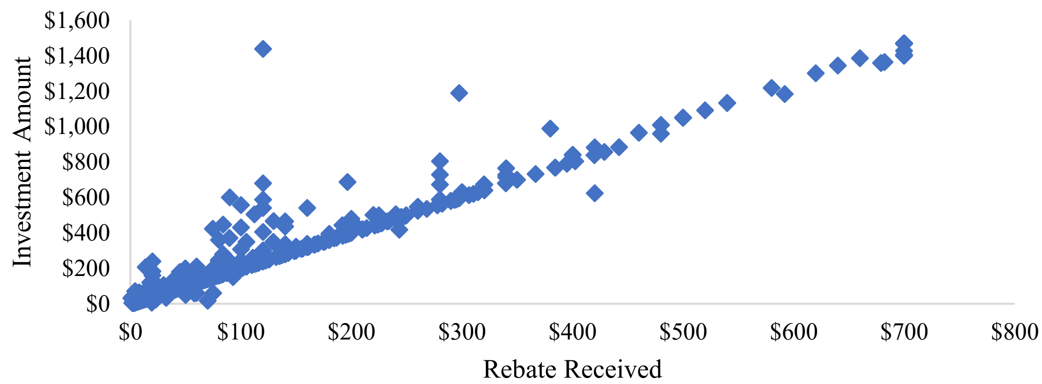


Fig. 3 Comparison of the amount invested in energy efficient lighting and rebate received

Air Conditioning (AC)

Central AC was the second most invested in technology and the most expensive among those studied. Fig. 4 shows that over 65% of homeowners changed their air conditioner only after they were broken, while 29% with them still running but with low efficiency. 5% were new installations. Amongst the 29% of units that were still running, over 65% of them had efficiency levels of 13 SEER or less, and 1% had efficiencies of over 13 SEER. The efficiency information of the remaining 33% were missing and thus not reported (Table 2).

Table 2: Summary of Characteristics of the old and new air conditioning units

N	Old Air Condition System				New Air Conditioning System				
	Capacity		Condition		Capacity		Unit's BTU retrofitting		
	SEER	Tons	Working	Broken	SEER	BTU (x1000)	Increase	No Change	Decreased
8	>=4	1-5	3	5	14-17	18-48	38%	38%	13%
8	5	1-3	-	8	14-15	30	63%	25%	13%
15	6	1-3	6	9	14-18	18-36	20%	67%	13%
17	7	1.5-3	4	13	14-16	18-24	18%	18%	59%
117	8	1-3.5	34	83	14-20	18-42	13%	63%	21%
12	9	1.5-3	3	9	14-16	24-36	25%	67%	8%
278	10	0.5-6	85	193	14-25	18-60	7%	77%	15%
26	11	2-4	3	23	14-18	24-48	-	85%	15%
21	12	2-4	5	16	14-18	24-42	10%	71%	14%
20	13	1.5-3	3	17	14-22	22-48	10%	20%	70%
5	14	2.5-3.6	-	5	16	30-36	-	60%	40%
3	15	3	-	3	14-17	24	-	-	67%
3	16	2-6	1	2	14-16	18-60	-	67%	33%
211 [1]	- [1]	1.5-3	72	121	14-33	9-60	2%	18%	6%
744 [2]	9.5	2.3	29%	65%	15.5	27	8%	52%	17%

[1] *These include new installation units (no previous unit existed), units destroyed by fire, and other units of which the SEER capacity was not possible to determine.*
[2] *Summary of the old and new air conditioning system*

The most common range of SEER values is between 8 and 10. The average estimated age for an air conditioning system is about 15 to 20 years (U.S Dept of

Energy, 2019). Nevertheless, bad installation (i.e. inaccurate sizing, refrigerant charging, air flow, fouling of the coil, and air leakage in the duct) can decrease the efficiency and lifespan of the equipment (Kleine et al, 2011). This might also be some of the reason for these results.

Similar to units that were still in use, the majority of units that were broken also had efficiencies of 9 SEER on average (Table 3). Over 70% of these units were running with efficiencies equal or less than 13 SEER, of which 61% of them had efficiency equal and less than 10 SEER. The total percentage of broken units plus working units with efficiencies less than or equal to 13 SEER, and excluding those with no data, is 98%. These older units had capacities ranging from 6,000 to 60,000 BTUs; the least efficient units had a capacity of 24,000 BTUs but was still running. The least efficient broken unit, nevertheless had a capacity of 30 000 BTUs.

Table 3: Homeowner investments in energy efficient air conditioning systems and rebate received per SEER value of the new system

SEER[1]	*N*	*Costs of new system ($)*		*Rebate received ($)*		*Total costs per SEER*	*Rebate per SEER*
		Average	SD	Average	SD	|(N-(N+1))|	|(N-(N+1))|
14	1	$3,973	$1,616	$411	$136	--	--
15	2	$5,446	$2,379	$505	$139	$1,467	$90
16	3	$7,230	$2,352	$636	$121	$1,784	$130
17	4	$10,677	$2,705	$600	$146	$1,275	$36
18	5	$10,677	$2,705	$614	$135	$1,564	$14
23	6	$11,244	$3,257	$600	$141	--	--
24	7	$10,010	$1,910	$700	--	$1,234	$100
25	8	$11,325	$970	$700	--	$1,315	--

[1] The units with SEER rating of 19, 20, 21, 22, 29 and 33 were excluded because only one air conditioning had these efficiencies, it was a new home installed units (i.e. they were not replacing an older system), and/or the rebate received was in the same amount (i.e. the 6 units with 20 SEER's, have total rebate received of $700 each and SD of $0), thus could not be used for this comparison

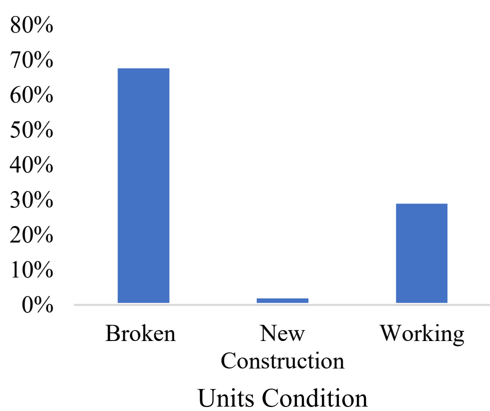


Fig. 4 Air conditioning system status before they were replaced with a new system

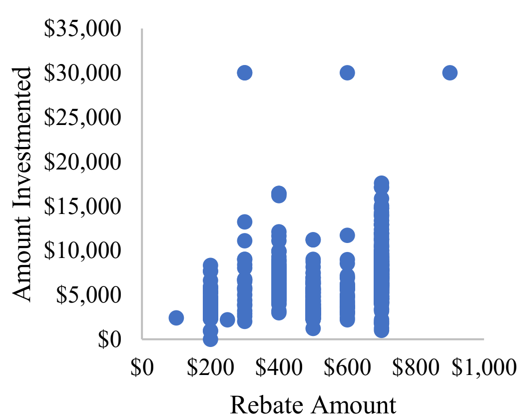


Fig. 5 Total money invested in new air conditioning systems versus the rebate amount received

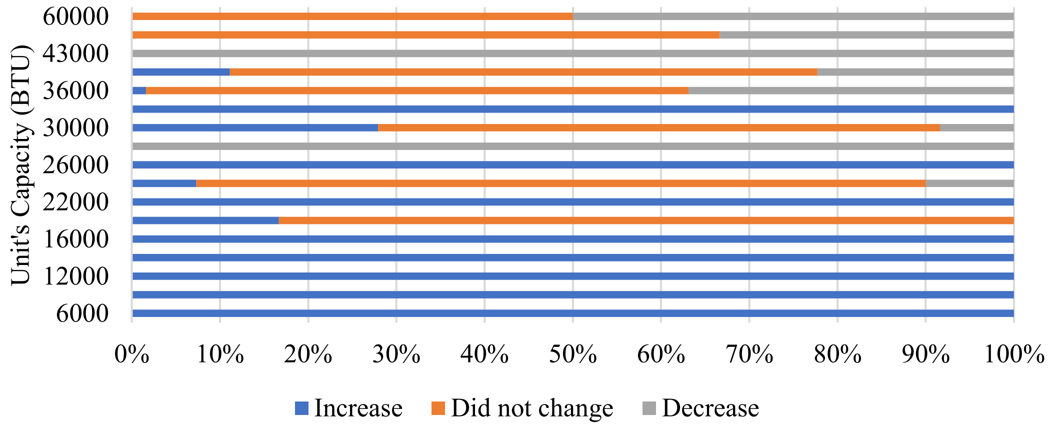


Fig. 6 Comparison of installed capacity of new versus old air conditioning systems

The correlation between the investment made per address and the rebate received were also analyzed. The result presents very low correlation (0.33) (Fig. 5). That is, the amount of rebate received might not have been a determining factor for homeowners' decisions to purchase a higher or lower SEER value system. The average expense incurred by a homeowner to increase the unit's efficiency, one of the main factors to increase the rebate received (Table 3), from 16 to 17 was $1,275 with a rebate of $36. That means, if a homeowner wanted to buy a 17 SEER unit rather than a 16 SEER unit, they would have to spend an average of $1,275 more. The lowest average rebate paid was $14, for an investment of $1,564, to increase the efficiency from 17 SEER to 18 SEER. Thus, the average total cost per each SEER increased would be $1,321 and the average rebate received would be about $42.

A comparison between the capacity of the old and new air conditioning systems (i.e. the capacity increased, decreased, or did not change) is shown in Fig. 6. Overall, approximately 8% of all old units had the cooling capacity increased, 16% decreased, and 54% kept the same cooling capacity. The old units' cooling capacity varied from 6,000 to 60,000 BTUs. These ranges changed to 18,000 to 60,000 BTUs, after retrofitting the units.

5. Conclusion

In this research, data from 2,471 households and 3,327 investments in energy efficient lighting, insulation, furnaces and air conditioning systems is used to assess investment patterns and behaviors of homeowners in Cedar Falls, Iowa. Approximately 80% of homeowners only participated once in investing in the technologies, with lighting being the most commonly invested in technology, followed by central air conditioning systems, furnaces and finally insulation. Several main conclusions can be drawn.

- Energy efficient lighting technologies among the most common technologies invested in, as they are cheaper to purchase and easier to install and operate compared to the other considered technologies. The average cost to invest in efficient lighting is approximately 10 times cheaper than the average cost to invest in insulation which is the third most expensive technology followed by the furnace and air conditioning.

- The refund received for investing in efficient lighting is strongly associated with the amount invested, also making their investment an attractive one. That is, under this program, homeowners receive back an average of nearly 50% of the investment made, compared to 38% for insulation, 6% for furnaces and 8.7% for air conditioning. In addition, the rebate received to invest in lighting is defined in percentage which, however, does not happen with the rebate received to invest in other technologies.

  Despite these advantages, lighting is not typically the first investment made by homeowners, despite this distinct advantage. The first investment which in an energy efficient technology, at least those that homeowners file rebates for, is the cooling or heating system of a home.

- For air conditioning systems, the rebate received is limited in comparison to the total amount invested in the system, with an average rebate of approximately 9%. As such, the amount received may have limited impact on the decision of a homeowner to purchase a more highly efficient system or increase the SEER rating of the system. The average additional rebate received by homeowner per 1 SEER increase was less than $50 on average, considering many factors. These findings suggest that the need for new cooling system was the main driving factor for homeowners to change the cooling system. Likely due to the high cost required for a new heating or cooling system, most of the homeowners only changed the cooling system after they were broken, even though they were running under very low efficiency which consequently increase operation cost.

- Despite the somewhat limited financial rebate from heating and cooling systems, among the technologies invested in, the most common first technology for investment was the air conditioning and heating systems, at 36% each (72% total) of all initial investments. This might point to HVAC systems failure/issues and the high cost of replacement as the source of homeowners seeking out and/or learning about the rebate program opportunities for investment in energy efficient technologies.

Moving forward, a larger set of energy efficient technology investment data is ongoing. The technologies studied in this research last for over 10 years (according to manufactures), thus it would be beneficial to expand the 3 years data analysis to a longer period of time to a more complete evaluation of homeowner investment behaviors. Additional beneficial research could include data collection on homeowners' feedback on the programs and comparison with other programs.

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Using Truss Rafting to Create Safer, More Efficient Construction Sites

D. P. Hindman[1]

[1]Associate Professor, Department of Sustainable Biomaterials, Virginia Tech, 1650 Research Center Drive, Blacksburg, VA 24061. (540)-231-9442. dhindman@vt.edu

ABSTRACT

Worker falls in residential construction are a common source of accidents and injuries. Of particular concern is the construction stage of setting roof trusses on a top plate, where there are few opportunities for the workers to tie off to for fall protection. One possible tool to help prevent some of these hazardous situations is the use of truss rafts, or groups of trusses built on the ground and craned into position. Truss rafts allow workers to create roof systems on the ground, or on the roof using the truss raft as a fall arrest anchor. Currently, few construction companies use truss raft systems. This presentation will collect several interviews with building contractors who use rafting systems and attempts to collect vital knowledge to conduct rafting and identify areas of future research needed to help more contractors use rafting methods.

INTRODUCTION

Building construction is a sociotechnical system that requires the movement of people, equipment and materials through uncompleted structures, which may not be capable of carrying full design loads depending upon the phase of completion. A lack of load-carrying capacity can create a hazardous environment, particularly if workers are unaware of potential hazards. According the Bureau of Labor Statistics (BLS), the National Census of Fatal Occupational Injuries (CFOI) recorded 887 fatal work injuries related to falls in 2017 (BLS 2019), or 19.2% of the total fatal work injuries (4,609). Of the fatal injuries from falls, 69% occurred at a height of 30 feet or less. While the total number of fatal injuries is less than last year (4,089), the percentage of fall-related fatal injuries as increased (BLS 2019).

Residential construction in particular provides many challenges to safety including smaller workforce, compressed time schedules and lack of uniform training and regulation of fall protection devices. Residential construction heights are relatively small compared to commercial construction, which may not allow enough height for common fall arrest devices to deploy.

Several authors have identified both technical and social challenges to the use of fall protection systems in residential construction (Kaskutas et al. 2009, Lipscomb et al. 2008, Lipscomb et al. 2003). It is important to recognize that residential construction contractors are not ignorant of safety standards or concerns over employee safety. These contractors are operating within their market and budgetary constraints to remain viable businesses while addressing their levels of worker risk as adequately as possible.

Recent changes to OSHA fall protection requirements have led to confusion and misinformation being distributed. It is important to review and understand the technical specifications needed with fall protection systems that will keep workers from experiencing a fall to a lower level. However, the typical fall protection systems and policies available may not be the most useful or efficient for residential construction situations. The purpose of this paper is to examine the use of an alternative fall protection system called truss rafting that incorporates a practice-to-research-to-practice (P2R2P) method where observations of good construction practices can be refined to help produce a viable and useful system applicable to construction. There are several technical challenges to the full implementation of the use of truss rafting units (TRU) for improving safety in residential construction which will be addressed in the conclusion of this paper.

OSHA REQUIREMENTS FOR FALL PROTECTION IN RESIDENTIAL CONSTRUCTION

Prior to June 2011, residential construction workers were exempt from OSHA requirements with regard to falls from elevation. STD 03-00-001 *Interim Fall Protection Compliance Guidelines for Residential Construction* required only a generalized fall protection plan but mentioned no specific safety equipment or methods except for toe boards used for roofs (OSHA 1999). STD 03-00-02 was put into place due to concerns by various trade associations that application of fall protection provisions represented an undue burden to residential construction (OSHA 1999). The intent of STD 03-00-01 was as a temporary guidance until further development of fall protection equipment and methods could be conducted.

On April 11, 2008, the National Association of Home Builders (NAHB) wrote a letter to OSHA requesting withdrawal of the interim standard STD 03-00-01. The NAHB recognized

> *Falls continue to be the leading cause of injuries and fatalities in the home building industry and we [NAHB] are concerned that the is too much confusion in the residential construction industry as to what fall protection standards must be complied with and what methods must be used to prevent fall-related accidents (OSHA 2010a)*

NAHB stated that following the 29 CFR Subpart M Fall Protection would "eliminate confusion" as to required safety procedures (OSHA 2010a). NAHB requested that OSHA redefine residential construction to reflect the methods and materials used in construction, rather than specific uses of buildings. The development of standardized fall protection plans for similar sized projects be develoed as an aid to construction firms was recommended. (OSHA 2010a).

On June 16, 2011, OSHA issued STD 03-11-002 Compliance Guidance for Residential Construction (OSHA 2010a), which rescinded the interim STD 03-00-001 provisions

(OSHA 1999) and stated that fall protection in residential construction will be endorced according to 29 CFR 1926.501(b)(13) (OSHA 1995a), stating,

> *Each employee engaged in residential construction activities 6 feet (1.8 m) or more above lower levels shall be protected by guardrail systems, safety net system, or personal fall arrest system unless another provision in paragraph (b) of this section provides for an alternative fall protection measure. Exception: When the employer can demonstrate that it is infeasible or creates a greater hazard to use these systems, the employer shall develop and implement a fall protection plan which meets the requirements of paragraph (k) of 1926.502 (OSHA 1995b)*

To aid in the understanding of the recent changes in fall protection guidelines, OSHA has produced an OSHA guidance document *Fall Protection in Residential Construction* (http://www.osha.gov/doc/guidance.html) which is designed to "help employers prevent fall-related injuries and fatalities among workers engaged in residential construction activities, such as roofing" (OSHA 2010b). While the concept of the document is helpful, little specific information on the use and installation of fall arrest equipment is provided. No technical information as to the capacity of particular anchors or fall arrest system configurations is given and no direction on product placement within the structure is provided.

Several of the images in the OSHA guidance document could be misinterpreted. For example, Figure 24 in the OSHA guidance document on *Fall Protection in Residential Construction* (OSHA 2010b) (reproduced as Figure 1) shows a self-retracting lifeline (SRL) attached to a wooden member. The image is so closely cropped that the type of wood member (i.e., MPCWT, rafter, temporary bracing, or additional member) cannot be identified, nor can the connections of the wood member to the surrounding structure. The problem with identification of the wood member in Figure 1 is that the load path for the anchor force cannot be adequately determined without knowing the connection of this element to the rest of the structure. The load path is visualized by highlighting the specific structural members needed to transfer the applied load from the point of load application to the foundation of the structure. Many elements such as trusses or rafters are critical to the load path while requiring additional bracing elements to prevent movement. Temporary bracing elements or additional wood members may have inadequate connections to transfer the fall protection system anchorage forces through the structure, which could result in failure of the anchorage to carry the fall protection loads.

Figure 1. Figure 24 in the OSHA *Fall Protection in Residential Construction* (OSHA 2010b)

Fall Protection Systems

Proper use and installation of fall protection systems requires the structural integrity of the anchorage location be assured. Also, the boundaries and limits of the fall protection system must be aligned with worker task requirements to allow work completion. The 29 CFR 1926.501(b)(13) references three specific gravity safety devices applied to fall protection for work at elevation – guardrails, nets and personal fall arrest systems (OSHA 1995a). Each of these three systems is further discussed as to the OSHA provisions governing strength and placement, as well as the work process demands associated with residential construction.

Guardrails

Guardrails are the most common form of fall protection throughout the construction industry (Ellis 2012). Guardrail systems are often utilized along building edges and around hazardous openings more than six feet above the lower level. ANSI Z359.0 defines a guardrail as "a passive system of horizontal rails and vertical posts that prevents a person from reaching a fall edge (ANSI 2007). Guardrails are considered a passive form of fall protection since workers cannot initiate a fall when a guardrail is used. According to OSHA 29 CFR 1926.501(b), guardrails must be at least 42 inches plus/minus 3 inches above the walking/working surface (OSHA 1995a). Openings in the guardrail are limited to 19 inches or less in width, indicating that a support point or other stanchion must be located every 19 inches along the perimeter of the guardrail system. The guardrail must meet a force of 200 lbs. applied "outward or downward" within 2 inches of the top edge of the guardrail, and the force "will not cause failure" in the guardrail system (29 CFR 1926.502(b)(3)) (OSHA 1995b). Disadvantages of guardrails include time for installation, storage of equipment and difficulties with installation of edge finish materials.

Safety Net Systems

Safety nets are commonly used throughout general industry to prevent contact with a lower surface in the instance of a fall (Ellis 2012). Nets used in construction should be placed as close as possible to the walking/working surface (29 CFR 1926.502(c)(1)) (OSHA 1995). Typically, safety net systems in residential construction are limited to interior netting. Safety nets are considered an active fall protection system, since the net does not protect a worker from initiating a fall. Net hole size is limited to a maximum opening area of 36 square inches, with 6 inches per side (OSHA 1995b). A testing standard for net impact is provided in 29 CFR 1926.502(c)(4)(i) stating that a 400 lb. sand bag with a diameter of 30 inches plus/minus 2 inches must be dropped at least 42 inches above the net, and the net must be capable of 'absorbing the impact' (OSHA 1995b). No damage specifications or deflection limit of the net are provided. While deflection limits for other construction industries may be negligible, the relatively short distances to the next story associated with residential construction may be a concern with net use. The interference of building elements placed on the lower floor may create obstacles obstructing net deployment in the event of a fall. Also, safety nets may impede work on lower levels.

Personal Fall Arrest Systems (PFAS)

A personal fall arrest system (PFAS) is used to arrest a single worker in the case of a fall. The PFAS consists of an anchor, connectors, and body harness, but can also include a lanyard, deceleration device, lifeline or suitable combination (OSHA 1995b). PFAS is preferred in many situations where passive fall arrest systems are not feasible (active edges of roofs). Figure 2 is a reproduction of Figure 5 from the OSHA guidance document on *Fall Protection in Residential Construction* where a workers seems to be using some good practices for a personal fall arrest system (OSHA 2010b). The worker is using a self-retracting lifeline (SRL) on an anchor attached to structural elements of the building, including the top plate of the end wall where the roof has been sheathed. A PFAS is considered an active fall protection system since the restraint initiates after a fall occurs. OSHA has several requirements for PFAS in 29 CFR 1926.502(d) including anchorage points, lanyards, lifelines and harnesses (OSHA 1995b). Proper inspection and use of PFAS components should comply with manufacturer's instructions.

Figure 2. Figure 5 in the OSHA *Fall Protection in Residential Construction* (OSHA 2010b)

While fall arrest systems can be more time and cost efficient than other fall protection systems, there are concerns such as the proper design of anchorages, ensuring that workers can be arrested before strking the next surface and the interaction of multiple workers and equipment on the same surface (Hindman et al. 2013). Angles et al. (2012) surveyed residential and post-frame roofers to examine fall protection usage and usability requirements. Highlighted concerns included harness placement, fall arrest system donning/doffing, harness design, adjustment during use, lifeline position and instruction (Angles et al. 2012).

OSHA specifies the individual strength of PFAS components. D-ring and snapohooks msut be able to carry 5,000 lbs. with no failure or permanent deformation present until 3600 lbs (OSHA 29 CFR 1926.502) (OSHA 1995b). Lanyards and vertical lifelines must carry 5,000 lbs. SRLs are routinely rated for 900 lbs (DB Industries Inc. 2007). Anchorages must carry 5,000 lbs per employee attached (OSHA 1995b). A large variety of anchorages are available on the market including both temporary and permanent installations, using a variety of fasteners (nails, screws, clamps), and can be applied through shingles or roofing materials if needed.

Integration of Fall Protection Systems

The three fall protection systems can be used independently or combined depending upon the phase of construction and project needs. Several fall protection systems may only be useful for certain areas on the construction site. For instance, nets may be used for interior fall protection while guardrails are used for exterior fall protection. Kaskutas and Hunsberger (2013) discussed the integration of guardrail and net protection methods for a Habitat for Humanity construction project in St. Louis. Several challenges in the adoption of these fall protection methods were reported, including attitudes of the current workforce and time lost due to using safety equipment. Kaskutas and Hunsberger (2013) recommended taking a proactive approach to construction safety by consulting with OSHA officials during the project.

Alternative Methods to Achieve Fall Protection Compliance

Some areas of residential construction, such as the initial phases of joist or truss erection, remain a concern for the use of OSHA prescribed fall protection methods. Fore example, in truss erection, there is no structure present to place guardrails on. Nets may be useful for interior falls when attached to the walls of the structure. A personal fall arrest system seems useful, but the only attachment location is the top plate of the wall – which workers are standing on (Figure 3). Attaching a PFAS anchor beneath the harness attachment point creates a pre-determined fall distance (vertical distance between the anchor and attachment to harness) that must occur before any deceleration time is activiated. Ellis (2012) has noted that the walking/working surface is NOT an optimal position for anchor installation. Further solutions for fall protection are needed.

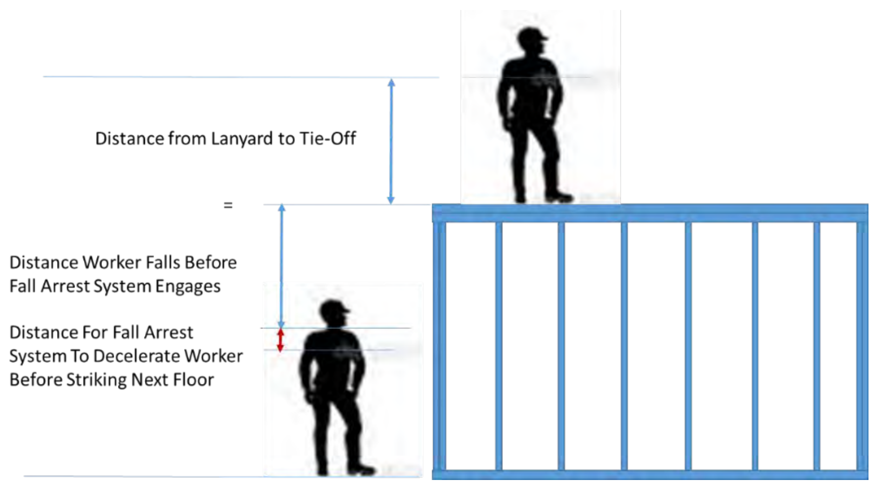

Figure 3. Illustration of Hazards of Workers Tie-Off to Top Plate of Wall

Clear solutions to these situations may not be generalizable, but may require individual specification by a qualified safety engineer. Alternative methods for construction have always been options when combined with current OSHA safety regulations. Ellis (2012) defines alternative methods as the use of other devices/methods for fall protection that inherently increase the safety of workers. Continued innovation in construction procedures is needed and may lead to increases in efficiency. Alternative methods for construction may need to be considered.

HAZARDS ASSOCIATED WITH RESIDENTIAL ROOFING

Residential roofing typically relies upon repetitive series of solid wood joists or metal-plate-connected wood trusses (MPCWT or trusses) used to span between walls and create the roof profile. Typical construction of truss roof systems requires workers to be positioned on the top plate of the wall on either side of the building while trusses are lifted to height (usually a crane is used, but smaller structures sometimes use hand lifting). The workers standing on the wall top plate must align the truss position and secure it to the top plate. After initially securing the ends of the trusses, a series of 2x4 bracing is placed between the trusses to provide lateral stability and rigidity perpendicular to the direction of the trusses. Workers are often required to climb onto individual trusses carrying bracing, and attach it with nails. Workers continue setting trusses across the roof and installing individual bracing. After a number of trusses are installed (usually between 5-6), diagonal bracing elements are applied across multiple trusses. This diagonal bracing can be placed in the interior of the trusses as well as on the top chord of the trusses. Next, 4'x8' sheathing panels (plywood or oriented strandboard) are nailed to the trusses. Then exterior finish materials of asphalt shingles or metal siding are installed.

The use of fall protection systems for roof system described above is difficult due to the challenges of truss placement as well as accommodating the changing conditions of roof surface through the application of bracing, then sheathing, then finish material. As mentioned above for the different fall protection systems, installation of edge materials such as ice guard, drip edge and fascia boards are often difficult with many of the guardrail systems. What is often not appreciated in designing the safety systems for residential roof systems is the speed of construction which is present. The different activities of truss setting, sheathing and exterior finish installation can all happen within the same 8 hour workday, and so the use of different fall protection systems to accommodate hazards represents a significant change in the time required to conduce the work, resulting in less productivity.

The use of fall arrest systems for truss setting has been explored by several researchers previously to examine if the trusses themselves could be used as anchor connections for fall protection systems. As previously noted, using the top plate that workers are standing on as an anchor is unacceptable (see Figure 3). Koch et al. (2014) examined the strength of a single truss to carry a lateral load applied to a fall arrest anchor placed at the top of the truss. An out-of-plane (perpendicular to truss) lateral load was applied to the trusses, since this load was considred the most severe loading of the truss. Maximum loads for single trusses ranged from 69 to 545 lbs depending upon the placement of the anchor along the top chord and truss slope (Koch et al. 2014). The major finding of this work was that a single truss is not sufficient to resist a fall arrest load and no worker should ever tie off to a single residential truss element.

Morris (2013) examined the lateral loading of a five-truss configuration with lateral and diagonal bracing using several different commercially available fall arrest anchors. The maximum fall arrest load that the five-truss configuration supported was 1,410 lb. An alternative bracing configuration using sway bracing of the web elements supported a maximum load of 2,440 lbs. The additional sway bracing applied to the five truss configuration was able to carry the fall arrest load associated with a single worker.

The maximum load found by Morris (2013) was less than half the 5,000 lbs required by OSHA 29 CFR 1926.502 (d)(15) (OSHA 1995b). In the author's engineering judgement, it is infeasible to expect that an anchor attached to a wood truss system will carry 5,000 lbs. Another provision in OSHA 29 CFR 1926.502(d)(15)(i) states that an anchor can be specified "as part of a complete personal fall arrest system which maintains a safety factor of at least two" (OSHA 1995b). Therefore, a fall arrest system anchorage can be designed for twice the maximum load capacity of the other fall arrest system components. Since SRLs are specified to carry 900 lbs, a suitable fall arrest system anchorage force would be 1800 lbs, which is well within the load observed by Morris (2013) for the five-truss configuration.

CONCEPT OF TRUSS RAFTING

One idea to reduce the fall risk of workers assembling truss roofs is to construct the roof in whole or a segment on the ground, then lift the section into place using a crane. This is commonly referred to as truss rafting with the lifted assembly being called a truss raft. The use of truss rafting allows workers to be in a relatively safe elevation for the early assembly of the truss roof, which is the most unstable stage where falls are most likely to occur. Assembly on the ground has many advantages besides a reduction in fall height. Because workers are wearing less required safety equipment, mobility and ease of motion is increased. Materials can be positioned next to the structure for ease of movement and materials. Also, truss systems on the ground can be easily inspected for quality and accurate construction before lifting.

Hindman and Bouldin (2013) observed a construction site using truss rafting methods to construct a multi-family development near Short Pump, VA. Truss rafts were approximately 20 feet long and 35 feet wide with internal bracing and sheathing installed. The truss rafts were built on the street directly in front of the structure (Figure 4). A 40 ton crane was used for the lifting of the truss rafts onto the three-story structure. A set of two slings were threaded through the crane hook and attached to four equidistant places on the structure. A small slot in the roof sheathing (approximately 3 inches long and 6 inches wide) was cut in the sheathing to allow the slings to connect in the structure below. The slings were looped around a triple 2x6 beam inserted between the truss webs and bracing. The triple 2x6 beams were left in place after lifting. This particular roof has a series of five different roofing profiles which corresponded to each of the five vertical units, so each different section was constructed on the ground. Each of the raft sections was lifted into position and fitted into place in approximately 15 minutes.

Figure 4. Truss Rafting of Roof Section Onto Townhouse

In discussions with the crew foreman, the initial use of truss rafting was for safety due to the changes in OSHA fall protection guidelines in residential construction. However, the use of truss rafts had increased productivity and allowed for a shorter construction time. As workers built the rafts, lumber and sheathing were located next to the raft, allowing workers to slide sheathing panels from the stack directly onto the roof. Workers were free to access the roof from a variety of different directions, allowing almost unrestricted access.

As with any process in construction, there are disadvantages and special challenges associated with truss rafting. The main challenge, especially for large roof construction, is locating a section of land that is level to build the truss raft on. Using a level surface is essential to ensure accurate fit and use of the truss raft. For many construction sites where space is limited or at a high slope, the use of truss rafting may be difficult.

The use of truss rafting requires a crane, which may not always be available or may represent an extra cost on the construction site. The construction manager must also ensure that the crane has adequate capacity to lift larger rafted section. While truss rafting can reduce the need for fall protection, workers who are helping install the rafts at elevation are still required to have fall protection.

Uplift connections, such as hurricane ties, are recommended to be installed on the outer face of the wall to avoid eceentricities and ensure a continuous load path (Simpson StrongTie 2010). In order to use rafting, a professional safety engineer is needed to ensure that the construction of the truss raft can resist the forces due to lifting, which is a stress reversal of the trusses considering typical vertical loads.

One of the largest hurdles to truss rafting is the lack of standard and exemplary methods for helping less experienced contractors use this method.

Truss Raft Unit (TRU)

Truss rafting is seen as a potential alternative construction method that can provide a safer and quicker assembly method for roofs. However, creating a truss raft of an entire roof may be an impractical solution given site constraints and crane ability. This paper suggests that a possible compromise between methods may allow for construction workers to continue similar roof construction methods but execute them in a manner with safety equipment installed.

Because the size and complexity of building an entire truss roof system on the ground and lifting it into place may be impractical, the construction of smaller sections of trusses – which could include difficult or unmanageable framing details (hip roofs, overhangs, valley sections) – can be accomplished on the ground in a small space, then lifted into place. These truss raft units (TRU) (Figure 5) can be placed strategically throughout the structure, then anchors and horizontal lifeline systems can be attached to allow workers to complete more conventional truss framing around the TRU. In this manner, the complex work can be done on the ground where the quality can be monitored closely. An added feature of the TRU is the metal angle beam that is attached to the bottom of the trusses. This is the primary alignment tool and will fit over the wall section, but also has connecitons to provide uplift connections to the wall below, ensuring that a complete loadpath for vertical and uplift forces is maintained.

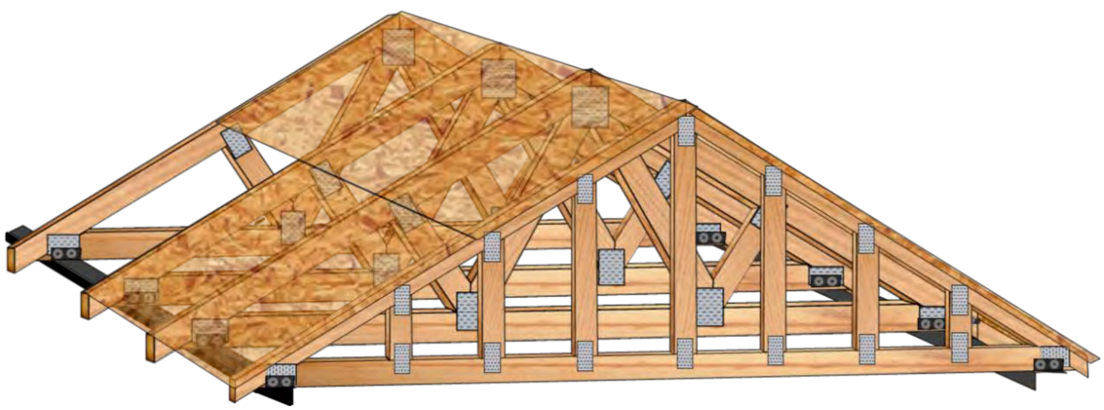

Figure 5. Schematic of Truss Rafting Unit (TRU)

Advantages of the TRU:

- Smaller ground footprint needed
- Workers can continue using conventional techniques
- Workers at elevation can now be tied off with horizontal lifelines allowing free movement along the top of the structure

RESEARCH CHALLENGES FOR TRUSS RAFT UNIT (TRU) DEVELOPMENT

At this time, the idea of the TRU is still a concept and has not been put into practice to the knowledge of the researchers. Current efforts are focused on finding research funding that will allow demonstration prototypes to be built to hopefully help contractors implement this idea in the future. It is important to note that this technology is not controlled or patented in any way and will be made freely available. A focus of the P2R2P strategy is to use commercially available products and methods rather than having proprietary control.

Items needed for development of the TRU Concept:

- Production of test structures – The creation of actual full-size modeling is needed to understand any safety hazards associated with TRU construction and how these hazards should be addressed. Also, selection of uplift connection to the lower wall needs further study, while adding as little material as possible to the structure. Also, giving advice on how must square footage is needed to construct the TRU and how to create the flat plane needed are important.
- Time vs. Conventional Construction – The TRU system needs to be tested against conventional construction, whether in an actual system or modeling-based. Time studies can demonstrate the relevance of the TRU for use.
- Testing to Optimize Anchor Placement – Testing of the final TRU section similar to Morris (2013) and others should be conducted to validate the strength of the system and help ensure that anchors are placed to prevent structural collapse in case of overload.
- A Real Demonstration – Finding a contractor who is willing to use the TRU method on a jobsite where the progress can be monitored.
- Putting It All Together – The development of a manual or training materials to help collect all of the information described above is the greatest challenge. The author describes one builder's experience in this paper and several other builders who use truss rafting have been found, but the process itself is not well known. Providing a clear understanding can help make truss rafting a common site in construction to provide a safer method for installing truss roof systems.

ACKNOWLEDGEMENTS

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Resurrecting Fire-Damaged, Glued Laminated Beams from Beyond the Grave: A Pilot for Attaining Serviceability Requirements

Cole H. Moller[1] and Brian M. Kukay[2]

[1]Structural Engineer (M.S., E.I.), CTA Architects Engineers, 13N. 23rd St., Billings Montana, 59101. (406)248-7455 colemoller@ctagroup.com.
[2]Professor and Department Head (Ph.D., P.E.), Montana Technological University, 1300 West Park Street, Butte, Montana, 59701. (406)496-4517, bkukay@mtech.edu.

ABSTRACT

There continues to be a need for restoring the flexural capacity of fire-damaged, glued laminated beams. In general, fire-damaged wood members result in reduced cross-sections, delamination, and other effects. Where warranted, the residual flexural capacity estimates are determined through a combination of post-fire assessments, white paper calculations, and engineering judgement. Thereafter, decisions are made for individual members: specifically, to remain as-is; to be repaired; or to be replaced. The focus of this research is on restoring serviceability to individual members unequivocally categorized for replacement.

Fire damage, extinguishment, and loading to maximum capacity all occur before applying carbon fiber reinforcement and conducting additional tests (in order to capture the worst-case scenario through this pilot study). The proof of concept derives from testing and pairing of 24F-V-8 DF/DF glued laminated beams. The measured values obtained from destructive and non-destructive test data facilitate the calibration of computer-generated models. The measured values also compare to the National Design Specifications for Wood Construction (NDS).

Once restored, the worst-case scenario beam not only exceeds the flexural requirements for beams in good condition using the NDS, but also produces a ductile failure once it is reloaded to maximum capacity. For these reasons, the methodology surrounding this feasibility study will also be of interest to others, including but not limited to residential building design and construction professionals.

INTRODUCTION

When structures are not ruled a total loss, the extent of fire damage becomes important to establish. This measurement drives the restoration effort and the feasible remedies that can be used to restore the strength and stiffness capacities of the structure (U.S. National Institute of Disaster Restoration, 2002). Admittedly, residual fire odors will be present and may need to be addressed. The issue of odor precedes the application of aesthetic sealers, paints, and/or other finishes (White & Kukay, Post-Fire Assessment of Structural Wood Members, 2014).

During a post-fire evaluation, White and Woeste (2013) recommend that steps for analysis begin with a paper study that will determine whether further study is required, or that a member should be replaced outright. When additional study is required, calculations are further refined and incorporate a cohort of field measurements up to and including identification and documentation of the species and grade; and the size of each timber. Additional considerations are presented in Kukay et al. (2012). The steps described, along with others as necessary, will ultimately dictate the outcome. Like wood members exhibiting varying degrees of degradation will require either no repair, restoration, or outright replacement.

Buchanan (2001) notes that residual wood under the charred layer of heavy timber structural members can be assumed to have full strength. The residual cross section can be determined by scraping away the charred layer and any wood which is significantly discolored. The exposed surface should then have the appearance of normal wood. Williamson (1982a) makes a distinction between design capacities controlled by compression strength or stiffness and those controlled by tensile strength. In the compression case, the removal of the additional 6 mm (0.25 in.) of wood is sufficient to use the residual cross section in the design calculations without any additional adjustment. For the case of tensile design calculations, Williamson (1982a) recommends an additional adjustment beyond the removal of 6 mm (0.25 in.) of wood. In calculations of residual tensile strength of the member, basic allowable design stress values should be reduced by 10%. An alternative is to take a reduction of 16 mm (0.625 in.) of wood beyond the char–wood interface and use 100% of the basic allowable design stress values.

The removal or degradation of any wood from a structural member will likely require regrading of the member to determine the proper allowable properties to be used in calculations of residual load capacity. Wood members should be re-graded after the char is completely removed. Grading procedures take into account the impact of residual dimensions on applicable grading rules for the reduced dimension as well as the altered relative locations of strength-reducing characteristics (such as knots) in the cross section. Current accredited grading agencies are listed by the American Lumber Standard Committee (ALSC 2019).

In instances where restoration is an option, access to perform the work may be easier to gainthan in cases where member replacement is needed (U.S. National Institute of Disaster Restoration, 2002), (Radford, Van Goethem, Gutkowski, & Peterson, 2002). In addition, the degree of damage becomes important because it drives the restoration effort and, in turn, the appropriate remedies to restore the strength and stiffness capacities of the structure (U.S. National Institute of Disaster Restoration, 2002). Accordingly, a new application to an existing method was evaluated in this study for wood members that would otherwise be replaced outright. This principle involves placing carbon fiber wrap on the wide faces and on the narrow, tension face of a glued laminated beam after it was not only fire-damaged but also loaded to failure. This approach was investigated on finite element models and subsequently performed on a full-scale glued laminated beam. The measured values are derived from the previous and the proposed tests. The measured values are also compared to values obtained from applicable code-based predictions using the National Design Specifications (American

Wood Council, 2012).

Carbon fiber purveys as affordable (Schober, et al., 2015) and useful in numerous applications (Hollaway, 2010). Among the applications, externally applied carbon fiber wraps are applicable to retrofit concrete, steel, and wood members; and stabilize them for both seismic and re-purposing reasons (Jones & Hanna, 1997), (Parvin & Jamwal, 2006), (Haedir, Zhao, Bambach, & Grzebieta, 2010). Carbon fiber has good fatigue strength (about three times that of steel), along with a low axial coefficient of thermal expansion. Carbon fiber also has favorable creep characteristics; resistance against abrasion (Gilfillan, Gilbert, & Patrick, 2003); and has been shown to increase the load-carrying capacity of an undamaged wood member with the full cross section intact, in comparison to an undamaged member that was not reinforced (Kim & Harries, 2010). Additional studies have demonstrated that the long-term behavior of the members is improved and the deflections reduced with the addition of a carbon fiber wrap (Schober, et al., 2015). Composite wraps can also compensate for wood defects like knots, misalignments, and the like (Bernardini, Credali, & Pistone, 2007).

BACKGROUND

Eight 24F-V8 DF/DF, 5 1/8 inch by 12 inch by 10 foot glued, laminated beams, four of which were fire-damaged, were all tested destructively prior to this research. The authors incorporated the prior data that were obtained from the destructive tests and also performed visual inspections on each of the test beams. Afterwards, two of the eight test beams, one of which was fire-damaged, were then salvaged and incorporated into this pilot study. The test beam that was not fire-damaged was used both as the control and to develop the methodology that would then be applied to the fire-damaged beam. The fire-damaged beam was then loaded to maximum capacity a second time, after it was restored.

The original measurement of the fire-damaged beam that was salvaged for this pilot study was 5.13 inches widthwise by 11.75 inches depthwise. The char layer was removed and the residual measurements were made. An average reduction in the cross-section of 14.2% with respect to average depthwise and widthwise reductions of 0.6 inches were found for this beam. The test beam that was fire- damaged and loaded to failure previously was then modeled, restored, and loaded to its maximum capacity a second time. The values obtained from these tests were also compared to service level values obtained from the NDS (American Wood Council, 2012) and from the International Building Code (IBC) (International Code Council, 2018).

Past Fire Damage, Residual Dimensions, and Destructive Test Results. Fire damage reflects a time-temperature curve intended to produce a significant zone of damaged wood due to elevated temperatures within the residual wood section. With this in mind, a longer duration and lower temperature fire exposure with a more gradual temperature gradient was made, in comparison to ASTM E119 (American Society for Testing and Materials, 2010) within the fire-damaged member (Kukay et al., 2013). *Figure 1* shows the distribution of elevated temperatures as they relate to the depth within the fire-damaged , glued, laminated beam.

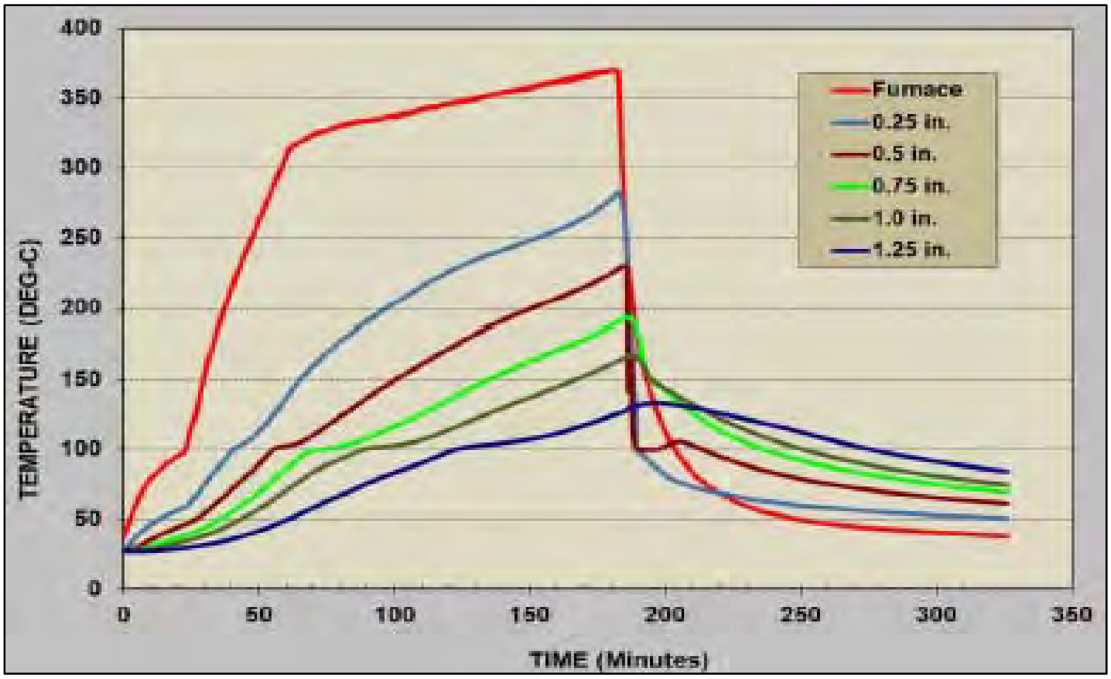

Figure 1: Temperature Distribution Versus Time at Various Beam Depths (Kukay et al, 2013 - adopted from 2013 ASCE Structures Congress).

Computer Modeling. Computer models were used to simplify the hand layup application. The plie orientations associated with the carbon fiber were intentionally limited as follows: 0^o, 45^o, and 90^o. These models were calibrated to within 10% of measured values. The measured values were obtained from linear elastic load tests for the two beams, as well as from carbon fiber tensile tests and shear tests. The latter were performed according to ASTM D3039 (American Society for Testing and Materials, 2015) and ASTM D5379 (American Society for Testing and Materials, 2015).

In the end, three 45^o (+/-/+) shear reinforcement plies and sixty-five 0^o tensile reinforcement plies were selected. Selection was based on two sets of computer analyses in which readily available software was used for the fire-damaged test beam until desirable deflections were achieved under simulated applied loads.

Beam Restoration. The first of the two test beams was used to evaluate bonding adequacy and load transfer in shear and in tension after the carbon fiber was applied to restore structural capacity to this previously failed beam using a hand layup method. There is little equipment associated with the hand lay-up method, and it would be feasible for in-the-field use (Alkhrdaji, 2015), (McConnell, 1999). Aside from the fiber orientation, a major question when applying the carbon fiber wrap to a structural member is that of bonding between the two materials. The external wrap is only going to provide as much strength as the bond will allow (Lyons & Ahmed, 2005). Once the bond is broken, there is not a mode of transfer for the stress between the two materials. The carbon fiber wrap, in turn, has no way of supporting the applied load.

The bond between wood and composite wrap can be increased with an increase in contact points between the two (Khalifa & Al-tersawy, 2013). The information gained from the tests on this first beam was then applied to the fire-damaged test beam. The most notable piece of information test results revealed was that scarifying the fire-damaged beam, then applying an initial layer of epoxy that was allowed to harden would both be necessary to properly prepare the bonding surfaces.

The fire-damaged beam was sanded lightly after the char layer was removed in preparation for the 2583 Unidirectional carbon fiber application (manufactured by Fibre Glast), since the surfaces to be bonded should be dry and dust-free with sufficient surface roughness (Schoeber, et. al., 2015), (Lyons & Ahmed, 2005).

Next, an initial layer of epoxy was applied to the bonding surface and allowed to cure. Afterwards, a second layer of epoxy was applied, followed by individual plies of carbon fiber and epoxy. The restored beam was then cured under a negative flow rate of 2.5 cubic feet per minute for a period of 24 hours.

Destructive Testing. As part of the destructive testing methodology, lateral vibrating wire displacement transducers were placed at the lengthwise mid span and ends of the simply supported test beams. The laboratory tests were performed using a destructive testing apparatus (Figure 2).

Figure 2. Destructive Testing Apparatus.

The destructive testing apparatus shown in *Figure 2* is a steel load frame that consists of a reaction beam and various support beams. Hydraulic loads were applied using a hydraulic ram at a standard rate according to ASTM D 198 (American Society for Testing and Materials, 2015). The loads and associated deflections were measured using 10,000-pound and 30,000-pound capacity load cells and a series of three lateral vibrating wire displacement transducers. An increasing point load was applied to the compression face at the lengthwise center of the test beams, and the load and associated deflection displacement was recorded for this simply supported member.

RESULTS and DISCUSSION

The results of this research are based on measured values that are obtained from destructive laboratory tests. The measured values are compared to allowable values from the NDS (2012) and from the International Building Code (2018); and to one another. Authors' note: It is not uncommon for the measured maximum values, arrived at through destructive testing, to exceed allowable values by two to five times (or more) when such comparisons are made in practice.

For the purpose of this pilot study, no adjustment factors were applied: rather, an un-factored service level load using the NDS for comparison was employed. According to the NDS (2012), the tabulated bending stress for a 24F-V8 DF/DF glued laminated beam is 2,400 pounds per square inch. This value corresponds to an applied service level load of 11,500 pounds-force, at mid-span of a 10-foot simply supported beam. The allowable deflection criterion of L/360 that is presented in the IBC (2018) corresponds to a value 0.33 inches. This value is a function of the span length of the beam and is applicable to roof members and to floor members. The measured values for the two test beams are presented in *Figure 3*, and are discussed next.

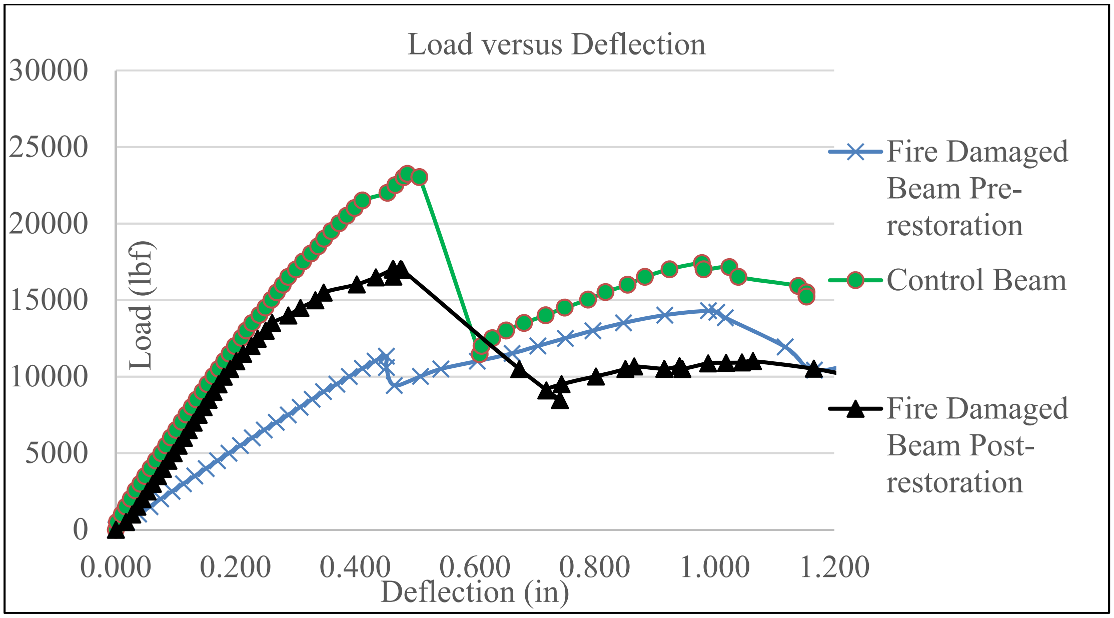

Figure 3. Measured Load-Deflection Responses.

The measured load-deflection response for the test beam that was not fire-damaged was

0.19 inches at the target service level load of 11,500 pounds-force. The results indicate that this control beam meets the serviceability requirements for loading at 57% of the allowable deflection. A maximum load of 23,250 lbs. at 0.5 inches deflection was achieved. The data for this response is presented through an applied load of 15,200 pounds and 1.15 inches of deflection.

The results that precede restoration for the fire-damaged beam are presented next. The measured load-deflection response for the fire-damaged beam (prior to being restored) is 0.66 inches at the target service level load of 11,500 pounds. The results indicate that the fire-damaged beam does not meet the serviceability requirement for deflection at the target service level load; and, that the requirement is exceeded by 200% at the target service level load. The measured load-deflection response data are presented through an applied load of 10,500 pounds and a measured deflection of 1.2 inches. The results from this response correspond to average depthwise and widthwise reductions of 0.6 inches in and to the temperature distribution presented in *Figure 1*.

The results for this fire-damaged test beam (discussed above), following restoration, are now discussed. At the target service level load of 11,500 pounds, the corresponding measured deflection is 0.21 inches at mid-span. This value is 63% of the allowable deflection and the results indicate that the serviceability requirements are met. The fire-damaged beam, once restored, is shown to support a maximum applied load of 17,000 pounds-force at a corresponding deflection of 0.48 inches. The destructive test results are presented through an applied load of 10,500 pounds-force and a corresponding measured deflection of 1 inch (*Figure 3*). The results depicted in *Figure 3* also highlight the analogous load-deflection responses between the test beam that was not fire-damaged, and the test beam that was fire-damaged, upon being restored. The results are also inherent to the successful calibration of the computer-generated model and the resulting ply orientations that constituted carbon fiber hand layup.

CONCLUSIONS

This research presents the use of proof loading, computer modeling and a hand layup application of uniaxial carbon fiber as a field-worthy restoration technique. The technique is shown to be applicable to fire-damaged members that would otherwise be taken out of service. Two 24F-V8 DF/DF, 5 1/8 inch by 12 inch by 10 ft. glued, laminated beams were tested destructively, and subsequently incorporated into this research. The test beam that was not fire-damaged served as the control and was also used to develop the methodology that would then be applied to the fire-damaged beam. The fire-damaged beam was loaded to maximum capacity a second time, after it was restored and the following conclusions were obtained.

Computer Models. Vendor recommendations were also incorporated into the computer models. The pre-restoration and post-restoration computer models provide reliable estimates of service level load-deflection responses for the test beams when calibrated to within 10% of the measured values from initial proof load tests. Uni-axial carbon fiber plies that are limited to 0^o, 45^o, and 90^o orientations and applied by way of the subsequent carbon fiber orientation-layups coincided with the computer models.

Three plies of 45º (+/-/+) were used to transfer the applied load in shear; 65 plies of 0º were used to support the applied load in tension.

Destructive Tests and Overall Comparisons. The data collected from the destructive tests pertain to the initial and restored flexural capacity of a fire-damaged, glued laminated beam; and, to a comparable glued laminated, control beam, that was not fire-damaged. The fire-damaged beam, upon being restored, closely trends the ductile load-deflection response of the control beam at service level loads. The fire-damaged beam was initially 200% of the allowable deflection criterion at the corresponding target service level load. Once restored, the fire-damaged beam was now agreeably 63% of the allowable deflection criterion at the applied target service level load. Comparisons indicate that serviceability requirements are readily attained and that the fire-damaged beam is successfully restored to a serviceable state using the methodology presented herein. Lastly, the values from the National Design Specifications and International Building Code were found to be readily attainable as a direct result. The restoration methodology is an accessible option that residential building design and construction professionals can use should repair of fire-damaged members be preferred in comparison to replacement.

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A COUPLE'S PASSIVE HOUSE – ENVIRONMENTAL RESPONSIBILITY WITHOUT CITY LIVING

J. Gary Gardner, AIA, CPHD, LEED AP

ABSTRACT

The author will share the challenges of designing a PHIUS+ compliant house that is not in an optimally compact three-dimensional configuration, particularly with regard to the building envelope. Designing walls and a roof with the very high required R-values and a high degree of airtightness proved to be challenging. This will be discussed in detail, including:

- Considering meeting the R-value requirements using different insulation options
- Embodied carbon comparisons for different wall assembly options. This is the chief concern for mitigating climate change.
- Intentional redundancy measures to achieve the required airtightness
- The ability of a first time Passive House builder to achieve air tightness requirements
- Constructability of the selected building envelope design and detailing options

Actual utility charges plus the contribution of solar panels for the all-electric house will also be shared. The electrical usage of the house will be compared with PA 2009 Code compliant usage, PA RECS averages and HERS.

The author will present the differential costs between those of the one-story house and a house of the same square footage constructed as a two-story configuration. The challenge of designing a low cost / low energy domestic hot water system that is somewhat different from the conventional will be presented as well.

In addition to the house, goals for a low impact landscape design will be examined. The two-acre property was a field full of woody weeds and poison ivy with no trees when purchased. The township is experiencing problems with too much stormwater run-off entering local streams. The presentation will discuss the owners' response to:

- Restoring the field from poor quality plants
- Mitigating contribution to the township stormwater management problem
- Adding carbon sequestration measures
- Reducing the need for gas powered lawn maintenance equipment

BACKGROUND

The house is single story with no basement (This is the way old people think – no steps if there is no elevator!). The floor plan morphed from an earlier design that was a courtyard concept. We loved the idea of a private outdoor space like the houses we saw in Beijing that were once occupied by the emperor's many children and their families. Our courtyard house floor plan wings were "smashed together" to create a more compact configuration with less exterior wall area as a major part of the path to a Passive House. The resulting design yielded a 2,400 SF main house that is provided HVAC and an untreated 400 SF detached garage. There are two bedrooms and an office in addition to a great room for living, dining and kitchen. The two buildings are positioned to provide the fairly private outdoor area that we always wanted. There are large attic spaces in both buildings where we store things.

FIGURE 1: Original inspiration for the house: The creation of private outdoor space. A royal hutong in Beijing used to house the emperor's many children and their families.

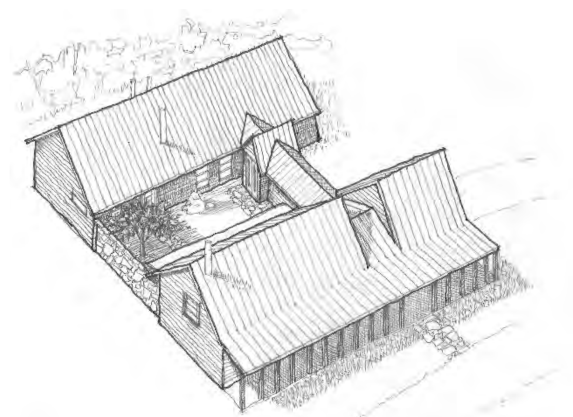

FIGURE 2: Original Gardner House design prior to adoption of Passive House design principles.

FIGURE 3: Drone view of Gardner house. Rear private outdoor space created by "detaching" the Garage from the main house volume.

The house sits on two acres in a minimum one-acre lot section of Brighton Township, 10 minutes west of Beaver, PA. The two acres were once pasture that had been unused for 40+/- years. It was full of weeds and poison ivy. There were no trees. It provides a home for groundhogs, rodents, snakes and many types of birds. Deer, possum, coyotes and who knows what else also regularly pass through.

The house is designed to assimilate into its context of smallish single-story homes with detached outbuildings set back from a busy road. Many are hip roofed with horizontal siding.

PROJECT PERFORMANCE

We hired a Passive House designer to do the Passive House modeling that determined the building envelope and energy requirements. Another consultant got us part way through the HVAC design.

Significant cost was added to the project by employing the building envelope details, high performing doors and windows. The house actually performs as it was modeled to perform, a rarity in sustainable design projects. The PHIUS+ certification quantitative performance requirements were achieved.

PHIUS+ Performance metrics:

- Heating Demand: 5.28 kBtu/ft2yr. Our total average monthly bill for heating, cooling, cooking, and convenience power is $112.
- Cooling Demand: 0.86 kBtu/ft2yr
- Primary Energy: 45 (with PV assist to offset to achieve the maximum 38.8 kBtu/ft2yr). The PV is to offset the energy lost in transmitting electricity. Virtually every Passive House home will require PV based on the current requirements of the certification agency.
- Infiltration: .058 ACH @ 50 even with misaligned doors which allow light leaks. The PHIUS+ maximum allowable is 0.899 ACH @ 50 pascals.
- Temperature difference between Indoor Air and Interior Surfaces: 1.0 – 3.2 deg F. The PHIUS+ maximum allowable is 7 degrees F. This is a key indicator of the degree of comfort a building provides. Conventional houses may have warm air but people are still uncomfortable because their skin is more sensitive to heat or cold radiating from wall and floor surfaces in a room.

Monthly utility bills for the all-electric house averaged 853 kWh for the entire 2018 period. The variation from month to month is not unusual, except perhaps in the small amounts between April through October. The lowest monthly usages were predictably in the cooling months. The house was also compared on a national basis and a state basis. The 2009 International Energy Conservation Code compliant annual energy use for a house of the same size is 114 million BTU's. The Pennsylvania RECS average annual energy consumption for a house the same size is 96 million BTU's. The predicted Passive House Planning Package annual energy modeling figure for the house, which includes the contribution from photovoltaic panels, is 31 million BTU's. When using the 35 million BTU's billed 2018 electrical utility usage, along with the offsets from photovoltaic panels to energy produced by a plant, the net amount consumed by the house for 2018 was 28.7 million BTU's. The photovoltaic energy amount is a combination of actual 2018 readings and 2019 readings because the PV's were not working for part of 2018. Some small variation with reality is to be expected. It appears that there is an 11% difference between the PHPP prediction and utility bills. The PHPP metrics were determined by using what a German family where both adults worked full time. The couple living in this house live there almost 24 X 7 – 3 meals a day, TV on a lot (sometimes two), more lighting, etc.

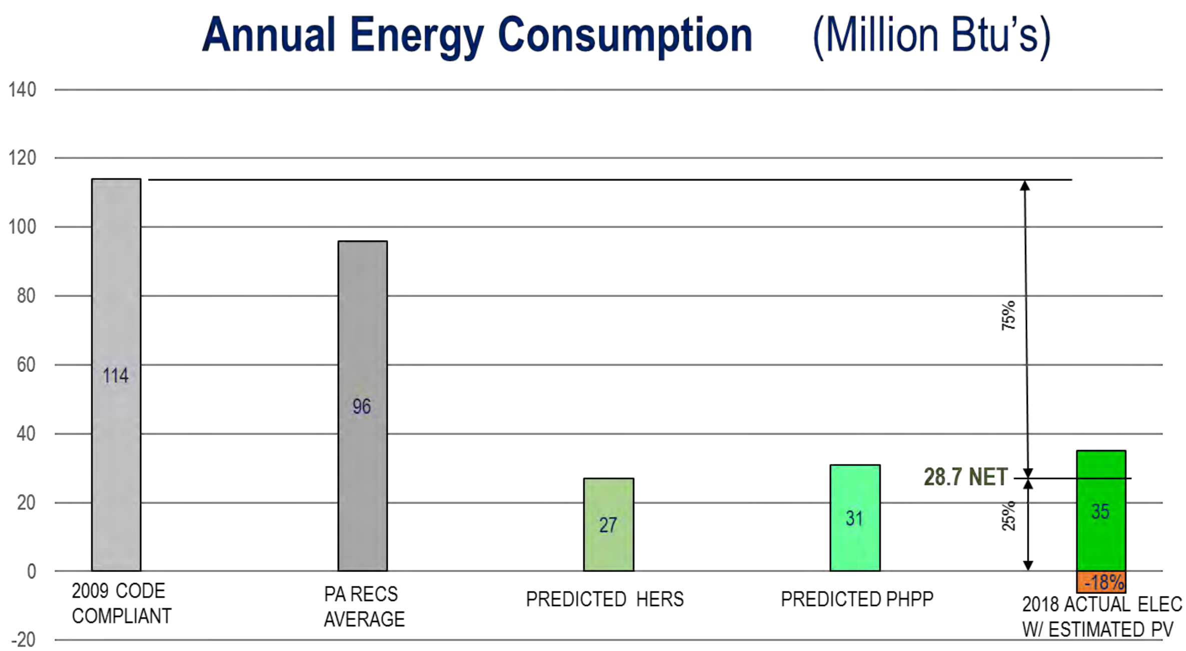

FIGURE 4: The 2018 Passive House energy consumption is 26% of the 2009 IECC Code maximum quantity. The IECC 2009 is the current energy performance requirement of 114 million Btu's per year for Pennsylvania's single- family housing industry. The house is also performing within the PHPP model prediction.

CONSTRUCTING FOR HIGH PERFORMANCE

Because the building envelope area to building volume is not lower – not a two-story volume - the performance of the envelope must be better in order to achieve the required energy consumption metrics. R-values for building assemblies appear in the table below.

BUILDING ASSEMBLY	R-VALUE/FACTORS
INSULATION SURROUNDING FOUNDATION	33.1
UNDER SLAB INSULATION	71.3
WALL ASSEMBLY	67.1
ROOF ASSEMBLY	78.3
WINDOWS	5.0
DOORS	3.85

TABLE 1: R-values for building envelope assemblies.

Air tightness is even more critical. The typical new house today has infiltration rates of 5 – 7 air changes in the building per hour (5-7 ACH @ 50 Pascals). This house could not exceed 0.6 ACH @ 50 in order to meet the maximum allowable energy usage metrics for PHIUS+ certification. The preliminary blower door test, done when sealant and taping was completed yielded a PHIUS acceptable .833 ACH. The final blower door test, done after the spray polyurethane foam installation was completed, yielded an infiltration rate of 0.58 ACH. A 0.60 ACH was needed for this house as part of the strategy to get the energy consumption metrics low enough for PHIUS+ certification. Many houses have achieved the required infiltration rates using membranes on the interior wall faces and fibrous insulation. We relied on spray polyurethane foam insulation alone to improve the air tightness of the building envelope.

Taping and sealing to achieve air tightness is time consuming, but it is not difficult. It is a quantifiable additional task that is just not common to typical house construction. We taped in addition to sealing joints with a caulk-like product. Redundancy is advised to achieve air tightness.

The requirements for air tightness are more stringent than conventional house construction, drawing the most concern from the builders. It is typically the Passive House requirement most often failed by builders. The air tightness requirement for this project was met by a first-time builder by following our installation directions. Our PHIUS Rater provided experience on the time required to complete the air tightness work. He also had possible fixes if/when blower door test results are not good enough, which we fortunately did not need. We used German construction tapes (tricks to learn here), roll-on weather barrier and special sealants to achieve an air tightness seven times better than a conventional house. The sealant and tape on sheathing, plus spray foam insulation in between studs, delivered the required air tightness without any additional air barrier components.

We did not need an interior air barrier since the spray polyurethane foam formed and airtight barrier by itself. Note that spray polyurethane insulation is difficult to install properly. Consequently, many in the building field who did not do it correctly blame the material instead of themselves.

The elimination of thermal bridging is another part of the strategy to lower energy consumption. Energy transfer from interior to exterior through materials being in contact with one another is a concern in buildings with such low energy usage. These seemingly very small energy losses have a magnified impact in a Passive House because they represent larger percentages of an overall very low energy load. Typical intersections of windows, walls, foundations and slabs, with their attachment components, would allow thermal energy transfers that are too large. Insulation is used to separate the intersecting building assemblies in the details for the house. Non-metallic flashings are also used to mitigate thermal bridging. These details are some of the ones that contractors see as unusual and therefore problematic. The first-time Passive House contractors were able to construct the details with on-site supervision.

Solar gain played a major part in the energy picture for the house. Our initial PHPP Passive House modeling work showed us that we still exceeded the maximum allowable heating energy usage for the house until we increased the amount of window on the south elevation by one 4' X 5' triple glazed window. The PHPP+ model allowed us to vary the amounts of glass, insulation, thermally bridged details and other details that impacted building performance so that we could determine the most desirable amounts of each, and the details used for them, in order to still achieve the PHIUS performance requirements. The house would require 26 more PV panels at an additional cost of about $30,000, in addition to the 5 it already has, to become a Net Zero Energy project.

The selected wall assembly was also run through WUFI successfully. The wall interior did dry out in the model, though somewhat slowly. The low amount of moisture absorbed by the insulation and the rain screen wall design are the probable reasons for WUFI success.

There was a fairly strong, but not absolutely consistent correlation between the cost of the wall assemblies considered and their embodied carbon. This seems to occur because the wall assemblies with the most embodied carbon also have the most components, even when their insulations the lowest embodied carbon. The chart (Figure 6) below summarizes:

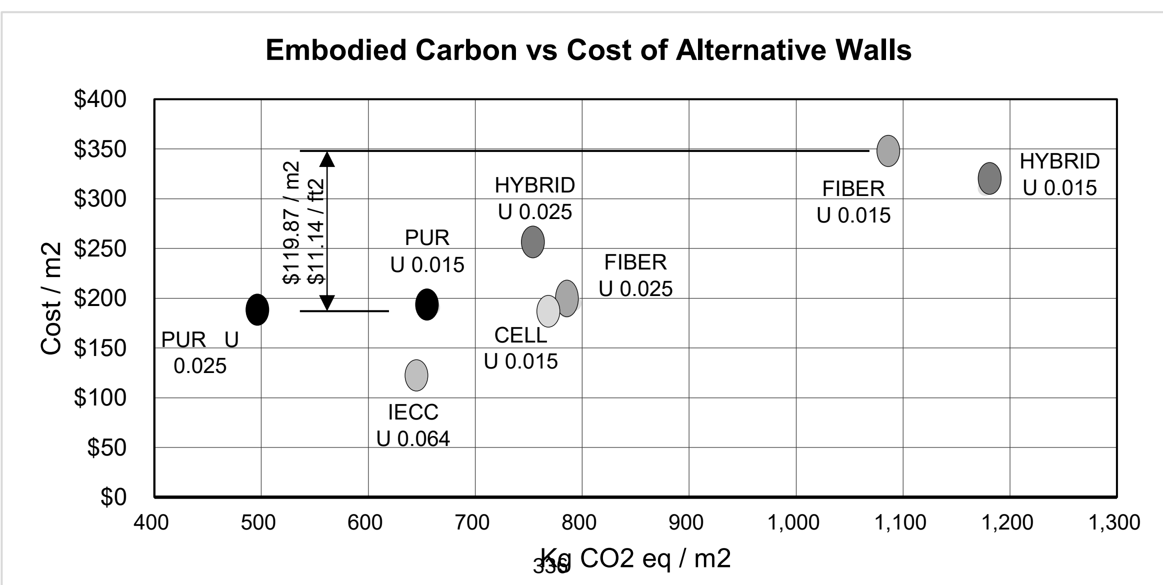

FIGURE 5: Wall assemblies achieving the same U-value using different insulations and related components can have higher embodied carbon and higher cost.

Wall assemblies achieving the same U-value using different insulations and related components can have higher embodied carbon and higher cost. because it takes more materials to achieve the targeted U-value than other wall assemblies with higher R-value insulations that do not also require components to hold the insulations in place. See Figure 8 and adjacent text for more information on wall assemblies' composition.

Typical Wall Section

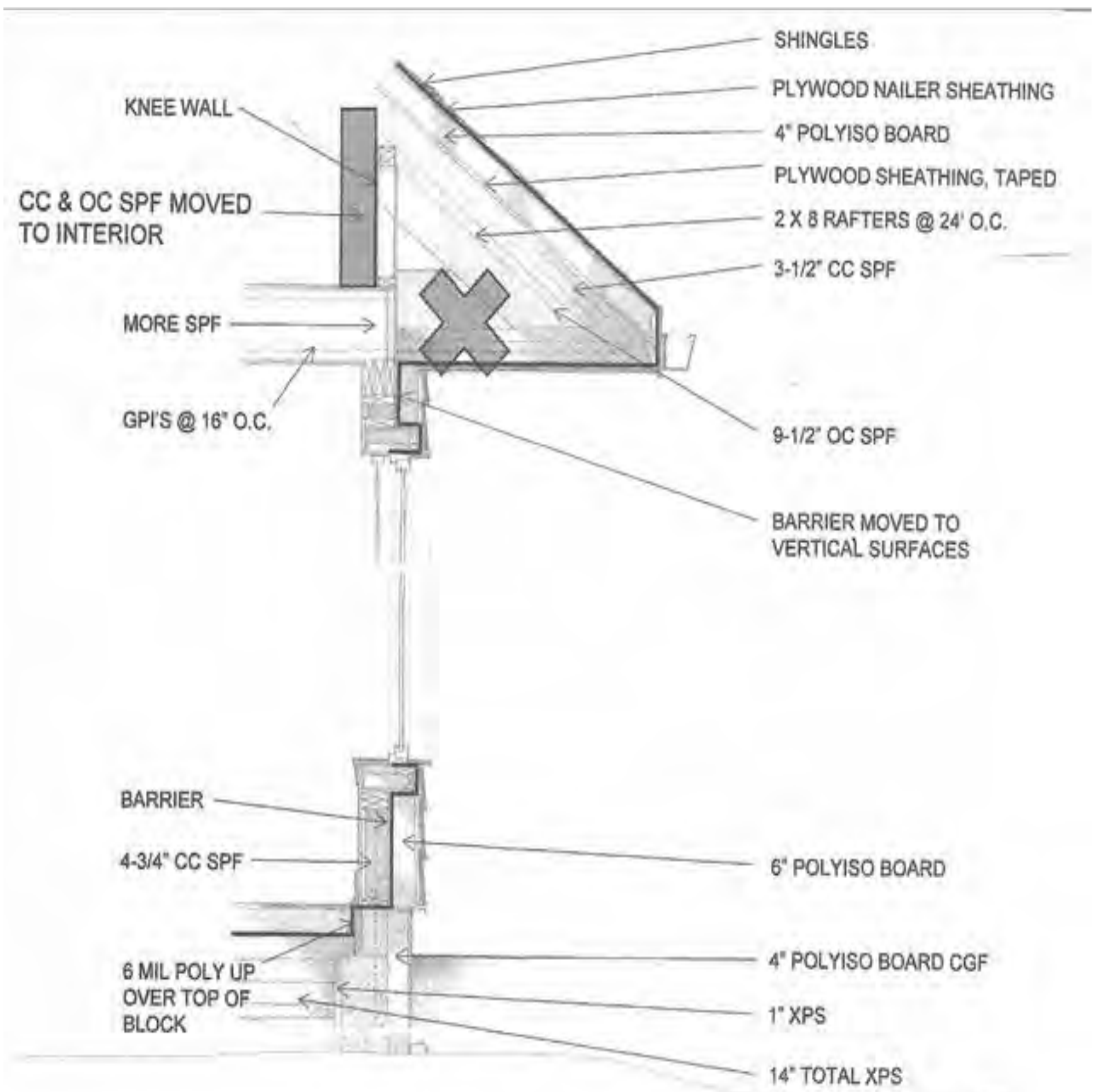

FIGURE 6: Air tightness requirements for PHIUS+ certification were achieved by taping the sheathing and sealant at joints.

Air tightness requirements for PHIUS+ certification were achieved by taping the sheathing. Additional air tightness was achieved with spray polyurethane insulation (SPF) in between the studs. The SPF installer surprised us when he came to do his work. We had to reposition the air barrier because he could not spray where we originally intended. Note that windows were moved forward away from the 2 X 6 structure to catch solar gain. Polyiso board and spray foam insulation were the only materials that could achieve the required insulation performance with reasonable constructability and cost. Other less rigid insulations would have required additional components to support the additional thickness to achieve the required R-value – attachment clips, additional studs and sheathing and an additional air barrier. The PHPP model told us to insulate the foundations for both general energy savings and for the prevention of thermal bridging. One-story small Passive House projects often have significant under-slab insulation requirements. The moisture/weather barrier (dark line above) continues from under the slab to over the top of the foundation wall. There, it meets the roll-on air barrier product applied to the exterior side of the sheathing. That barrier extends around windows and openings barrier in the form of tapes and non-metallic flashing. It extends then to the roof sheathing covered by a breathable membrane.

Typical Window Detail

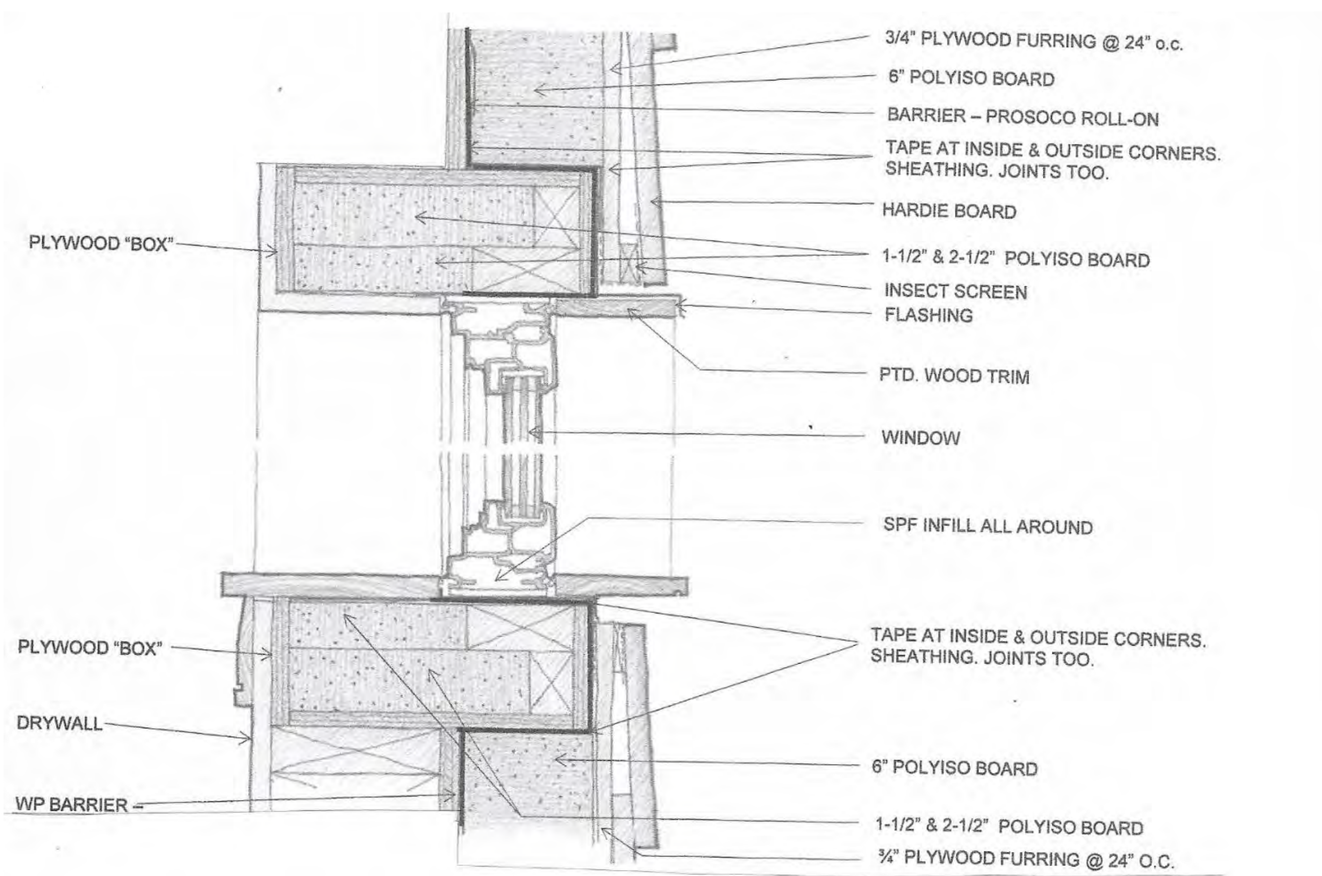

FIGURE 7: Wall and "window box" framing is configured to avoid thermal bridging. The "window box" positions the window to receive solar energy at the optimal times. The dark line indicates the weather barrier location. It is made of roll-on material, non-metallic flashings and sealant.

IMPORTANCE OF EMBODIED CARBON RELATED TO CLIMATE CHANGE

In addition to the need to reduce operational energy usage for the long-term use of the house, there is a need to greatly reduce the embodied carbon of the materials used to construct the house. Both the AIA 2030 Challenge and the 2015 Paris Accord, the United Nations group concerned with climate change, have stated that the only way to reduce the amount of carbon entering the atmosphere enough in time to stop a catastrophic global warming outcome is to lower the embodied carbon in the products and materials used in constructing our buildings. It is a race to reduce the impact of carbon on global warming that cannot be won with just reducing the operational energy usage of new and retrofitted buildings to zero by 2030. Embodied carbon in buildings must be reduced by 100% in new buildings by 2030. Embodied carbon in all building materials, for new and retrofitted buildings, must be reduced by 100% by 2050 in order to mitigate global warming enough to prevent climate disasters.

The materials for the house wall assembly were selected for their high R-value, their resistance to moisture and their contributions to a low embodied carbon solution. Wall assemblies using different types of insulation were considered. In the end, the assembly that had the lowest embodied carbon, met the PHPP model's insulating requirement, and, the lowest unit cost was a combination of polyiso board and spray polyurethane foam. That assembly did not need additional components such as are needed to support semi-rigid insulation – clips, additional sheathing, air barrier membranes, etc. It's higher R-value insulation also meant that less material was needed to achieve the insulation requirement. Less material for insulation and other wall assembly components resulted in lower embodied carbon for the assembly. The chart below illustrates the situation.

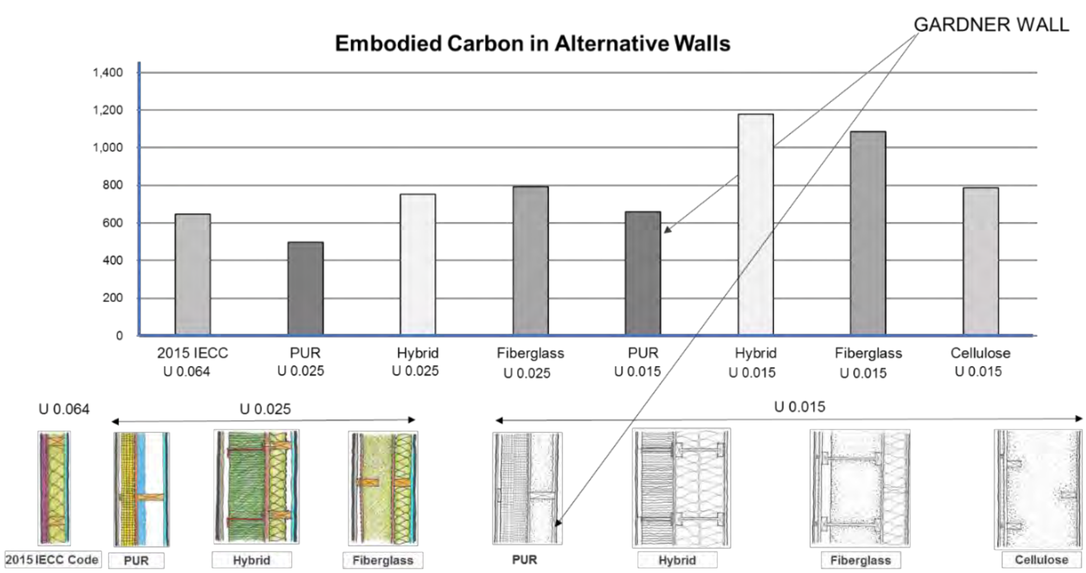

FIGURE 8: The chart above shows embodied carbon quantities for the alternative wall assemblies that were considered. Note that the PUR assembly with the lowest U-value also had a lower embodied carbon metric than two assemblies using fibrous insulation that have higher U-values.

Each wall assembly in the chart above also included an exterior fiber cement board cladding, 2 X 6 or 2 X 4 wood studs and a drywall interior finish. Wider wall framing components such as Larsen trusses or double wood studs are required for thicker amounts of fibrous insulation.

The following Table summarizes the components that make up each wall assembly shown in Figure 8:

Wall Assembly	U-value	Continuous Insulation	Weather Barrier	Sheathing	Insulation Between the Studs	Air Barrier
2015 IECC	0.064	1" Polystyrene	Tyvek	Plywood	3.5" Mineral Wool	Permeable Membrane
PUR (Polyurethane insulations)	0.025	4" CGF Polyiso Board	Roll-on	Plywood	2" Closed Cell SPF	None
Hybrid	0.025	5" Mineral Wool w/ Clips	Roll-on	Plywood	5.5" Fiberglass	Permeable Membrane
Fiberglass	0.025	6" Dense Pack Fiberglass	Roll-on	Plywood	3.5: Fiberglass	Permeable Membrane
PUR (Polyurethane insulations)	0.015	6" CGF Polyiso Board	Roll-on	Plywood	4.75" Closed Cell SPF	None
Hybrid	0.015	8" Mineral Wool w/ Clips and Larsen trusses	Roll-on	Plywood (2)	11" Fiberglass	Permeable Membrane
Fiberglass	0.015	6" Dense Pack Fiberglass w/ Larsen trusses	Roll-on	Plywood (2)	3.5" Fiberglass	Permeable Membrane
Cellulose	0.015	N/A. Double studs	Roll-on	Plywood (2)	18" Dense Pack Fiberglass	Permeable Membrane

TABLE 2: Components in wall assemblies.

Some may select other wall assemblies using other insulations out of other concerns such as healthy materials or recyclability. However, it appears that if global warming is the primary concern in higher R-value wall assemblies, then polyiso board for continuous insulation and spray polyurethane for cavity insulation may provide one of the best results. This is contrary to what most people would believe. It is the performance of the insulation materials that make it possible. And while no one insulation or assembly is the right choice for every situation, the work on this house shows that the palette of "good low carbon" materials is larger than most believe.

HVAC SYSTEM AND COMFORT

The electric heat pump system combined with 24/7 fresh air ventilation actually works. There are HVAC subcontractors in the area that can build them successfully. Simple control systems work best.

The 24/7 Energy Recovery Ventilator (ERV) uses a supply duct system and a return duct system to deliver fresh air to the rooms in the house. The air is pre-heated in the winter and pre-cooled in the summer with a ground source heat loop over which incoming air is blown. A 9,000 BTU electric split system heat pump with a supply air system to rooms in the house and a large return air vent in the hallway provides heating and cooling at low air speeds. There are also ducts that allow return air to move from certain spaces to the hallway where a large return air vent connects with the heat pump.

DOMESTIC HOT WATER SYSTEM

The domestic hot water system uses a high percentage of all of the energy used in this Passive House because the building enclosure makes the overall house so energy efficient for heating and cooling. PHIUS+ requires the energy used to heat domestic water to be counted in the energy calculated maximum allowable metrics. The system uses a room by room on demand system with a manifold to direct the water only to the room that called for it. There is no conventional hot water loop coursing through the house connected to a hot water heater. This system uses much less energy than a conventional hot water loop system. System design consists of an occupancy activated water pump, a manifold to direct water flow to the desired room and insulated return piping back to the heat pump hot water heater. It takes 10 seconds after the infrared sensor is activated for hot water to reach a faucet in the house.

Figure 9: Window "box" partially exposed as continuous insulation is installed. Note tape at all sheathing joints and around window. Tape and sealant were installed by first timers.

Figure 10: Manifold that routes on-demand hot and cold water to the various plumbing fixtures in the house.

ONE STORY PENALTY

A single-story house can achieve Passive House certification but not as easily as a two-story house of the same square footage. There were cost penalties that totaled about $20 / sq.ft. above the typical $200 per sq. ft. Passive House cost, for not being more compact in configuration:

- Higher required R-values for walls and roof; as much as 50% more than a two-story house with the same area.
- Increased lengths of ductwork.
- Increased siding and roof cost.
- Slab-on-grade/foundation/wall interface problems.
- Roof/wall detail problems

Table 3 below summarizes the cost variations totaling approximately $20/sq. ft. between a one-story and a two-story configuration. Figure 13 delineates some other project specific issues that also served to increase the project cost. The table below summarizes the cost story.

Total Project Cost	$238 / sq. ft.
Less One Story Penalty	($20 / sq. ft.)
Less Project Specific Issues	($18 / sq. ft.)
"Typical Passive House Cost"	$200 / sq. ft.

TABLE 3: Cost "history."

Building Component	Two Story / More Compact	Our One Story Configuration $20/ sq. ft. Penalty
Roof	~ R 45 - 55	R 78.1
Above Grade Wall	~ R 45	R 67.1
Under slab insulation	R 12	R 71.4
DHW	Shorter pipe runs	At the limit of capacity for Primary Energy. Non-recirc. system.
HVAC	Less duct	Duct length not impactful on performance.
Infiltration	PHIUS allows 0.89 ACH	Must have 0.6 ACH Got 0.58
Primary Energy	PV often required	PV required. 5 panels to deliver
Cost	$200 / sq. ft.	$20 / sq. ft.

Table 4: Cost Variation Between One Story and Two Story House Configurations.

Cost Adjustments	Project Specific Issues
Extensive grading	($4,000)
Township stormwater pit	($6,500)
Construction paid for twice	($3,570)
Electrical issues	($11,451)
	($25,521)
Changing contractors	($30,000)
	($55,521)
Adjustment	($19.83 / sq. ft.)
Adjusted house cost	$218.17 / sq. ft.
Additional penalty over $200 / sq. ft.	$18.17 / sq. ft.

Table 5: Project Specific Cost Issues totaling $18 / sq. ft., that along with the $20 / sq. ft. one story cost penalty, increased the project cost over $200 / sq. ft. to a total of $238 / sq. ft.

RAINWATER HARVESTING

The township required a storm water retention pond on the site to offset the substitution of hardscape for field. We also constructed an underground rainwater collection system. It takes rainwater from the roofs, the driveway and the rear patio to a 600-gallon cistern. That water is used for bushes, flowers and the vegetable garden instead of potable water. Since the processing of potable water uses a great deal of energy, the need for less of it is a very environmentally responsible thing to do.

LANDSCAPE FOR MINIMAL IMPACT

In addition to the design of the house, the landscape received some attention.

Ornamental grasses that require little in the way of resources are a major planting on the property. A Pennsylvania meadow grass containing wildflowers giving us beauty for virtually no maintenance covers a large part of the property too.

We also planted the balance of the property with "No Mow" grass. It grows a maximum of 8" a year and only requires cutting once a year, minimizing the use of mowers, which have the highly polluting engines on a per horsepower basis. It will take two more years to fully establish this ground cover.

We have planted eight trees on the property that had none, to upgrade the environmental contributions made by the property – trees for carbon sequestration. We plan to plant more.
The overall result is a landscape that requires fewer resources to maintain than many conventional yards, even though it is a semi-rural area and is larger than the typical yard.

CONCLUSION

Building new in an area that is not densely populated is considered by some to be a fundamental sin from a sustainability viewpoint. Living in more densely populated areas is considered to be more environmentally responsible than building new and increasing suburban sprawl. However, many older people choose not to live in a dense urban area. This house offers one way to be fairly responsible environmentally and still live where one wants. Water use, low impact landscaping and field restoration are areas of endeavor, when combined with energy conserving construction and low embodied carbon materials, provide a path toward better solutions.

So, if you must build out beyond the city, this project offers a way to do so without feeling so guilty. It also addresses a desire by many people to live in a single-family dwelling as long as they can, while minimizing the environmental impact in doing so.

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Participatory Design in Housing

Nilou Vakil[1] and Joe Colistra[2]

[1]Assistant Professor, Interior Architecture and Design Program, School of Architecture & Design/University of Kansas, 1465 Jayhawk Blvd., Lawrence, KS, 66045. 303-669-3675, Nilou.Vakil@ku.edu

[2] Associate Professor, Department of Architecture, School of Architecture & Design/University of Kansas, 1465 Jayhawk Blvd., Lawrence, KS, 66045. 720-203-5678, jcolistra@ku..

ABSTRACT

This paper describes a participatory development strategy used to empower community. When residents in a historic residential neighborhood of Denver, Colorado learned of a plan to build speculative housing, they tapped architects to assist them in pooling resources and expertise in order to build a project they felt would be more congruent with the scale and character of their neighborhood.

Recognizing that only those affected by an environment have any right to its determination, forty-two long-time residents all living within a few blocks of the project put their own homes up for collateral in order to secure construction loans for this development. The design and development process described contests the traditional roles of both the architect and client.

Architects often view broad participation with skepticism, believing that participatory design that aspires to operate in a way that might be categorized as emancipatory cannot possibly yield the same level of design quality afforded projects that are not shackled by the marginalization of a shared vision or "design by committee."

The architects were cognizant of the political nature of this process and led the citizen group through the participatory actions of establishing a pro forma, setting up a Limited Liability Company (LLC), acquiring the land, securing financing, selecting professional engineers and contractors, and ultimately constructing the project.

Sharing resources allowed community members to become active participants in their built environment. The willingness to invest in one's own neighborhood reflects a willingness to invest in oneself and the belief that these actions can allow a group to act strategically and critically to restructure a world they cannot wholly remake. This self-development model generated a great sense of pride and accomplishment as the neighborhood witnesses the emergence of a community asset shaped with their own ideas and resources.

INTRODUCTION

The design of our built environment is almost exclusively accomplished by a fee-for-service framework. This ensures that only those with means and privilege are able to commission designers to bring their ideas to fruition. It is even common for this professional client to build the professional services into the financial performance of a real estate venture. The typical model leverages the anticipated return on investment against the upfront costs of completing a project. There exists a clear irony, not lost on those of us committed to participatory design, that this model makes it very difficult for those affected by an environment to have any right to its determination.

Participatory development empowers community by giving it a voice through both the design process and by delivering a built environment that reflects the values and mores of the community. When planned strategically, it also reflects transitioning market values. This is one of the primary characteristics of gentrification: it prevents marginalized community residents from participating in the increased valuation of their neighborhoods.

Many designers aspire to practice participatory design in a way that might be categorized as emancipatory. This is usually looked upon by the design community as not possibly being able to yield the same level of design quality afforded projects that are not shackled by the marginalization of "design by committee."

In *The Production of Space*, Lefebvre wrote of the idea that space in contemporary society could be produced like a commodity and is therefore inherently politically contested. (Lefebvre, 1991) Does participatory design then nullify the possible existence of a cohesive design philosophy? The Viennese architect Ottokar Uhl, in writing of the 'democratization of aesthetics', conceptualized the notion of a popularized aesthetics of the many; that participants in the design process could reject the aesthetic standards of others in forming their own environments. (Uhl, 2003)

Milestones in participatory design such as Lucien Kroll's Louvain University Medical Dorm, Ralph Erskine's Byker Housing, and Giancarlo de Carlo's Nuovo Villaggio Matteotti do tend to have a nonhierarchical organization that one could argue elevates the individual and provides various if somewhat disjointed ways of living. Put another way, they are messy. Kroll's "wandering columns" were intended to provide for flexibility in the location of internal partitions and the creation of self-directed spaces. This somewhat loose formal ordering system became labeled as 'adhocism' in Charles Jencks' seminal book, *The Language of Post-Modern Architecture*. (Kroll, 1987) He described this improvisation and pluralism as intentional and where "disparate parts are unified creatively for a specific purpose." (Jencks, 1977)

Thomas Dutton reinforces this notion,

> "Issues of agency, process, and social action are not antithetical to beauty and

> good form. Often social responsibility is equated with designing for the lowest common denominator, appealing to mass interest unreflectively, without theory. As such, social responsibility is positioned against beauty and aesthetics as the negative other, a hindrance to be avoided because it compromises formal interest and investigation. This need not be the case, as richer form can come through social responsibility." (Dutton, 1996)

Indeed, design education tends to validate idealized form-making through the absence of a user. Of course the student-tutor relationship simulates architect-user engagement, however, the significance placed on disciplinary-coded drawings and language perpetuates the notion that the expert knowledge of the designer is certainly privileged over the tacit knowledge of the user. It negates the design process as a two-way negotiation and would threaten what we believe sets us apart and in fact defines the discipline.

Giancarlo de Carlo offers, "…the intrinsic aggressiveness of architecture and the forced passivity of the user must dissolve in a condition of creative and decisional equivalence where each – with a different specific impact – is the architect, and every architectural event – regardless of who conceives it and carries it out - is considered architecture. (de Carlo, 1971)

PAOLO FREIRE: PROBLEM-POSING SPACES

In attempting to bring theoretical underpinnings to our participatory design work, one can examine the increasing number of designers that are finding ways to break free of a practice dependent upon clients paying for professional services. (Feldman, Palleroni, Perkes, and Bell, 2013) A new 'entrepreneurial' model of practice may loosen the constraints of designers who are torn between the need to operate within a viable business model and the desire to bring design engagement to traditionally underserved neighborhoods. Entrepreneurship is a process by which individuals pursue opportunities without regard to the resources they currently control. (Stevenson and Jarillo, 1990) The entrepreneurial designer, then, is one who is able to identify opportunities for change in our communities and *independently* takes constructive action.

The de-coupling, or at least re-framing of the client role that may free the design professional from responding solely to the needs of paying clients, redraws boundaries that may allow us to address more complex challenges facing our society head-on.

The relatively small urban interventions explored here serve as demonstrated attempts to transition residents from passive bystanders that are acted upon to active participants in the shared process of community redevelopment. In this case, it is the professional knowledge surrounding real estate development and valuation that allows for this transition to active participant. Brazilian educational theorist Paulo

Freire's 'banking' concept of empowerment is relevant to this point. His analogy contends that in the traditional educational model, the teacher 'deposits' knowledge into the student as though the student is an empty container. The passive learner is acted upon and the potentially emancipatory process of gaining knowledge (and therefore power) is negated by being reduced to a one-way mechanical transaction. (Freire, 2005)

Applying this 'banking' analogy to the design profession reinforces the expert-layperson relationship. Freire wrote,

> "The more students work at storing deposits entrusted to them, the less they develop the critical consciousness which would result from their intervention in the world as transformers of that world. The more completely they accept the passive role imposed on them, the more they tend simply to adapt to the world as it is and to the fragmented view of reality deposited in them." (Freire, 2005)

He rejects this banking model in favor or what he refers to as a 'problem-posing' model of education that holds participatory dialogue as indispensable. (Freire, 2005)

Stakeholders sharing in the visioning process for community redevelopment projects has long been held as a requirement of any sensitive revitalization effort. How can stakeholders be elevated from peripheral players to decision-makers that may be able to invest (even modestly) in a community's transformation and thus directly benefit from shared investment efforts? This mode of shared participation transcends the monetary transaction. The willingness to invest in one's own neighborhood reflects a willingness to invest in oneself and the belief that these actions can allow one to act strategically and critically to restructure a world one cannot wholly remake. (Colistra, 2016)

CASE STUDY 1: CHAMPA TERRACE TOWNHOMES

The author's firm, in situ Design, was contacted by a group of neighbors living in the historic Curtis Park neighborhood of Denver, Colorado. A short walk from Denver's Central Business District, Curtis Park is one of the oldest neighborhoods in the city. It once contained the main thoroughfare connecting downtown to the since-relocated Stapleton Airport. Believing that this neighborhood would one day be the primary connector to the airport, city planners rezoned blocks of turn-of-the-century Victorian mansions, Italianate rowhomes, and quaint Queen Anne bungalows to a high to medium density commercial zone district. Two decades later, the explosion of growth south of the city and the relocation of the airport left a tree-lined walkable neighborhood largely intact but with inappropriate zoning.

As increasing vibrancy and walkability began to transition Curtis Park into a desirable location ripe for redevelopment, outside developers began building what has since become referred to as "slot-homes." (Kenny, 2017) These are side-by-side row homes that maximize allowable density by configuring units perpendicular to the street. The result is typically a bare wall presented to the street with any opportunity for a residential porch or stoop buried deep within the block. When neighbors learned of a developer's plan to construct such a 16-unit project on an empty lot between two historic homes, they began exploring opportunities that would allow them to tie up the land.

An initial group of eight families, all living within a few blocks of the property, formed a Limited Liability Company called Curtis Park Investors Group (CPIG) and purchased the lot for $40,000. The group then began recruiting other interested parties within the neighborhood. They set out to construct a viable real estate development while protecting the neighborhood's historic character. As the venture gained momentum, town hall-style design workshops were held to manage the project. The resident group was from a diverse range of economic backgrounds that included such professions as a city planner, a teacher, an historian, a lawyer, and several residents who worked in the construction trades. They were brought together by concerns for the future of their neighborhood. A true example of crowdsourcing, these long-time neighborhood residents put their own homes up for collateral in order to secure a construction loan of $1 million. This group of twenty-three neighbors recognized the power that came with organizing politically. (Fig.1)

Figure 1. Champa Terrace groundbreaking.

The firm worked with CPIG over the following months to develop a 4-unit townhouse project that would be called Champa Terrace Townhomes. The solution maximizes the allowable site build-out while blending into a block of historic homes. Design features that enhance the residential character include front doors that all face the street, front porches that provide a pedestrian scale, and exposed steel columns that accent the porches and hint at modern interiors. The units have been designed to cluster service functions (powder, closet, laundry, stairs) along interior demising walls providing sound insulation that is essential to multi-family dwelling while maximizing the perimeter walls for large double-hung windows that have been selected to match historic windows throughout the neighborhood.

Large skylights centered above custom steel staircases cap double-height spaces. Fitted with cable-rails and Alderwood treads, these stairs are the focus of the central space. (Fig. 2) Like the development process itself, these stairs are designed to utilize off-the-shelf systems and components to reflect a certain do-it-yourself nature. Floor-to-ceiling glass partitions allow light deep into spaces typically windowless due to demising walls in townhome or row home configurations. Light-colored bamboo floors also help to make the spaces feel brighter. Resident-investors ordered the kitchen cabinet components in bulk from Ikea and held an assembly party to construct the boxes. Also, residents assisted with forming the hand-poured concrete kitchen counters and bathroom vanities. Predictably, they reflect an aesthetic that leans more DIY than the refined precision of finish carpentry.

Figure 2. Champa Terrace interior.

Roof decks provide views that reveal the downtown skyline and Rocky Mountain Front Range beyond. The rails surrounding the roof decks are set back from the cornice and provide a modern interpretation of the Mansard roof form common in the neighborhood.

The project sold out within six weeks of the completion of construction and investors realized an approximately 65% return on investment. This type of infill project is likely to raise property values. However, a key distinction from typical gentrifying developments where all return on investment leaves the neighborhood, this framework allows all profit to stay within a few blocks of the project. The process also resists gentrification by consciously weighing profit against affordability and setting up a structure in which investors are not driven solely by return on investment but also on community cohesion.

CASE STUDY 2: MERCHANTS ROW BROWNSTONES

Champa Terrace was lauded in the local press for its proactive approach to community development. Feeling enfranchised and seeing the opportunity to replicate this development model, the group looked into rolling its returns into a second project. They investigated a vacant lot on an important corner that anchors an historic district. As additional neighbors became interested in joining the investment group, they realized they would need to establish a more sophisticated investment structure. A second LLC was established that included both guarantors and non-guarantors of the loan. Within this framework, forty-two neighbors co-signed a construction loan.

This second self-development model is called Merchants Row Brownstones. This $2.5 million multifamily housing development is modeled after a rowhome prototype common to the neighborhood. Sensitive of context, the group prioritized the relationship of form, mass, and scale to the surrounding buildings. Raised entry stoops all face the street with glass canopies that mimic the cable-stayed canopy of the adjacent 1890’s structures. The entry stoop elevation is set at 5’-4” allowing for inhabitants to engage the passerby at the sidewalk while maintaining a comfortable separation between the public and private realms. (Fig. 3)

Figure 3. Merchants Row Brownstones, exterior.

As the section illustrates, this strategy does not allow for the ceiling height required for a garage and thus unit interiors step up around a three-story lightwell that allows daylight to penetrate deep into the units. (Fig. 4) This alleviates the challenge of letting light into long interior units where side windows are typically not possible.

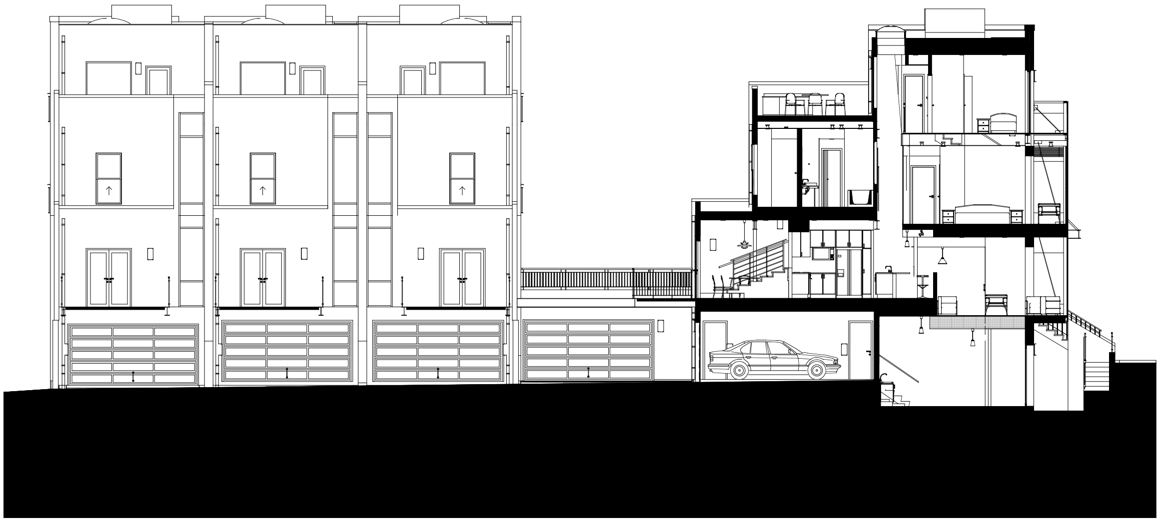


Figure 4. Merchants Row Brownstones, section.

Also, the primary feature of the exterior is a reinterpretation of the historic bay: a three-story mullionless curtainwall. These not only allow daylight to penetrate into the units, they also represent metaphorically the visual connection to openness and transparency. Despite historic district design guidelines that require punched windows in a solid field, the group was able to convince the design review board, Denver's Landmark Commission, that the pattern of frosted and clear glass configured in the proportions of window openings in the neighborhood met the intent of the guidelines. Stepped out from the façade, side windows at the bay frame views to downtown while translucent bays glow to activate the street with vitality at night. Convincing the group to challenge the literal reading of the historic district design guidelines was no small accomplishment given that many of the investors have an affinity for historic preservation that borders on militant.

Also significant in swaying the design board's ruling was the fact that many of the investor-residents had been involved with establishing the historic district. The glass bays also reflect a certain do-it-yourself ingenuity. The components are all off-the-shelf and designed by the structural engineer. (O'Hara, 2006) The risk in configuring such an assembly with no clear warranty and the lack of clarity in assigning responsibility for resistance to moisture intrusion would cause most developers to pull back. The neighborhood group, perhaps naively, greeted this calculated risk with enthusiasm.

While the land cost drove the development, it was important to the group that the project be configured in such a way that it could resist the homogenizing mechanisms of gentrification. Walk-out basements labeled as "flex-space" on city permit drawings sidestep parking requirements and provide a potential home office or live-work scenario. They are also easily configured into an affordable rental unit or granny flat. It was also important to the group that critical design concepts not be compromised by what they felt to be misguided zoning regulations or design guidelines. The carefully labeled "flex-space" is a case in point.

Another procedural nuance that offered some resistance to the regulation of the built environment and was critical to the project's success was the categorization of the units as Attached-Single-Family. Not only did this reduce professional liability associated with condominium developments but also allowed the group to avoid the creation of a homeowner's association. One requirement of this classification is that each unit must maintain its own lateral bracing; that is, should one unit's lateral bracing be compromised, adjacent units must maintain their own lateral stability. This is made visible in the design by exposing the steel cross bracing in the three-story lightwells. (Fig. 5)

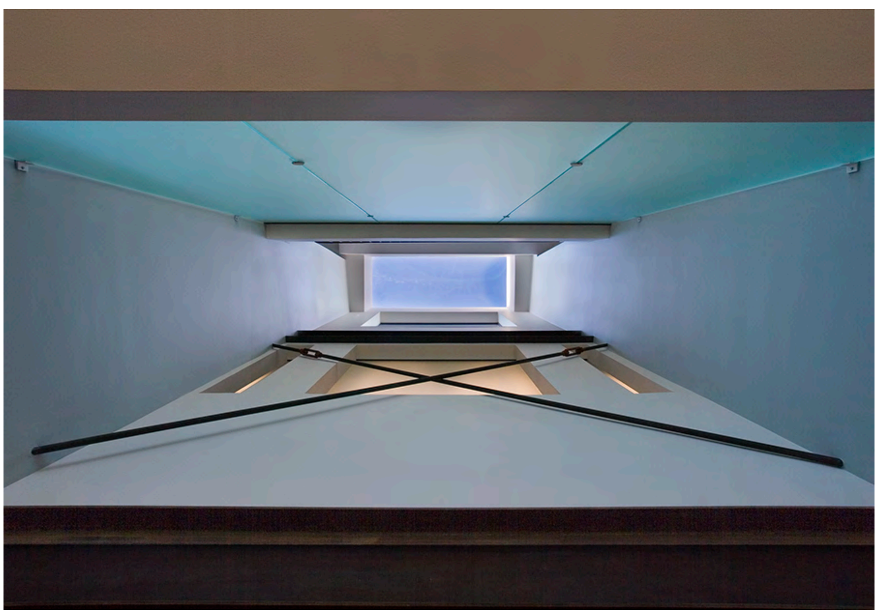
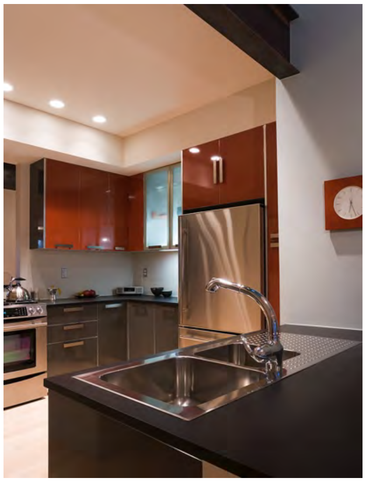


Figure 5. Merchants Row Brownstones, cross-bracing.

The steel structure also frames views both to the front and the back of the unit. Beams and columns were left exposed and hand-rubbed with tung oil. This gave the steel a weathered and nearly a hand-hewn look. The presence of these steel frames served to define layers of space opening up from the frosted glazing of the bay windows. (Fig. 6) The kitchen peninsula and sink are centered below the three-story lightwell. European cabinets are topped with Richlite solid surface countertops. (Fig. 7) Vanity pedestals are configured of simple steel stock and welded by a fabrication shop in the neighborhood. (Fig.8)



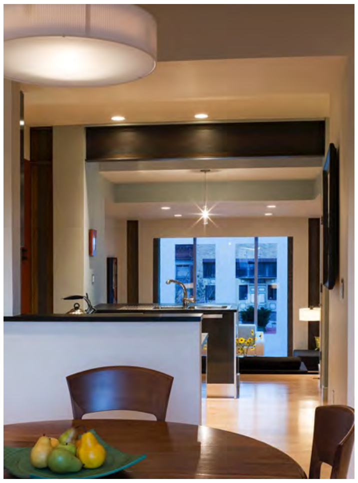
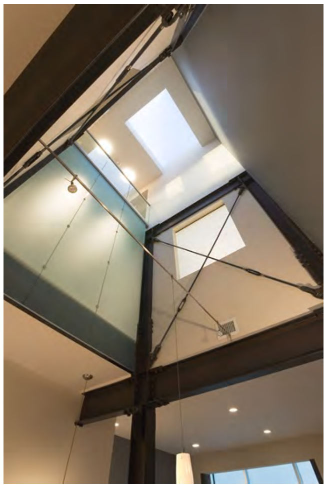


Figure 6. Merchants Row Brownstones, interior.
Figure 7. Merchants Row Brownstones, interior.
Figure 8. Merchants Row Brownstones, interior.

The long, narrow units are configured to bring light from the glass bays and skylights into every interior space. Floor-to-ceiling interior glass partitions allow for borrowed light from the lightwell into the master suite and bridge to a roof deck. (Fig. 9) Stairwells, buried deep against demising walls are also lighted through glass partitions and skylights. (Fig. 10)



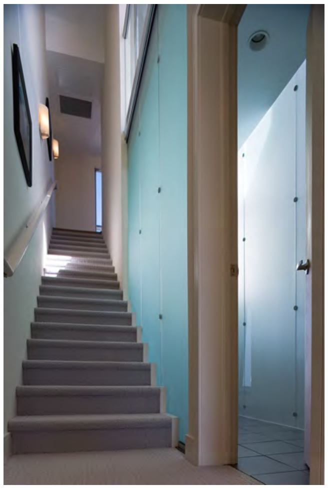


Figure 9. Merchants Row Brownstones, interior.

Figure 10. Merchants Row Brownstones, interior.

This project, like the earlier example, sold out soon after the completion of construction. The pride the group took in witnessing a cultural enterprise emerge from their shared ideas and resources was evident. Open house events and tours were more of a neighborhood celebration than marketing event and inexplicably extended even after all the units were sold. Guarantor investors received a pref return as the project closed out and non-guarantors received their proceeds soon after. Several investors, in various structures and configurations, continue to roll over development proceeds into neighborhood investments of various scales.

CASE STUDY 3: KANSAS CITY SALES TAX

One of our principal designers, Joe Colistra, is currently engaged in a self-development project in Kansas City, Missouri that has the potential to demonstrate a city-wide strategy for the revitalization of marginalized communities. In April of 2017, Kansas City voters were asked to approve a one-eighth-cent sales tax to spur economic development in the city’s most blighted neighborhoods. Spearheaded by the Urban Summit, partner nonprofits and area churches led the charge to have the initiative placed on the city ballot. (Stafford, 2017) The initiative would also compete with three general obligation bond questions that supported infrastructure improvements. The initiative thus brought considerable opposition from Mayor Sly James’ office who feared voters would reject pleas for funding parts of the city where they don’t live and jeopardizing all four tax questions. (Stafford, 2017)

The Central City Economic Development Sales Tax is to be in place for 10 years and provides a projected revenue of $8.6 - 10 million each year. This citywide tax would only be utilized in an area bounded by Ninth Street to the north, Gregory Boulevard to the south, the Paseo to the west and Indiana Avenue to the east. Essentially, Kansas City’s traditionally most underserved neighborhoods. An appointed board made up of designees of such entities as the Mayor’s office, the school board, city council, etc. will oversee the distribution of the tax revenues. Colistra, with affiliated faculty from the Kansas City Design Center (KCDC), engaged citizenry from within this established boundary in order to respond to the city’s Request for Proposals.

A sales tax is often hurtful to the poor, however, rather than reinvesting the tax revenue in neighborhoods that are well-positioned, the revenue from this initiative will be limited to an area identified with high crime, unemployment, dilapidated housing stock, and a lack of development. (Kades, 2016). Leaders of the initiative cited two reasons why this tax makes sense: 1. When a city’s core is healthy, the entire city is healthy; and, 2. Residents of these neighborhoods have consistently supported similar tax initiatives that funded major projects outside the core, including a $1billion airport improvement project. (Gray, 2017) The vote was telling. Most neighborhoods voted in favor of the tax despite the reality that it would not directly affect them. (Knox, 2017)

A resident group of approximately 14 investors has engaged Legal Aid of Western Missouri to form a development entity called KC Equity Builders LLC. The group has targeted a Land Bank-owned property in the Key Coalition Neighborhood and are beginning to work with designers to establish the highest and best use of the site. Initial pro forma analysis indicates 6 affordable townhome units developed by 20 investors willing to put up an initial investment of $4,000 will payout approximately $5,000 within 18 months. At this time, the Central City Economic Development Sales Tax Board had not yet selected finalist respondents to the current Request for Proposals.

CONCLUSION

The notion of the self-developed community revitalization projects is an exciting one, not only because it implies inclusive participatory input from those affected by revitalization efforts but also because it implies that participants have an opportunity to share in the increased value that is brought to their neighborhoods by real estate development. The value created by architectural production has been one of the most stable and well-performing strategies for growing wealth. Yet, participation in real estate development is an impossibility for the vast majority of the population. Through entrepreneurial design thinking, architects have the potential to ease the barriers to such community investment opportunities and share in the transformative act of building community.

Although the scale of the community interventions shared here are small, these projects remain as clear territorial demarcations of community empowerment. Participants move through and away from these experiences forever changed from passive occupants of a built environment to citizens armed with the knowledge and resources to act upon the world.

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Figure 9: photograph by the author, diagram courtesy in situ Design

Envelope and Systems Synergy for High Performance, Affordable Housing

Michael D. Gibson[1] and Paul W. Karr[2]

[1] Associate Professor and Licensed Architect, Department of Architecture, Kansas State University, Manhattan, KS 66506. mdgibson@ksu.edu
[2] Instructor and Licensed PE, Department of Architectural Engineering and Construction Science, Kansas State University, Manhattan, KS 66506. paulkarr@k-state.edu

ABSTRACT

The Net Positive Studio is an interdisciplinary research and design effort in the College of Architecture, Planning, and Design at Kansas State University seeking to develop housing prototypes that are affordable, safe, high-quality, environmentally sensitive, and functional while demonstrating broad tenants of sustainability: energy and environmental conservation, economic tenability, and positive social and community impact.

In the Net Positive Studio's first iteration, the team partnered with the Mattie Rhodes Center, a community organization in Kansas City, to develop and build a single-family infill housing prototype, in a community known as Indian Mound, intended to be constructed for near $100/ft2 while achieving an EUI (energy use intensity) lower than 15 kBtu/ft2 per year. The project and the studio team are also participants in the current Solar Decathlon Build Challenge, sponsored by the U.S. Department of Energy.

In the design, a high-performance building envelope was integrated with a strategic approach to maximizing the efficiency of the home's environmental control systems. This paper elaborates in detail upon innovations in the building envelope and heating and cooling systems, describing how these systems work together. Using computational fluid dynamics simulation, the Indian Mound prototype's operation is compared to contemporary approaches to envelope and HVAC systems common in affordable housing. In summary, the project's design and the analyses presented in the paper show that critical improvements in envelope design can work in sync with modern HVAC technology, resulting in a solution that is both more affordable and better-performing than today's contemporary affordable housing solutions.

PROJECT BACKGROUND

Today, residential buildings are at the root of our society's energy crisis, consuming more than one fifth of all U.S. energy (EIA 2019), more energy than commercial and industrial buildings combined. At the same time, nearly half of Americans are over-burdened by housing costs (U.S. Census, 2013-17) and average annual household utility costs have climbed to nearly $2,000 (BLS 2019). Nearly half of American households earning less than $50,000 are overburdened by housing, yet for every inexpensive home built for $150,000, over 18 are built for over $350,000 (U.S. Census 2019). These statistics illustrate that the crisis in housing affordability is multidimensional: the U.S. housing market has an urgent need for lower cost and lower energy homes.

Unfortunately, poorly designed and poorly engineered *new* affordable housing has the potential to increase the energy cost burden of economically threatened households. Discussed later in the paper, owners of a recently constructed 'affordable' home were subjected to back-to-back wintertime heating bills that totaled $642.96. Utility bills of that magnitude cripple a family's economic stability, competing with mortgage payments, childcare, food costs, healthcare, and other critical expenses. On paper, the specs of the house and its heating and cooling systems seemed acceptable and ordinary. What happened?

Housing in the U.S. is driven by strongly held conventions and ordinary new housing doesn't receive the professional design and engineering oversight given to commercial buildings from start to finish. In the Indian Mound project presented here, a team of students working with their expert faculty advisors (co-authors on this paper) were able to start from scratch with the prototype home's design, keeping things simple while thoughtfully integrating the building's architectural design with the operation of its systems. While this paper will not elaborate on the full extent of the home's design and construction strategies, it will bring focus on decisions made by the student design team in the building's assemblies and form that enabled an innovative application of HVAC design. Together these decisions show how the Indian Mound house will leverage its simple approach to architectural form to maximize the performance of its systems, putting forward an improved model for thinking about how to integrate HVAC systems into affordable housing.

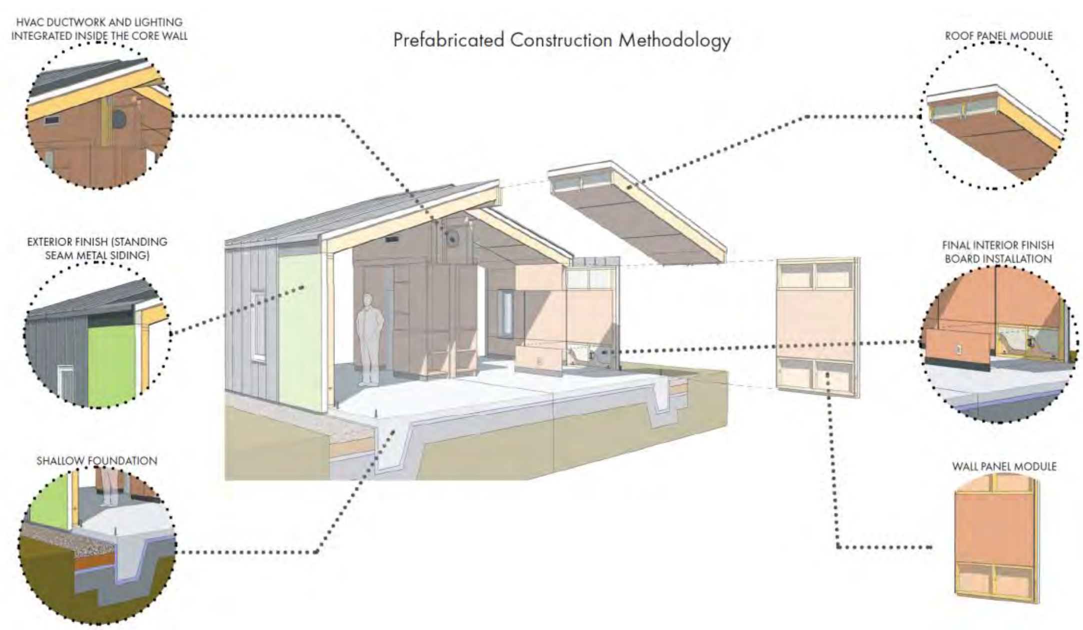

Figure 1: The cross-section of the Indian Mound prototype home exhibits its important features, working in synergy: a prefabricated envelope with robust levels of thermal control, a fully insulated slab coupled with the conditioned zone, and a central 'core wall' to contain essential building systems.

HOUSING IN SECTION: PAST AND PRESENT ISSUES WITH BUILDING CLIMATE AND SYSTEMS

The quintessential American home is a homey living space, anchored by its cellar and topped off with an attic. The structural and material systems in use in today's typical construction are intertwined with the presence of basements, crawlspaces, and attics, which also happen to make building systems easy to resolve and locate. Yet these unconditioned spaces present a host of major environmental control troubles – both energy- and health-related. For one, the neatly organized thermal, air, vapor, and rain barrier systems in vertical walls are challenged to maintain continuity and their appropriate sequence when the vertical envelope transitions to basement and attic boundaries. Aside from draining heat from the home year-round, uninsulated and unconditioned basements introduce moisture to homes: moisture that, along with moisture from other indoor sources, must be vented out of the attic by intentional, uncontrolled, year-round infiltration of outdoor air. For modern, energy efficient buildings that are designed to be as 'tight' as possible, leaky, uncontrolled basements and attics are somewhat absurd. These spaces are also the last place one would want to put expensive and sensitive heating and cooling equipment and ductwork – yet this is what is commonly done.

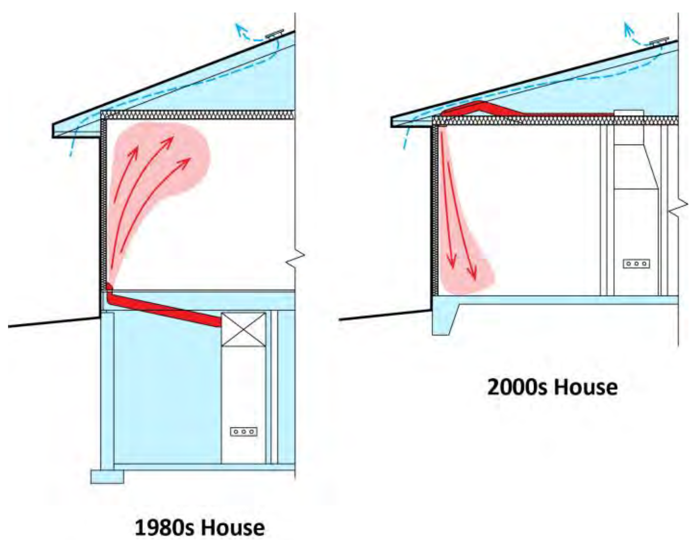

Figure 2. Two prolific ways of organizing conditioned, unconditioned, and HVAC systems: a house with a full basement, with HVAC equipment and distribution in the basement; and contemporary affordable housing, built on a slab with HVAC equipment on the occupied floor and distribution through the attic. These scenarios are introduced (respectively) as the 1980s and the 2000s house later in this paper.

In the post-war housing boom, when simplification and cost-efficiency in construction became a serious issue, basements and attics were quickly trimmed from the recipe for the midcentury home. Lofty, raftered attics beneath high-slope roofs were replaced with lower-slope, compact roofs with minimal framing. Basements were replaced by slabs-on-grade, or in milder climates, simple post foundations. In sum, resources were focused on the habitable living space: a basic approach persisting today in single family, affordable housing.

Modern homes on slabs, however, present challenges for the location of heating and cooling equipment and distribution systems. In such slab homes, the prevailing solution is to move the equipment to the living level and run forced air ductwork through the cramped, unconditioned, leaky attic where systems interfere with increasingly critical ceiling insulation. Recognition of the problems that ensue from this approach (see Lstiburek 2013) has yet to unseat conventional practices of locating ductwork in unconditioned attics.

Today, ductwork in homes is said to average a 20-40% loss of heating and cooling energy before it reaches living spaces as reported by the Department of Energy: a sobering statistic rooted not just in the location and installation quality of ductwork, but in its *configuration* for many houses. The uninsulated (or minimally insulated) building envelopes of the past dictated that heating and cooling should be supplied to the perimeter of the home to combat comfort problems at the weakest areas of the envelope, such as old drafty windows. For many houses, getting the ductwork to the perimeter involves little to no engineering or analysis, and the extra distance and air resistance that is introduced in doing so ensures, above all, that HVAC sizing should take no risks: it's better to 'go big' with furnaces and A/C installations. It is no surprise that over half of a typical U.S. household's energy is consumed by air conditioning and space heating according to the U.S. EIA. While the design of the building envelope has taken center stage in modern high-efficiency homes, the building design must also incorporate better approaches to air distribution in order to fully address energy conservation and indoor air quality goals. When compared to conventional approaches to HVAC integration, the Indian Mound prototype fully realizes the efficiency of new HVAC technology at the cutting edge of efficiency.

THE INDIAN MOUND PROTOTYPE

Aware of the issues tying together building systems with the building envelope, the Indian Mound prototype home was designed by its faculty and student team around a simple volumetric strategy. Emphasizing a wall and combined roof/ceiling assembly with similar construction, the prototype home was designed without an attic and utilized a panelization approach to prefabricate walls and roof/ceiling components. Lacking soffits and cantilevers, the home's envelope maintains ideal alignment of structural, air barrier, and water barrier systems from wall to roof. Outboard of the home's conventional wood frame and structural sheathing, three inches of XPS insulation and a combined air barrier and weather resistive barrier OSB system completes the package, which will be sealed with liquid flashing after assembly on site. Thermal resistance values for these assemblies are shown in Table 1. The frost-protected, reinforced edge foundation will also be continuously insulated.

Table 1: Thermal Resistance Values of Envelope

	Installed Insulation R-Value [h*ft2*°F/Btu]	Assembly R-Value [h*ft2*°F/Btu] [1]
Foundation Slab	R-10	-
Walls	R-14 + R-15 continuous	R-30.9 [2]
Windows	-	R-4.0 (U-0.25) [3]
Roof/Ceiling	R-31 + R –15 continuous	R-49.3 [2]

[1] Total assembly R-Value with air films
[2] Determined using area-weighted summation from ASHRAE Parallel Path method for cavity assemblies.
[3] Manufacturer rating using NFRC-certified testing methods

Overall, this approach to the home's structure and the envelope not only saved the extra expense of a separate ceiling structure, but it also avoids areas where the thermal, air, and moisture/rain barriers of wood framed houses usually have gaps and failures. More than just high R-Value construction, we expect this approach to the envelope will allow it to be more effectively sealed and will result in long term resilience.

While the scope of this paper cannot discuss the evolution of the home's design in detail, the students' intent in the floorplan and interior spaces was to split public and private areas of the homes while minimizing unassigned circulation area. This allowed the kitchen and eating areas of the home to be quite generous, despite the home's roughly 1000 ft2 footprint. In a further effort to maximize the benefit of prefabrication and reduce the amount of linear wall construction, the design team created a thickened "core wall" in the middle of the home that serves as both a partition between bedrooms and common areas, and a place for ample enclosed and open storage.

HVAC System and the Core Wall. Early in the development of the design, the opportunity to use the thickened core wall to locate HVAC systems emerged. Because of the relatively small heating and cooling loads of the house, the HVAC equipment and distribution systems could be housed in the upper volumes of this wall, freeing up floor area that would normally be dedicated to a mechanical room. Further, the configuration of the thickened, multifunctional core wall would allow equipment and distribution to remain entirely within the thermal control layers of the building, offering a direct and efficient pathway for conditioned and ventilation air that would eliminate losses to an unconditioned basement or attic.

With the air handling unit positioned on an equipment loft, a main supply duct was designed for center of the core wall as depicted in Fig. 3, below. Locating the equipment up off the floor minimizes duct runs which keeps costs down and fan power low. Equipment service access was not sacrificed for efficiency, with all serviceable parts accessible or replaceable from a large door, using a stepladder.

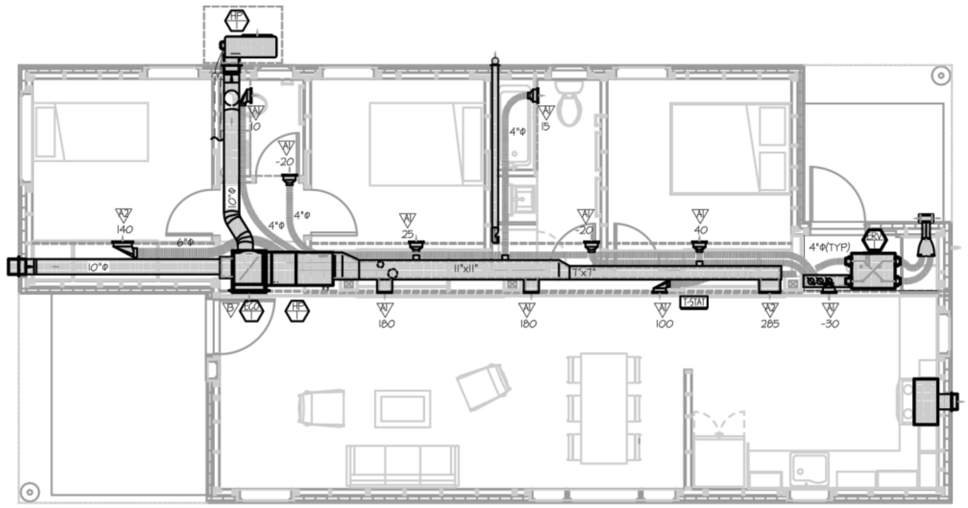

Figure 3. HVAC Floorplan of Indian Mound Affordable NetZero Home with HVAC unit in loft and ductwork centrally located.

The design also took advantage of a strategy gaining traction in many well-insulated, efficient homes where air distribution is consolidated in the core of the building, rather than at the perimeter (Burdick 2011). Supplying air to the building perimeter in this setting was a challenge addressed later in the paper.

A high-efficiency, mini-split, air-cooled heat pump system with central air handling unit was chosen for its mid-range cost and recognizable components. The cost is double the traditional furnace/ac system that is common to this market (retailing cost is $4,800 versus $2,700 respectively) but efficiencies can render a 10-year payback. Heat pumps have the additional benefit of heating without burning fossil fuels but must be carefully selected to operate through the cold winters of Kansas City. Additionally, the package utilizes a variable speed compressor for modulating cooling capacity in part-load. It also makes use of a "dry" control setting which can dehumidify when needed.

Using HVAC load calculation software at the Energy Star recommended design conditions of 1% cooling DB and 99% Htg DB (which are 94°F summer and 9°F winter in Kansas City, MO), peak cooling and heating load values were obtained, as shown in Table 2.

Table 2: HVAC Loads and Equipment Selection

	Loads	Capacity	Efficiency Rating
Heating	14,821 BTUH [1]	18,000 Btu/h at 9°F	13.6 HSPF
Cooling	18,611 BTUH [2]	27,000 Btu/h at 95°F [3]	18 SEER

[1] Using the CEC-DOE2 model
[2] Using RTS Heat Balance model
[3] The cooling capacity is more than needed but choosing the equipment to satisfy the heating load is the priority.

Heat pumps installed in Kansas City are often supplemented with electric or gas heat to handle the demand of extreme cold weather, particular with the loads from conventional construction. We did not want to complicate the system with supplemental heat and therefore selected equipment that could deliver the capacity needed at low ambient temperatures. Notably, the excellent building envelope design and coupled thermal mass in the home minimized equipment capacity selection in design, and these features should also reduce the impact of short term temperature extremes.

Whole-House Ventilation & Economizer. A commonly overlooked HVAC strategy in the affordable residential market is free-cooling using whole-house ventilation. While everyone knows you can save energy on temperate days by turning off the AC and throwing the windows open, homes in the 70s and 80s frequently used whole-house fans to accomplish the same effect. In both cases the occupant must be home and consciously decide to turn off the AC, open windows, and/or turn on the fan – and then perform the reverse when it is too warm or humid outside. Fresh air is not filtered, and moisture content of outside air is usually not considered. If ventilation could be accomplished automatically when conditions were favorable, the number of free cooling hours per year can be maximized for very little cost.

A residential economizer was therefore selected for this project with built-in controls that can interlock with the heat pump system to optimize the use of free cooling. Outdoor air temperature and humidity is monitored and compared with return air temperature and humidity. When the indoor cooling load can be satisfied with outside air, the economizer damper will automatically open and free cooling is achieved. Furthermore, the system is smart enough to allow the compressor to kick in during second-stage cooling and refrigerate outdoor air when it is cooler than return air, squeezing the last bit of free energy out of the system until the room is satisfied. In addition, the controls will allow occupants to program or manually increase thermostat setpoint to extend economizer usage when occupants are okay being a bit warmer or when they vacate the premises. Conversely, at the occupant's discretion after a warm day, the setpoint can be reduced at night to take full advantage of cool evening air to reset the building mass temperatures.

We believe that automating the whole house ventilation process and making the occupant a partner in their own energy savings by teaching them these techniques will result in significant free cooling over and above what the energy models predict. After the house is built and systems are running, we are interested in logging the economizer hours and comparing it to compressor run time and weather conditions to better understand the relationships.

Constant Ventilation. In order to deliver code-required ventilation, an energy recovery ventilator (ERV) with continuous operation was specified for the home – which saves energy by providing a heat and moisture exchange between exiting indoor air and entering fresh air. The ERV chosen for this house allows fine-tuning of fresh air and exhaust air quantities separately, allowing us to satisfy the code-minimum 20 cfm continuous exhaust per restroom, 25 cfm continuous exhaust from kitchen, and 45 cfm supply of outside air. The outside air values were set above code-minimum to create positive building pressurization which helps to minimize infiltration through building walls. Outside air is delivered directly to the main living quarters through a supply register on the wall. This fresh air is then naturally distributed throughout the house by the HVAC recirculating system.

The ERV system is an important component to mitigating humidity in the home, especially during the winter when it could pose a condensation risk in the home's insulation cavities (see Psychrometry Analysis, later in this paper).

Energy Analysis. Whole building energy analysis was conducted for the final design using EnergyPlus 8.4, with loads and utilization shown in Table 3 and graphically in Fig. 4. The resulting analysis shows a low Energy Use Intensity (EUI) of 14.3 kBtu/ft2 per year, which is approximately 1/3 of the regions typical residential EUI. Notably, energy analysis results from the whole building study were smaller than the worst hourly values used in sizing the systems. This is most likely attributable to the exposed concrete slab in the home, whose continuously insulated boundary keeps this relatively large mass in sync with the thermal conditions of the interior, tempering heat and cold swings.

Table 3: Whole Building Annual Energy Analysis Results

	Energy [1] [kWh]		**HVAC Loads [2] [KWh]**		**HVAC Fuel [3] [kWh]**		**Total Energy**	**PV Energy Prod.**
	lighting	equip	heat	cool	heat E	cool E		
Jan	71.55	178.22	391.08	4.45	218.48	0.84	**469.10**	286
Feb	64.63	160.97	305.42	18.70	170.62	3.54	**399.76**	314
Mar	71.55	178.22	98.61	44.56	55.09	8.44	**313.30**	417
April	69.24	172.47	3.60	70.15	2.01	13.29	**257.01**	443
May	71.55	178.22	0.22	111.04	0.12	21.03	**270.92**	470
June	69.24	172.47	0.00	365.36	0.00	69.20	**310.91**	479
July	71.55	178.22	0.00	474.39	0.00	89.85	**339.62**	509
Aug	71.55	178.22	0.00	450.81	0.00	85.38	**335.15**	464
Sept	69.24	172.47	0.00	303.22	0.00	57.43	**299.14**	431
Oct	71.55	178.22	3.94	92.04	2.20	17.43	**269.40**	361
Nov	69.24	172.47	119.16	36.57	66.57	6.93	**315.21**	299
Dec	71.55	178.22	348.33	7.65	194.60	1.45	**445.82**	249
Annual	842.48	2098.35	1270.36	1978.94	709.70	374.80	**4025.33**	4722

[1] Lighting loads assumed an all-LED house with optimum use of daylight. All occupied rooms achieve an average daylight factor greater than 3%. Equipment loads include electric point-of-use, tankless water heating.
[2] Loads included occupancy of 4 people and constant ventilation rate of 0.2 ACH, accounting for the ventilation rate of systems and their efficiency ratings.
[3] Fuel utilization for space heating and cooling used efficiency factors noted in Table 1. A final heating COP of 1.79 was used, derated from the manufacturer's HSPF shown in Table 1 according to climate factors.

In summary, the home is expected to achieve very low energy consumption values. In comparison to the EUIs exhibited by passive houses, the Indian Mound house's envelope and systems have been optimized to make net-zero performance affordable and relatively easy to implement using an array of available technology. The small building volume, rigorous envelope design, and coupled thermal mass also work together to make the high efficiency HVAC systems more promising and less risky in the mixed climate of Kansas City.

Indian Mound HVAC Design: Introducing the "Supply Casting" Concept

Air Distribution. As previously noted, a benefit of locating the HVAC system central to the space is the ability to minimize duct runs and omit elbows to minimize material cost and fan static pressure losses. Another improvement on the duct system was the use of a rigid-phenolic duct system instead of traditional sheet metal. The duct has a self-contained vapor barrier and insulation layer which helps maintain conditioned air temperatures and eliminates any danger of sweating. Installation is aided by its light weight and has inherently tight construction. Runs between segments can be longer than sheet metal duct which reduces the number of joints, all resulting in even lower leakage.

Displacement Ventilation Considered in a Residential Context. Locating supply and return grilles 10-feet high on the wall creates the risk of inadequate mixing and short-circuiting of supply air in the upper strata of the space. Supplying air down to the occupied space therefore became a high priority in the HVAC design. Traditional air distribution systems often introduce conditioned air into a space from ceiling diffusers or floor registers at a high velocity with the intent of fully mixing with the room air to achieve a uniform room air temperature throughout. In this type of system, simply known as "mixing", impurities are diluted to a large degree, but not carried away very efficiently.

The size and shape of this building suggested a ventilation strategy often used in large structures, but rarely seen in residential construction known as displacement ventilation (DV). This design strategy typically features the delivery of supply air down by the floor from large perforated supply diffusers and returning up high. Since DV can have as much as a 21% energy-saving potential over traditional air distribution systems in commercial applications (Goetzler et al., 2017) and produces better indoor air quality than traditional mixing systems (Chen, Q., Glicksman, L., Yuan, X., Hu, S., Hu, Y., and Yang, X., 1999), we were curious if DV could be used as an energy-saving strategy for this house. Displacement ventilation typically delivers low velocity, 65°F supply air to gently fill the lower portion of the room with fresh conditioned air while allowing the upper portion of the room to stratify at higher temperatures. This saves significant energy because only the occupied zone of air in the lower six feet must be conditioned while air in the higher portions of the room may be allowed to drift to warmer. The 65°F supply air temperature takes less energy to generate than 55°F supply air thereby increasing the number of available free cooling hours in the typical year.

Integrating large DV diffusers by the floor was not practical for this project, however, but the high warm ceilings still made DV appealing. Recent experiments using "confluent jet ventilation" by British and Swedish researchers (Cho, Awbi, & Karimipanah, 2008), supplied high-velocity air from the ceiling in an air-curtain down a wall. Once reaching the floor, the airstream slowed down and started behaving like DV. Fig. 4, below, compares traditional air distribution methods with displacement ventilation and confluent jet displacement.

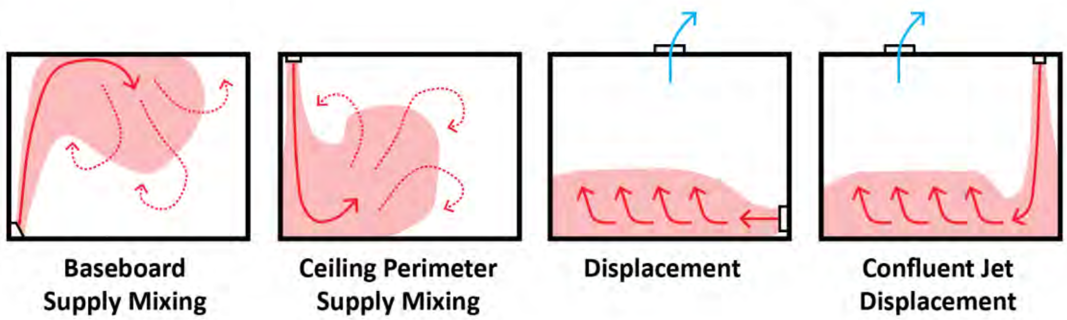

Figure 4. Comparison of traditional residential air distribution strategies.

Supply Casting: A New Approach. Making the most of the shape of our house, we imagined using the confluent jet strategy, but instead of aiming the supply air straight down, we would aim high-velocity air jets across the sloped ceiling like an angler casting a line across a river, efficiently planting a lure among far-away fish. Several point-source supply registers, as noted in Fig. 4, would deliver air in parallel streams against the perimeter of the space. If enough energy (both supply temperature and velocity) is preserved in this configuration, the supply air could cascade into the occupied zone with the required heating and cooling.

The Coanda effect would assist the airstream by keeping it close to the ceiling as it travels down the outside walls to the floor. This keeps high-velocity air away from the occupied zone as it hugs the surfaces while transporting the supply air to its destination. After reaching the floor, it would then behave like DV, tempering the occupied zone and carrying impurities up and out as illustrated in Fig. 6, below.

This Supply Casting air distribution pattern solves a notorious weakness of DV which is heating. Low-velocity warm air from DV diffusers tends to rise quickly from buoyancy and return to the air handling unit before mixing with the room. Most DV systems therefore require costly supplemental perimeter heating. The high-velocity air pattern, we hypothesized, would overcome the buoyancy effect of the warm supply air and carry it all the way to the floor. This theory would later be tested in a computational fluid dynamics (CFD) analysis discussed later in this paper.

By designing for an HVAC system inside the high-performance building envelope, incorporating a residential economizer for whole-house ventilation, and letting the building shape and ceiling slope inspire a new kind of airflow pattern all working together, we felt available resources were effectively optimized to achieve an affordable high-performance home.

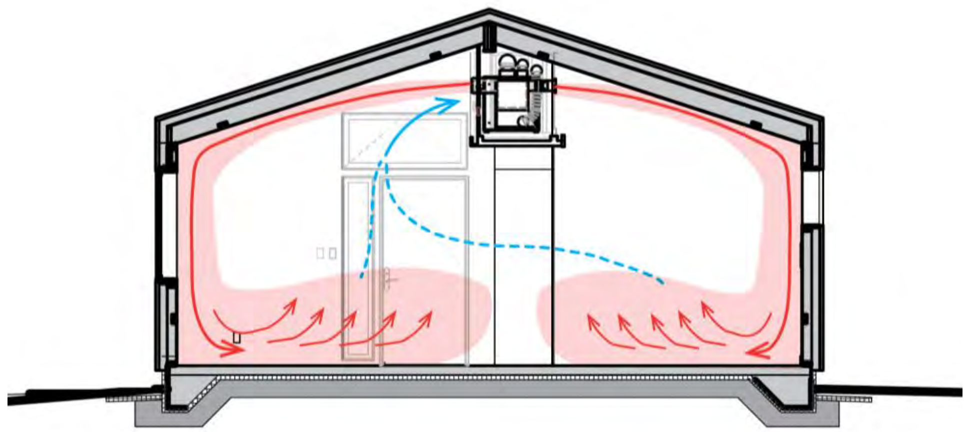

Figure 5: Building Section of Indian Mound Affordable NetZero Prototype Home with proposed "supply casting" airflow pattern

ANALYSIS: SUPPLY CASTING IN THE INDIAN MOUND HOME COMPARED WITH TWO CONVENTIONAL LOW-COST HOUSING APPROACHES

As a mixed climate, Kansas City exhibits winter and summer environmental concerns, though winter heating fuel used is typically much greater in magnitude than cooling for residences. As discussed earlier, heating output was more critical than cooling output in sizing the heat pump, and the performance of air source heat pumps in the region is still met with some skepticism. Given the relatively modest temperature output from our heat pump, would the combined outlet velocity and temperature at diffusers provide enough energy to maintain comfort on a cold day, given the anticipated temperatures in the room?

Computational Fluid Dynamics simulation was used to evaluate the heating and mixing hypothesis in a typical room in the home, using designed outlet temperatures and velocities along with thermal boundary conditions of the air volume. Boundary conditions were derived from the temperature gradient through the assembly for the design temperatures and given the assembly's layer R-values, resulting in the approximate surface temperature that would interface with the air film. Initial conditions of each simulation were set at 68°F for the interior air volume. The results of the simulations show how, given a steady state condition, the incoming air flow and temperature would mix with and raise the occupied zone temperature.

Two Comparison Houses Introduced. For the purposes of this paper, two comparison cases – referred to as the 1980s house and the 2000s house, illustrated in Fig. 7, were introduced into the analysis and simulated using the same CFD methods. The 1980s house is the home of a co-author, constructed with typical insulation for the period and featuring a full basement and attic, with steel ductwork and perimeter distribution from below, and featuring a substantial propane-fired furnace. In the comparison, this home represents a still-common strategy for residential construction and environmental control: oversize your heating and cooling source in order to produce robust outlet temperatures to the perimeter, compensating for a relatively weak thermal envelope.

The other home – the 2000s house – was a home built by regional affordable housing program, whose occupants were experiencing extremely high wintertime utility bills: approaching $400 during cold months. Though a relatively new home, it was built outside a code jurisdiction and had R-11 insulated walls lacking continuous insulation, no perimeter insulation for the slab-on-grade foundations, and had blown-in attic insulation that was installed with great difficulty (and poor results) due to low-slope trusses and voluminous, untrimmed flex-ducts in the attic. The energy consumption problems for the home were only multiplied with the installation of an undersized air-source heat pump that frequently resorted to its backup resistance coil to supply heat. The heat pump's tepid output was also a source of complaints from the owners. On a cold day the house just didn't feel like it was being heated and the furnace ran constantly.

CFD Results: Supply Casting Versus Conventional Approaches. Results of the CFD simulations are summarized in Fig. 8. The 1980s house, despite the relatively poor performance of its envelope, mixes heated air effectively in the occupied zone, exhibiting temperatures well above the initial conditions in the simulation. This appears a result of the high output temperatures from the propane furnace, and as this heat is delivered from the baseboard level, some combination of buoyancy and residual momentum moves it through the room to the return, despite some hot spots. The 2000s house yields a very different picture of heat dissipation and mixing. Low temperature heat arrives at the perimeter from the ceiling, where it quickly loses energy when it encounters the cold, uninsulated slab. In this relatively large room, the incoming heat reserves little energy for raising the temperature of the zone, and the resultant room temperatures are much lower than the 1980s house. Moreover, incoming air in the 2000s house spends a great deal more time meandering in the room – an average of 40 minutes as predicted by the CFD particle traces.

The two comparison houses use perimeter heat distribution, yielding modest inlet velocities. However, the 1980s house overcomes inefficiencies in distribution with extra heat capacity. Having lived in the house for some time, the author attests that this is the same case for the cooling months. The subpar flex duct installation in the 2000s house, combined with the cool interior slab temperatures, creates a distribution challenge that an air source heat pump – even with a more appropriate model – would have trouble serving.

In contrast to the two cases, the Indian Mound home's simulations yield a very different result. Higher outlet velocities and a well-insulated envelope preserve a considerable amount of heating energy, even though the air supply is originating from the middle of the home. By the time this heated air reaches the interior room, it is still carrying a significant and balanced amount of heat through the occupied zone. While the air has slowed down below the thresholds of immediate perception, important in avoiding the feeling of drafts, the conditioned air reaches the air return efficiently.

The sum of these results show that even with the modest heat outlet temperatures from the air source heat pump, the strategy of Supply Casting provides similar or better comfort than that provided from an oversized, fossil-fuel heated furnace of the past.

Consolidated ductwork into a compact form within the conditioned volume is also key to this strategy, as it maximizes heating/cooling energy delivered into the space as well as velocity.

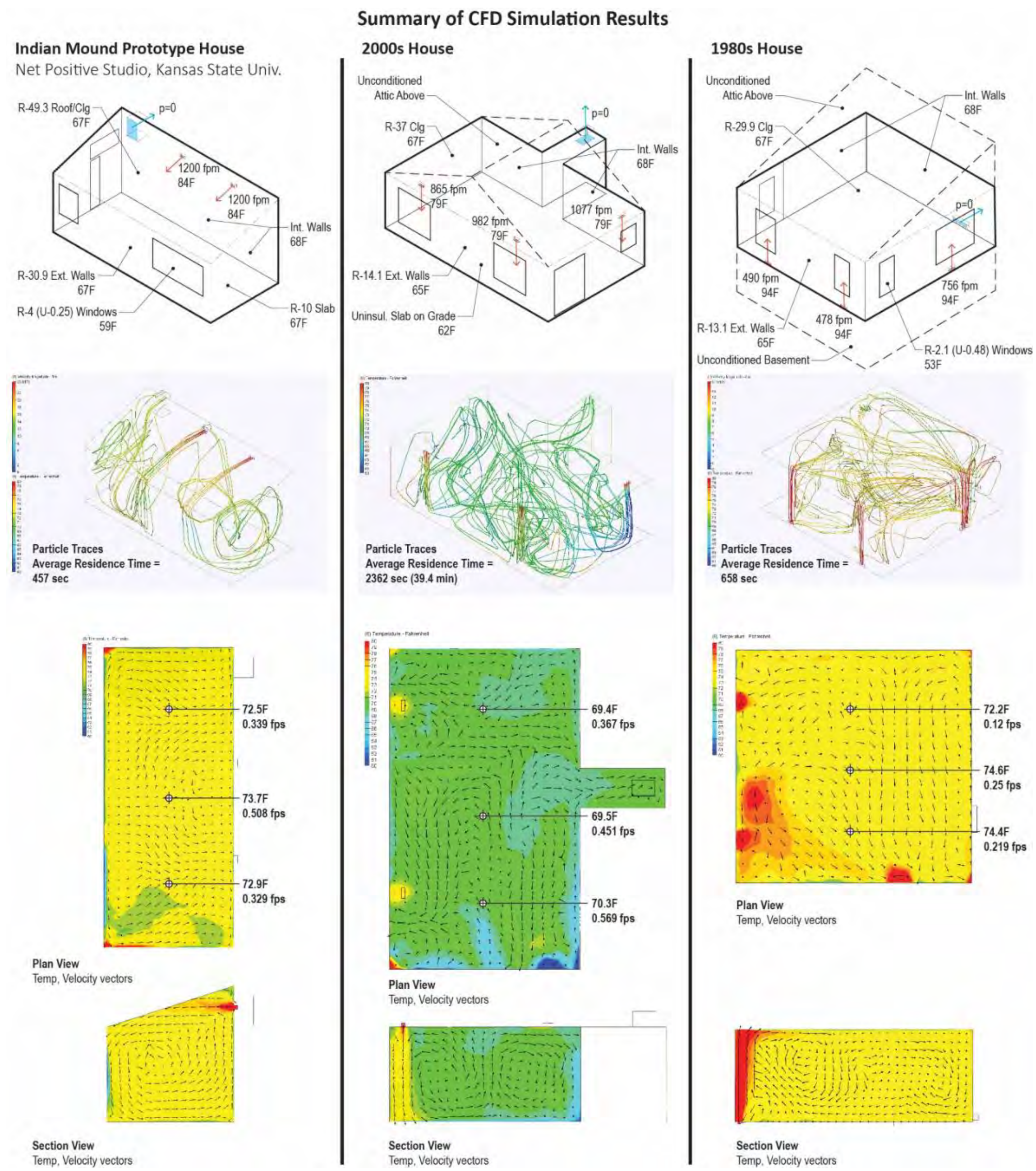

Figure 6. A summary of CFD simulation results is shown above, along with the boundary condition inputs for temperature and the general zone geometry. The outlet velocity and temperatures for the 1980s and 2000s house were measured in-situ.

The Importance of an ERV System: Pyschrometric Analysis. Designing for the Kansas City environment is challenging because the presence of both extreme cold winters and hot, humid summers. Improperly designed HVAC systems have been known to exacerbate indoor relative humidity rather than lower it. Condensation is a particular risk for the prototype due to its unventilated roof panels and low permeability of its exterior insulation and metal cladding. Given the presence of the ERV system, analysis was conducted to examine if the interior air in the winter would be dry enough to encourage inward drying and prevent moisture migration into cavities.

The first step in this process was to predict typical condensing surface temperatures, using average wintertime temperatures and the thermal resistance of assembly layers. Following the method described by Lstiburek (2001), for a median January outdoor temperature of 26°F, the condensing surface temperature at the underside of the roof deck would be 40°F – indicating the interior of the home would have to remain below 35% RH in the coldest months in order to prevent condensation. Next, a psychrometric analysis on the house in both heating mode and cooling mode was done to confirm humidity levels could be kept under control during all seasons. In the winter, we noted convergence on a room setpoint of 70°F, 20% RH. More importantly, the indoor dewpoint was seen to follow the outdoor dewpoint temperature and therefore always be lower than the indoor building envelope surface temperatures. This is significant to prevent condensation and ensure inward drying and vapor pressure. In the summer, we derived a steady-state room setpoint of 75°F, 52.5% RH, which is an acceptable indoor condition. Operating an ERV at a steady state serves as the overriding humidity control mechanism that keeps the indoor air moisture at bay.

CONCLUSION

In an effort to conserve energy in today's homes, modern equipment such as heat pumps and ERVs are increasingly common in homes. While it is important to engineer these systems properly, the exercise in design shouldn't stop merely in the specification of systems. The Indian Mound prototype home, designed and constructed in part at Kansas State University, shows the possibilities of what can be achieved in a small, modest home when investment has been made in bolstering the environmental performance of the envelope, while also taking advantage of architectural attributes of the design to distribute heating and cooling in the simplest possible approach.

Comparisons made in the paper, however, show the consequences of changing the status quo of oversized heating and cooling equipment, and to some extent relying on infiltration and attic ventilation for drying the home's climate. If the envelope isn't improved and the materials, assemblies, windows, and other elements kept in synchrony, a new house can actually perform much worse than an old house. Nowhere is this truer than in affordable housing, where decisions must be balanced between long term energy savings and first costs. As a truly integrated project, the Indian Mound prototype home has made use of design, engineering, and building expertise throughout its process and we hope that this effort will demonstrate that it is possible to succeed – and excel – in energy performance even in an ultra-affordable home.

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Barriers in implementing Material Transparency in LEED® v4.0 projects

Susan Thomas[1] and Paul Crovella, Ph.D.[2]

[1]Department of Forest and Natural Resources Management, State University of New York College of Environmental Science and Forestry (ESF), 1 Forestry Drive, Syracuse, NY 13210, (315) 247-5232, email: sthoma11@syr.edu
[2]Department of Forest and Natural Resources Management, State University of New York College of Environmental Science and Forestry (ESF), 1 Forestry Drive, Syracuse, NY 13210, (315) 470- 6839, email: plcrovella@esf.edu

Abstract

Americans, on an average, spend approximately 90 percent of their time indoors (U.S. Environmental Protection Agency, 1989) where the concentrations of some pollutants are often 2 to 5 times higher than typical outdoor concentrations. (U.S. Environmental Protection Agency, 1987). That means that our living, working, and playing is mostly done inside buildings. Materials make the built environment possible and the choice of which materials to use can have significant consequences for human health and the ecosystem that we all share. Information about impact of materials on human health and environment is becoming more prominent. However, lack of guidelines and potential tools that could help us access this data makes the process of material selection difficult for designers. This difficulty can be reduced through disclosure of material ingredients and its impacts. The Material and Resource category in LEED® v4.0 (Leadership in Energy and Environmental Design - Version 4) has placed more focus on material transparency through the Building Product Disclosure and Optimization credits under the Material and Resources category and the Low Emitting materials credit under the Indoor Environmental Quality category. Out of 1573 projects certified by 12/17/2018 under the LEED® v4.0 Building Design and Construction rating system, 404 projects (25.6%) have scorecards available for evaluation and 162 (40%) of the 404 projects have achieved one or more points for these credits. This background study and previous studies indicate barriers in implementing material transparency. The research identifies gaps in information as well as gaps in access to or availability of transparent material ingredient documentation that will help material producers better understand the needs of designers who are responsible for green material selection. It will also help to identify future research opportunities related to the development and evaluation of sustainable materials and material transparency.

Introduction

The world now faces one of the most complex and important issues it has ever had to deal with: climate change. Climate change scientists believe that the Earth is rapidly getting warmer and that human activity is playing a significant role in accelerating this process. The biggest way in which construction firms are causing an impact on the environment is by contributing to carbon dioxide emissions. According to Architecture 2030 (2018), buildings generate nearly 40% of annual global greenhouse gas (GHG) emissions as shown in Figure 1.

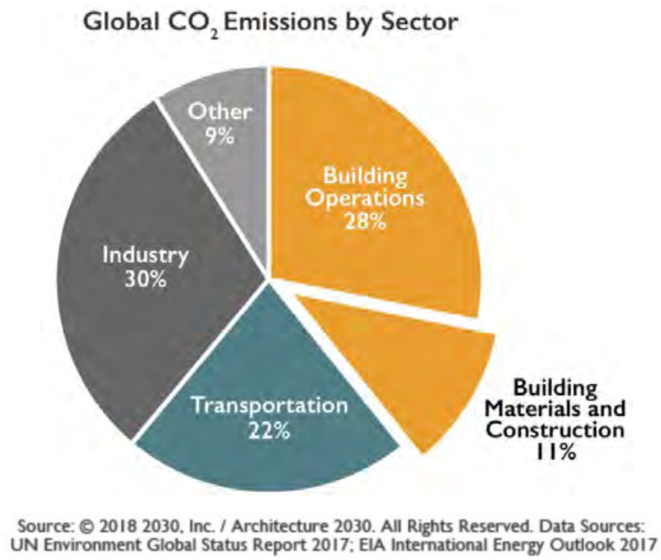


Figure 1: Global carbon dioxide emission by sector

Today most buildings are constructed from a multitude of materials, each with very specific functional demands and complex assembly requirements (Crisman, 2017) , of which many have an adverse impact on the environment. The green building movement emerged to mitigate these effects and to improve the building construction process. There are several green building certification systems that have different benefits, considerations, requirements and costs, namely ENERGY STAR for buildings, Leadership in Energy & Environmental Design (LEED®), Living Building Challenge, WELL Building Standard, Passive House, Green Globes, ENERGY STAR for Homes, HERS: Home Energy Rating System and National Green Building Standard.

Americans, on an average, spend approximately 90 percent of their time indoors (U.S. Environmental Protection Agency, 1989) where the concentrations of some pollutants are often 2 to 5 times higher than typical outdoor concentrations. (U.S. Environmental Protection Agency, 1987). That means that our living, working, playing is mostly done inside the buildings. Materials make the built environment possible and the choices made of which materials to use can have significant consequences for human health and the ecosystem that we all share. While regulations can help guide us in the right direction, project teams need product reporting such as the Health Product Declaration™ (HPD) to be able to make healthier choices when specifying building products. Until recently, it was believed that embodied energy formed a very small percentage of energy consumption as opposed to the operational energy over the life span of the building. The embodied energy of a conventional building represents 38% of the life cycle energy use (Sartori & Hestnes, 2007). This implies that material selection plays a crucial role in reducing the overall environmental energy impacts of the building.

With the growing trend in reducing the embodied energy in buildings there is a need for verifiable and transparent documentation regarding the manufacturing of green building products (Ingwersen & Stevenson, 2012). Transparency stems from the idea that knowing what is in our products is a necessary first step toward making more informed decisions about the materials we use, especially around how materials impact human health and well-being (AIA, 2016). Sustainable rating systems, such as (LEED®), have responded to this by implementing credit categories based on product manufacturing process, health product declarations, corporate sustainability report, and other forms of disclosure (USGBC, 2014). The material and resources (MR) category of LEED® Building Design and Construction (BD+C) and Interior Design and Construction (ID+C) rating systems aims at reducing the embodied energy of the building through a life cycle approach. Earlier versions of LEED® MR category focused on recycled content while v4.0 focuses more on transparency (Life cycle assessment, Environmental Product Declaration and HPD) in the MR category. In LEED® v4.0, MR: BPDO: EPD and MR: BPDO: Sourcing of Raw ingredients pertains to the environmental impact of the materials while MR: BPDO: Material Ingredients and Indoor Environmental Quality (EQ): Low-emitting materials is related to the health impacts of materials on the eco-system (Figure 2).

Material Transparency in LEED® v4 MR and EQ credits				
Category	Name of credit	Intent	Options	Points
Material and Resources	Building product disclosure and optimization (BPDO) - environmental product declarations	To reward project teams for selecting products from manufacturers who have verified improved environmental life-cycle impacts	1. Environmental Product Declaration (EPD)	1
			2. Multi-attribute optimization	1
	BPDO- sourcing of raw materials	To reward project teams for selecting products verified to have been extracted or sourced in a responsible manner	1. Raw material source and extraction reporting	1
			2. Leadership extraction practices	1
	BPDO - Material Ingredients	To reward project teams for selecting products for which the chemical ingredients in the product are inventoried using an accepted methodology and to minimize the use and generation of harmful substances	1. Material ingredient reporting	1
			2. Material ingredient optimization	1
			3. Product Manufacturer Supply Chain Optimization	1
Indoor Environmental Quality (EQ)	Low-emitting materials	To reduce concentrations of chemical contaminants that can damage air quality, human health, productivity, and the environment.	1. Product Category Calculations	Upto 3
			2. Budget Calculation Method	Upto 3

Figure 2: Material Transparency credits in LEED v4.0

The American Institute of Architects (AIA) published "Prescription for Healthier Building Materials" in Spring 2018 which is a result of an 18-month research project led by Arup. It is an initiative relative to materials that will influence their member base, who in turn, should be better able to educate the owners about the value of incorporating healthier materials. A chapter of the document is on overcoming common barriers:

- Addressing difficulties in obtaining buy-in from peers, clients, and the market.
- Understanding the risks involved with materials selection and claiming "healthy" materials
- Opportunities to learn and share best practices

The barriers identified based on the research conducted by Arup (Yang & Tepfer, 2018)are :

- Limited knowledge about healthier materials
- Conflicting assessment tools and criteria
- Lack of alternative products
- "The ask" for content transparency
- Recognizing the value of healthier materials for owners, design construction teams and manufacturers
- Real and perceived risk
- Limited platforms and mechanisms for collaboration

Background study

The 1573 LEED® v4.0 certified projects under the BD+C and ID+C rating systems including New construction, Core and shell, Healthcare, Multifamily Midrise, Schools, Retails, Distribution Centers, Hospitality and Commercial interiors were evaluated using the USGBC project directory, retrieved on 12/17/18. The three MR: BPDO credits and one EQ: Low emitting materials credit for each project were analyzed in the preliminary data collection to identify how many projects have successfully achieved at least one point of the 4 credits. Out of 1573 projects, 404 projects (25.6%) have scorecards available for evaluation and 162 (40%) of the 404 projects have achieved one or more points for these credits. There are 10 out of 67 projects that attempted the low-emitting credit (14.92%) that have achieved all 3 points for the credit under EQ while there is only one project that has achieved more than 1 point (EPD credit) among the three BPDO credits. Figure 3 indicates that EQ: Low Emitting Materials has the highest number of projects that have achieved at least 1 point among the four credits under consideration, followed by 47 projects under MR: BPDO: Sourcing of Raw Ingredients. MR: BPDO: Environmental Product Declaration and MR: BPDO: Material Ingredients have the lowest number of projects that have achieved at least one point. The achievability of each credit varies depending on the option pursued. These 404 projects that have the scorecard available will be used to understand the barriers of implementing material transparency in the construction industry.

Based on Figure 3, the study focuses on MR: BPDO: Environmental Product Declaration as well as Material Ingredients credits to find the reasons for the lower number of projects to achieve more than 1 point among the material transparency credits. The MR :BPDO – Material Ingredients has the lowest rate of achievement of any credit (19.14%), followed by MR : BPDO – EPD (25.31%).

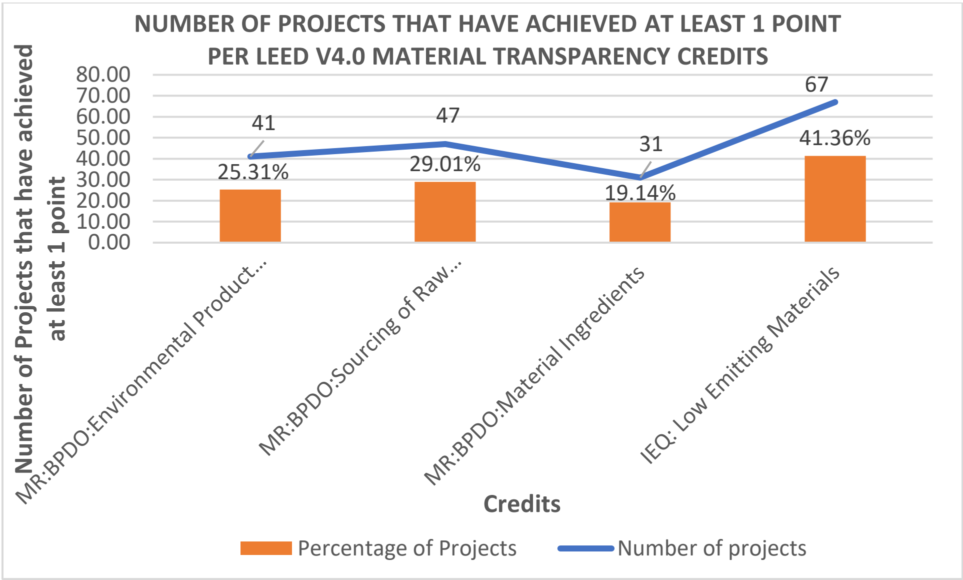


Figure 3: Number of Projects that have achieved at least 1 point per credit

Out of the 404 projects with scorecards available for evaluation, the projects that have achieved one or two points for MR: BPDO: Material Ingredients (HPD) and MR:BPDO: Environment Product Declaration (EPD) were separated and the projects were categorized based on the years from 2014 to 2018. The projects with scorecard available each year is seen to steadily increase over the years from 2014 to 2017 from 5 to 64 projects and there is a sudden jump in the number of projects to 271 in 2018 (Figure 4). The number of projects that have successfully attained 1 or 2 points for MR:BPDO: Material Ingredients credit have not been more than 15% of the number of projects with scorecards available that year (Figure 5).

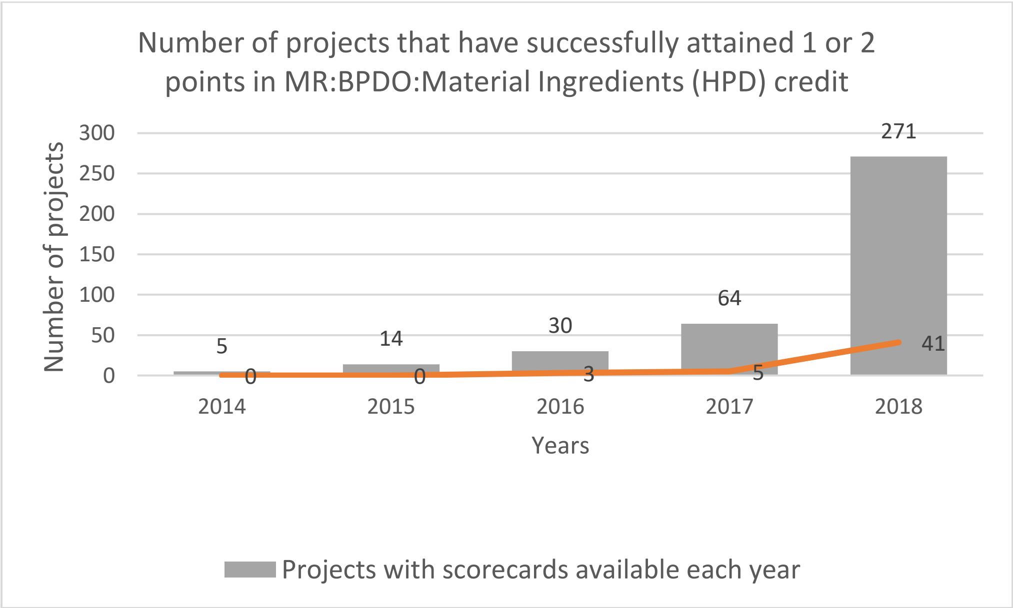


Figure 4: Number of projects that have successfully attained 1 or 2 points in MR:BPDO:Material Ingredients (HPD) credit

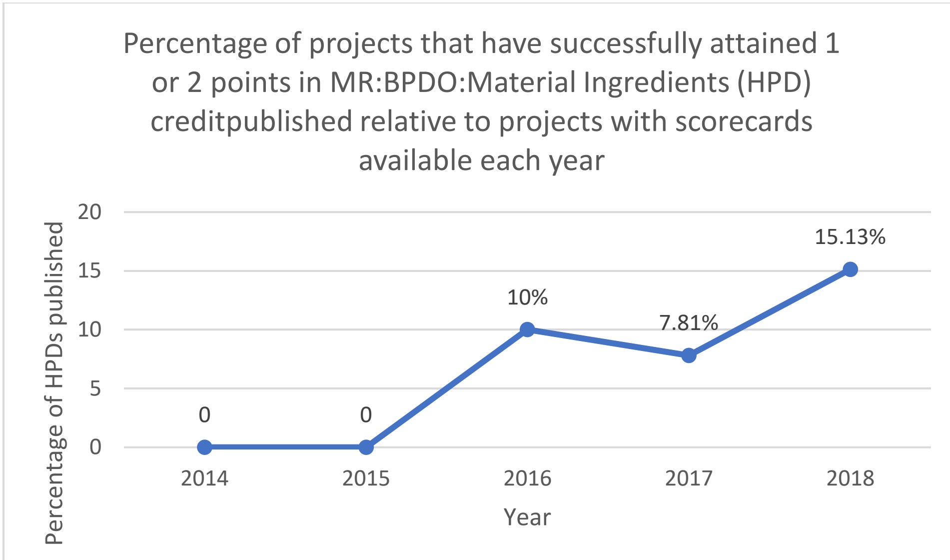


Figure 5: Percentage of projects that have successfully attained 1 or 2 points in MR:BPDO: Material Ingredients (HPD) credit published relative to projects with scorecards available each year

The number of projects that have successfully attained 1 or 2 points for MR: BPDO: EPD are not more than 20% (52 out of 271 projects) of the number of projects with scorecards available that year (Figure 6 and 7).

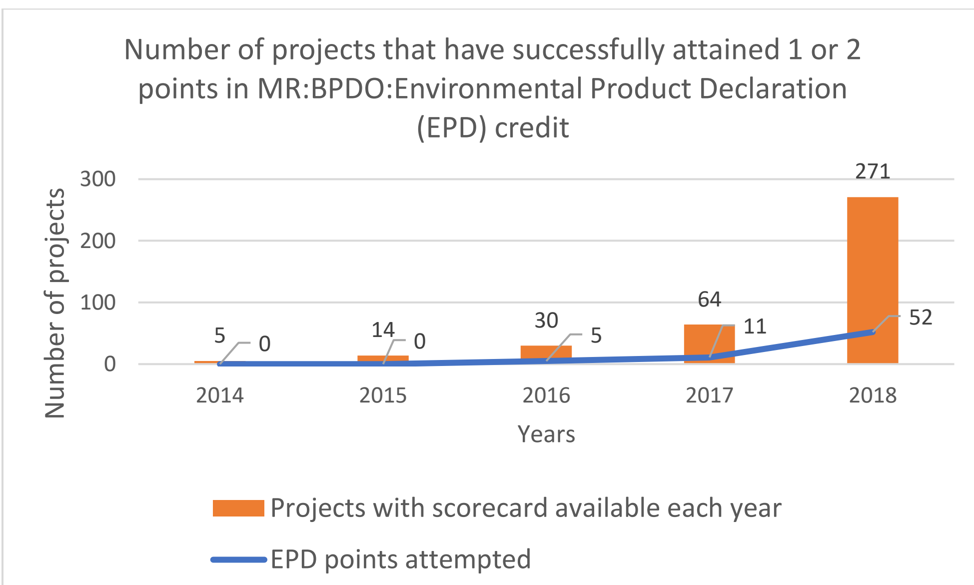


Figure 6: Number of projects that have successfully attained 1 or 2 points in MR:BPDO:Environmental Product Declaration (EPD) credit

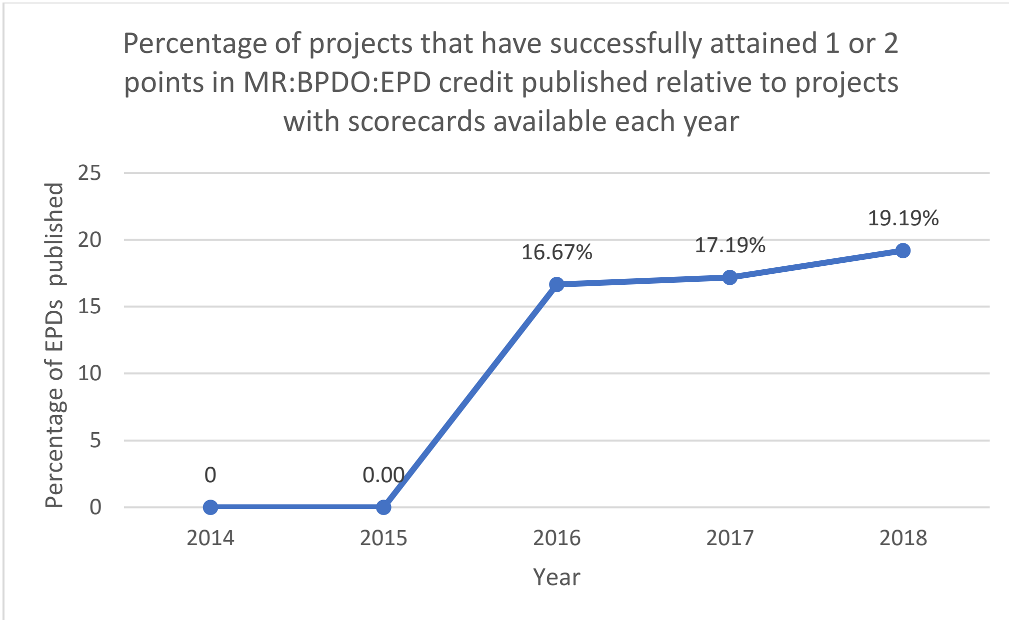


Figure 7: Percentage of projects that have successfully attained 1 or 2 points in MR:BPDO:EPD credit 's published relative to projects with scorecards available each year

Methodology:

The method chosen for the qualitative research is snowball sampling (chain referral) for collecting data by conducting phone interviews of manufacturers of the products listed in the Declare database, local architects and interior designers from the ASID list, architects or sustainability consultants of the 162 projects that have successfully achieved at least one credit among the 4 credits under the MR: BPDO and EQ categories out of the 404 projects.

The questions asked to Architects were mainly under 5 categories:

- Transfer of product information
- Material selection decision making authority
- Creating demand in the market
- Lack of knowledge to interpret or compare the documents
- Barrier in achieving the EPD and Material Ingredients credits

The questions to the manufacturers were regarding:

- Transfer of product information
- Proprietary ingredient exclusion

Participants were contacted via email and those who agreed to be interviewed as part of the study were asked to commit 15-30 minutes to the interview process. Interviews were conducted over the phone and Total Recall was used to record the phone calls to allow for playback and transcription later. Recorded interviews were transcribed manually on to the interview instrument and was then entered into Microsoft Excel file under each theme and question. The same set of questions were asked to each participant.

Thematic analysis was used to distill and organize the data. The process followed Braun & Clarke's (2006)description of thematic analysis. First, once all of the interviews were complete, the researcher read through all of the interviews from beginning to end, allowing them to view the narratives as a whole (Braun & Clarke, 2006). Next, initial codes were generated in order to assign coding categories to the raw data. The original codes were distilled into 1-2-page lists of categories to make the number of items more manageable. Those categories were then linked to construct the overarching themes.

Results:

A total of 22 phone interviews of architects, consultants and sustainability directors of manufacturing companies were conducted from August 6, 2019 to September 17, 2019 of which 12 were with architects or consultants and 10 were with sustainability consultants of manufacturing companies from Declare database.

- Architects

35 invitations to participate in the research interviews were sent by email out which 12 were conducted. 5 out of the 12 participants have worked on LEED v4.0 projects which were a part of the certified projects under USGBC Project Directory. The other 7 participants were a result of snowball sampling of interviewees who suggested them based on the research parameters and their knowledge of the main companies working on these issues. This category of participants consisted of 4 architects, 2 interior designers and 6 sustainability specialists with experience in the construction industry ranging from 5 to 40 years.

<u>Transfer of product information :</u> 75% of the architects use both manufacturer's website as well as material databases to search for materials with transparent documentation while 16.67% use only material databases. 66.67% of architects do find it difficult to access material and product information and 25% of these architects feel there has been progress too over the years. Difficulty in identifying healthier products in material databases was indicated by 8 out of the 12 architects while 2 architects indicated that there has been progress. Origin/Mindful Materials is the most used material database

(83%) followed by Declare (75%) while Building Green Approved on Designer Pages is the least used database.

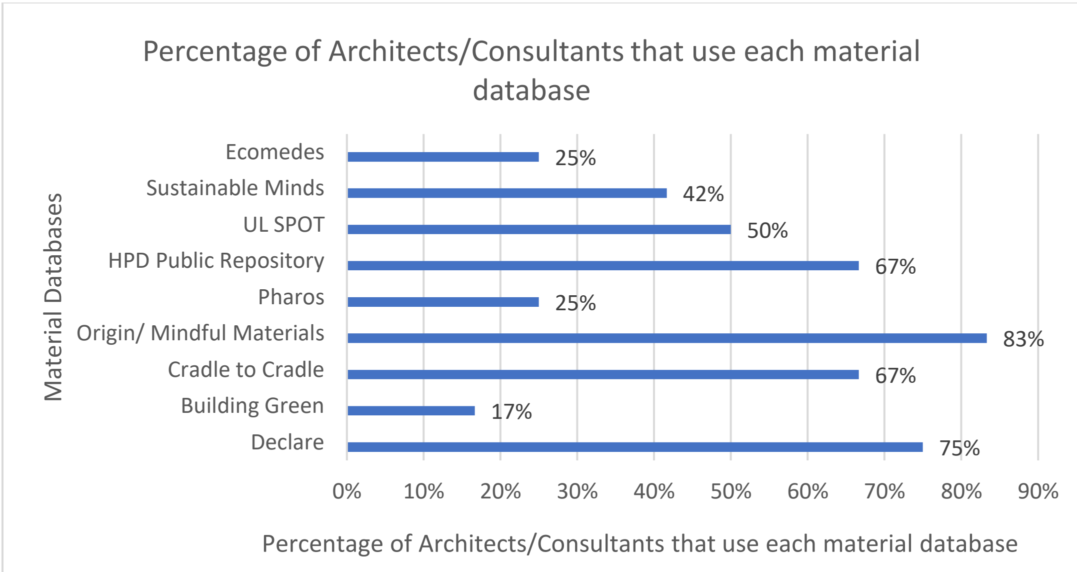


Figure 8: Percentage of Architects/Consultants that use each material database

Material selection decision making authority : 8 out of 12 specified that the architect is the one who specifies the brand of materials and products to be used. The others indicated that the contractor selects the commodity materials while the architect specifies the architectural products like finishes, curtainwall systems, carpets etc. which are manufacturer specific. All the respondents mentioned that the contractor handles substitutions and it is mostly based on the cost (41.67%) or based on equal sustainability outcomes (41.67%) and 25% indicated it varies by client. More than 90% of the respondents said that the specifications are both prescriptive and performance based.

Creating demand in the market: Most of the architects (91.67%) do feel that they are moving the market by specifying products that openly share the material ingredients.

Lack of knowledge to interpret or compare documents: 11 out of 12 architects felt the need of a material expert or specialist in choosing the materials for a project.

The architects were asked the barriers they felt in achieving the MR:EPD and Material Ingredients credits and 50% of them talked about the increased time and cost involved in the process followed by 42% who said the limited knowledge to interpret or compare the documents makes material selection difficult (Figure 9). Other material selection factors like cost and aesthetic along with sustainability, bigger companies vs. smaller companies and lack of availability from manufacturers were the least indicated barriers.

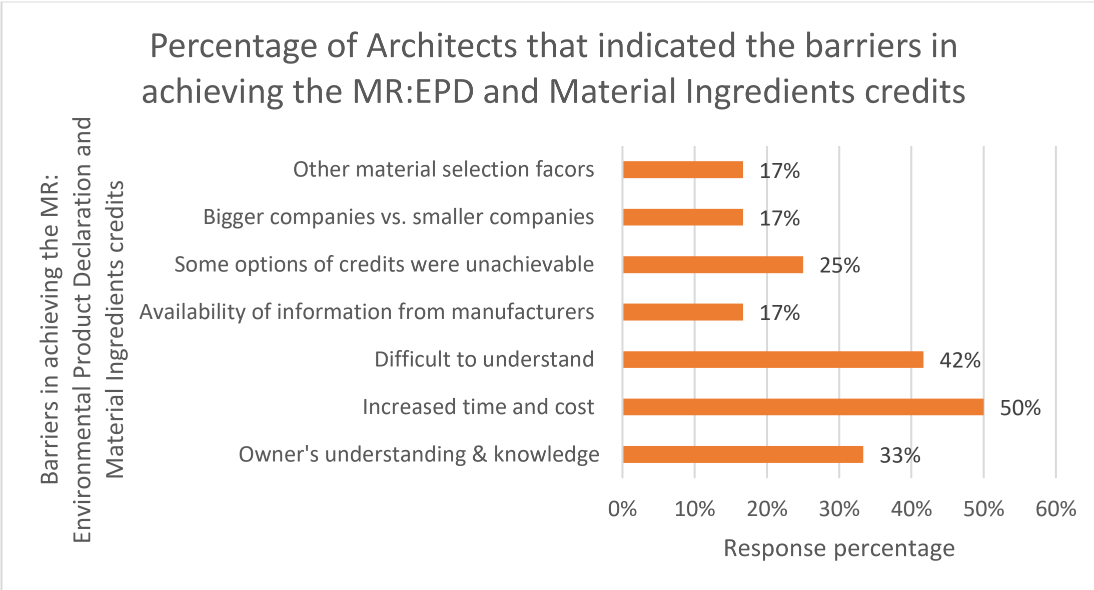


Figure 9: Percentage of Architects that indicated the barriers in achieving the MR:EPD and Material Ingredients credits

- Manufacturers

The sample of manufacturers were from the Declare database which is a transparency platform and product database that is transforming the material database organized by the International Living Future Institute (ILFI). Invitations for phone interviews were sent out to 44 of the manufacturers, 11 responded and 10 interviews were conducted. Table 1 shows the participant role of each interviewee and corresponding CSI Division of the company's products. The work experience in the industry among the respondents varied from 6 to 30 years.

Table 1: Participant Role in company and CSI Division of product

#	Participant role	Manufacturer CSI Division by interview
1	Compliance, Risk & Certification Manager	64000 Architectural Woodwork
2	Director of Sustainability	26 Electrical + 09 Finishes
3	Founder	07 Thermal and moisture protection
4	Technical Director	09 65 00 Resilient Flooring
5	Environmental Sustainability Manager	09 Finishes
6	Sr. Advisor - Sustainability	05 40 00 Cold Formed Metal Framing
7	Compliance and Environmental Manager	10 Specialties
8	Sustainability and Environment Director	03 Concrete
9	Director of Sales & Marketing/Sustainability Champio	08 Openings
10	President of Corporate Strategy and eCommerce	22 Plumbing

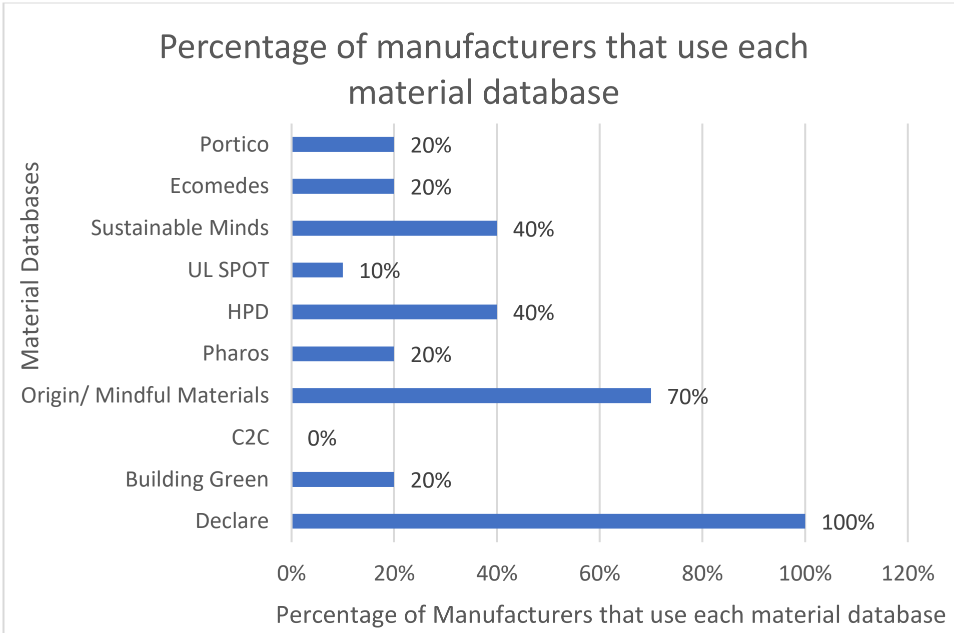


Figure 10: Percentage of manufacturers that use each material database

Origin/ Mindful materials is the most commonly used (70%) material database after Declare. The least used database is Cradle to Cradle certification. The main factor for choosing a database is based on the market demand, data accuracy, standards and formats and finally the cost of registering or uploading products in the material database (Figure 11). Half of the respondents think that the 1% proprietary ingredient exclusion in Declare database would eliminate the manufacturer's risk around intellectual property in a product.

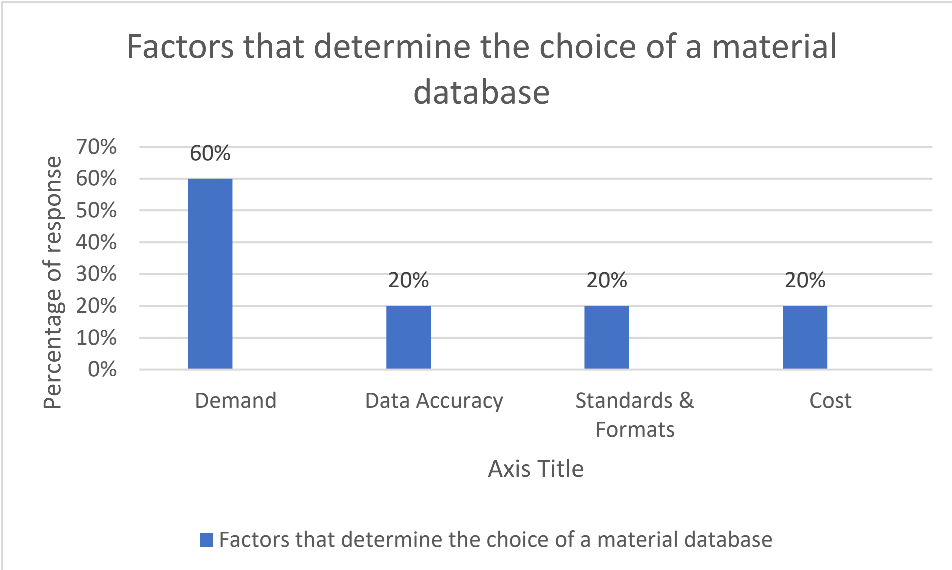
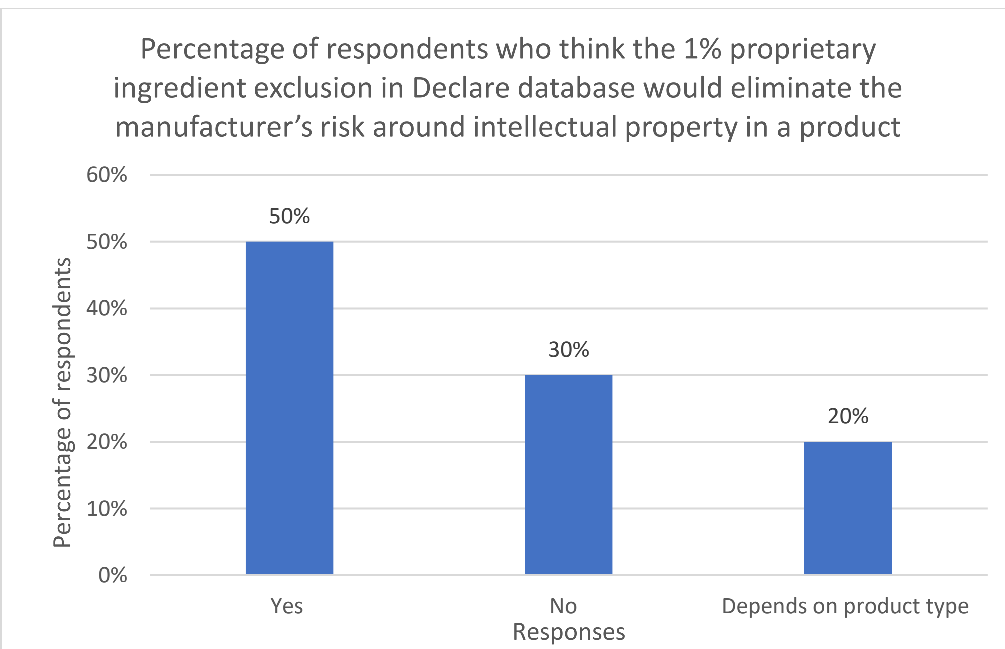


Figure 11: Factors that determine the choice of a material database



The only common question asked to both manufacturers and architects was regarding their choice of material database for the transfer of information. Figure 12 shows that

Declare and Mindful Materials are the choice of material database for architects as well as manufacturers.

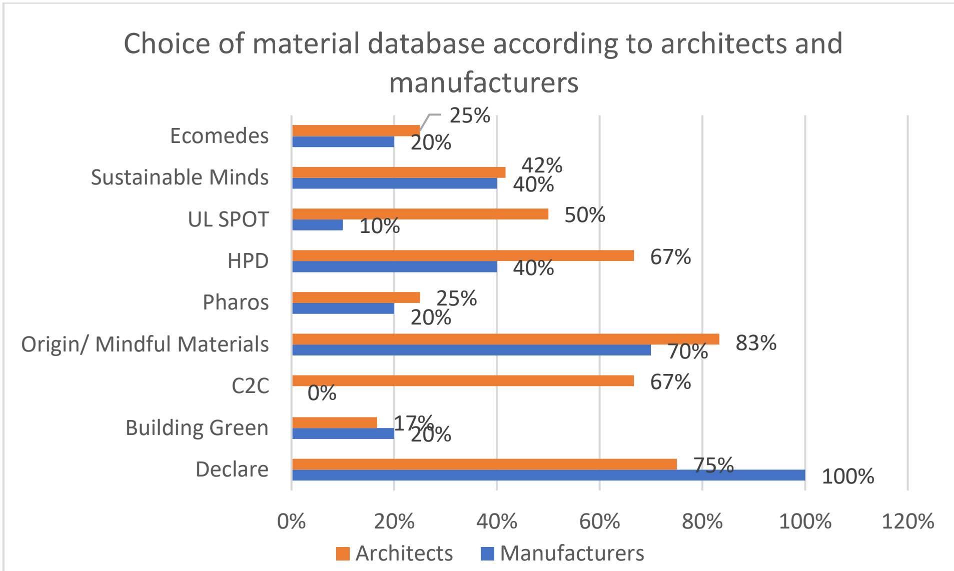


Figure 12: Choice of material database according to architects and manufacturers

Conclusion:

The need for more education around material health, transparency and disclosure, however, was referred to in all 22 interviews. The need for consumer education around interpretation of transparency and disclosure was the most prevalent of all issues raised in the interviews, regardless of a manufacturer's product types or the architects. Most of the architects expressed the need of a single database with all the disclosure information rather than doing all the documentation and searching through multiple databases and manufacturing websites for material ingredients. A lack of standardization in the industry was cited as particularly problematic for gathering, interpreting and reporting information on product content and material health. The increased time and cost for accessing material ingredients is partly due to the lack of knowledge to interpret chemical content and material ingredient information and time-consuming procedure of searching multiple databases for a single product's information. These are factors to consider when comparing small manufacturers to bigger companies as they may not have the time or resources to get the testing done for their products. The intent of this study was to further understand the following common barriers in material transparency in the construction industry identified from literature and background study:

- Transfer of product information between the designers and manufacturers
- Material selection decision making authority within design teams
- Need for education and training on material transparency among design teams
- Motivation for achieving material transparency credits in LEED® v4 projects

The results of the research indicate the need for education on material transparency among design teams, owners and especially contractors since they handle substitutions in a project. Standardized and easy to use transfer of product information is essential for designers to use healthier materials regardless of the sustainability outcomes of the project.

Limitations:

- Out of the 1573 projects, only 404 projects have scorecards available to evaluate the projects so there is a lack of complete data
- The scorecards from the USGBC LEED® v4.0 project directory does not provide information on which option was pursued to achieve the credits.
- Types of manufacturers interviewed did not represent all sectors of the industry as there is a wide range of products produced for the built environment.
- Due to the exploratory nature of the study, and the limited number of participants, extrapolation of the results to the larger industry is not possible.

Implications of Research:

The research would help to identify the problems in achieving material transparency in LEED® projects which would in turn bridge the gap between manufacturers and consultants or end users. Manufacturers, design and building professionals need accurate and comparable product data in order to make informed design and healthier product selection decision. This would help more projects to have easily accessible database for material selection and help in achieving material transparency.

List of figures

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Mass Customized Cross-Laminated Timber Elements for Residential Construction

D. P. Hindman[1]

A. M. Memari[2]

[1]Associate Professor, Department of Sustainable Biomaterials, Virginia Tech, 1650 Research Center Drive, Blacksburg, VA 24061. (540)-231-9442. dhindman@vt.edu

[2] Professor, Bernhard and Henrietta Hankin Chair of Residential Building Construction and Director, The Pennsylvania Housing Research Center (PHRC), Department of Architectural Engineering and Department of Civil and Environmental Engineering, Pennsylvania State University, 222 Sackett Building, University Park, PA 16802. ((814) 863-9788. amm7@psu.edu

ABSTRACT

Cross-laminated timber (CLT) is a new building material rapidly expanding in use in the United States construction industry. Current CLT construction style has focused on exterior load bearing walls systems to create a range of buildings. CLT combines uses of modular construction and building information modeling (BIM) to create pre-manufactured elements which are easily and quickly assembled on-site, creating significant savings in construction labor costs. As CLT enters the building code and market to a higher degree, it may be helpful to examine other structural material systems currently in use where CLT materials could improve current systems. Specific areas discussed in this paper include the use of CLT for elevator shaft wall systems, wall segmentation placement to create open structures and the use of CLT products for tornado and storm shelters.

INTRODUCTION

Introduction to Cross-Laminated Timber

Cross-laminated timber (CLT) is a new building material being used in the United States construction industry. The architecture, engineering and construction (AEC) community has shown great interest in the use of CLT construction methods. According to a report by Zion Market Research, the North American CLT demand was around $130 million in 2017 and is expected to grow, with an overall global growth rate of 15% per year until 2024 (Zion Market Research, 2018).

The current CLT building style focuses on a set of exterior load-bearing walls with the addition of interior bearing walls for buildings of greater heights (Green 2012). CLT construction has been used for a range of building types, from residential, educational, commercial and light industrial. Currently, the tallest CLT building is Brock Commons, an 18-story dormitory at the University of British Columbia in Vancouver, British Columbia, Canada (Connolly et al. 2018). However, a 21-story CLT building has just passed plan approval in Milwaukee, Wisconsin as of January 2019 with expected completion by spring of 2021 (Daykin 2019). A distinct advantage of CLT construction methods is the quick assembly time – Brock Commons needed less than 70 days for completion (Woodworks, 2019).

Cross-laminated timber as a structural building material has proven its value based on the recent construction of various large-scale buildings throughout the United States. The appeal of CLT is very multi-faceted. First, this is the first truly two-dimensional massive structural element available in the area of timber products, allowing an increased use and flexibility of design and construction. Another advantage is the ease of connection of CLT panels using metal plated connectors and self-drilling, self-tapping screws. These connections also allow CLT members to be easily attached to steel elements and integrated into the design. From the construction viewpoint, an advantage of CLT is the modularity of design and ability to complete most of the construction preparation of the panels off-site. This tends to lower construction costs and delivery times since the only on-site operations are lifting and installation of the panels, which is facilitated by interlocking connections and self-drilling, self-tapping screw connections.

In a recent article in the University of Washington alumni magazine (Duff 2017), the benefits of CLT construction were expounded upon to produce light, efficient, carbon friendly buildings. Perhaps the greatest advantage of CLT construction noted was the revitalization and job growth in many rural areas where forest resources exist and employment is scarce (Duff 2017). Much more than just a building material, CLT is viewed by many as an economic force. Many CLT production facilities in the United States are being placed in timber-rich portions of the country to provide rural economic development.

The appeal of CLTs as low-carbon buildings, while not canonized in the United States building requirements, has been a major influence on CLT construction in Europe and continued focus on low-carbon structure initiatives will give CLT an advantage over other materials. Zion Market Research notes that the increased use of CLT is in part related to desires for sustainable construction (Zion Market Research 2018).

The true value of CLT is hard to capture and often hard to understand due to the unbridled enthusiasm of its supporters. CLTs represent a truly 2-dimensional structural form in a wood material, something which has not been available before. While the concept of plywood and cross laminates has been around and available commercially, these products were never able to be load-bearing entitites in and of themselves. Plywood and oriented strandboard require a support frame of 2x lumber to provide for bearing, support and connection to other building elements. CLT can function independently from other materials, or CLT can be easily married to other wood or structural products to create optimal building systems.

Modular Construction Methods

Modular, or pre-manufactured, or prefabrication systems refer to units of buildings produced off-site, then transported and assembled on site (Pasquire 2002). Pre-manufactured systems can vary from assemblies of individual components (trusses, walls, roofs) (Generalova et al. 2016) to three-dimensional assemblies complete with plumbing, electric and finish trim (O'Brien 2000). Benefits of pre-manufactured construction were examined by a survey of building professionals in Hong Kong, who rated (in order of preference) better supervision, consistent design from early stages, reduced construction costs and shortened construction time as the most beneficial assets (Tam et al. 2007).

An essential component of the successful integration and use of pre-manufactured elements is building information modeling (BIM), which unlike 3D CAD system, allows data and attributes of model elements to be incorporated into the model, providing specific information about the components and assemblies used (CRC Construction Innovation 2007). Lu and Korman (2010) presented several case studies of how BIM can be implemented in modular and pre-manufactured construction projects.

MODULAR CONSTRUCTION USING CLTS

The modular aspects of CLT have been highly espoused, allowing construction of unitized systems and assemblies (Kremer 2018). Due to transportation difficulties, it may be best to consider panelization strategies focusing on planar construction that can be shipped to the site or near the site, then assembled. The idea of constructing larger three-dimensional units is interesting, but comparing the shipping ability of a set of panels versus an assembled structure is very expensive. To wit, it is neither efficient nor cost-effective to ship space.

With the stated vision of using CLT as an economic driver, the question was raised about how the economic profile of CLT materials could be expanded further in the area of construction. As CLT enters the building code and market to a higher degree, it may be helpful for us to reevaluate current uses of conventional materials and understand how CLT can be incorporated or substituted to produce more efficient structures in terms of time and labor. The intent of this article is to start a conversation about different uses of CLT materials in building subsystems. Several examples of building subsystems are suggested.

EXAMPLES OF CLT BUILDING SUB-SYSTEMS

Shaft Wall Systems

Shaft walls are continuous wall systems which penetrate through several floors to provide access (elevators, stair cores) or services (MEP shafts) to the building. Several resources for the design of wood-based elevator shafts are available from Woodworks (McLain 2016) and discuss the design and construction methods of shafts.

According to the 2018 IBC, a shaft is defined as "an enclosed space extending through one or more stories of a building, connecting vertical openings in successive floors, or floors and roof" (§202) (ICC 2017). Provisions describing shaft enclosures are given in Section 713. Shaft enclosures are also constructed as fire barriers, which must conform to Section 707 as well. Furthermore, the materials permitted should conform to the type of building construction (713.3) and must have a fire rating of at least 2 hours when connecting 4 stories or more, or a fire rating of at least 1 hour when connecting less than 4 stories (713.4). An important quality of shaft enclosures is the idea of continuity of the fire barrier to prevent fire from entering the shaft or entering various floors that the shaft passes through. McLain (2016) provides specific details of wood construction to achieve fire barrier continuity.

A recent project at Trinity Western University in Canada used a CLT shaft wall for the elevator core system of a light-framed five-story building (ThinkWood 2019). The use of CLT for shaft walls of light-framed structures seems an ideal pairing given the greater shear strength of the CLTs to act as lateral bracing for the light-framed structure, possibly providing a reduction in shear wall lengths needed, and also allowing more architectural freedom in design.

A CLT elevator shaft was recently completed by Smartlam for a building in Whitefish, Montana in 2016 (www.forconstructionpros.com 2016, Smartlam 2016). Specific advantages of the use of CLT elevator shafts over more conventional concrete-masonry-units (CMUs) were given as dimensional stability, environmental performance, lower costs and quicker assembly. For this project, the CLT elevator shaft walls were assembled in several hours with three people and a crane. The equivalent sized CMU elevator shaft would have taken three weeks to construct using 8-12 people. Cost savings were estimated between 70 and 75%.

Figure 1. Elevator Shaft Constructed by Smartlam (Photo Credit: Smartlam)

Wall Segmentation and Separation

One advantage of CLT wall systems is the high shear strength compared to similar sized wood-based system. The use of CLT wall segments placed strategically throughout the structure (corners of walls, transitions or joints) can provide adequate lateral capacity to a building, while allowing almost a complete design flexibility in the other areas of the wall. This flexibility could result in the placement of extensive banks of windows, doors or even open space.

A possible concern with wall segmentation that would need to be addressed for energy efficient buildings is the difference between thermally insulated walls and CLT sections. Compared to typical insulation, the CLT will act as a thermal bridge allowing the transfer of more heat through the building envelope. Additional insulation, which may change the exterior shape or profile of the building could be used to address this.

An example of the use of CLT materials to increase wall sizes was a design example created to demonstrate the use of CLT wall sections in post-frame constructed buildings (Hindman 2015). Comparisons of the interior frame deflections when using a typical post-frame endwall versus a CLT wall showed little difference. However, when examining the deflection of the endwall itself under loading, a typical solid post-frame endwall had a similar deflection to a 3-layer CLT wall with a 60% area opening or a 5-layer CLT wall with an 80% area opening. The change in deflection was due to the larger shear stiffness associated with the CLT panel versus a typical post wall with attached skin.

Disaster Preparedness and Tornado Shelters

Because of the high shear strength and impact resistant properties to storm debris, CLT materials have also been considered for use as tornado and storm shelters. Recently, Falk et al. (2019) produced a publication from the Forest Products Laboratory detailing the testing of a CLT tornado shelter. Several versions of the structure were created, including a nailed cross-laminated construction which could be created using lumber in an existing home, as well as a typical glued CLT panel construction. Special reinforcement details including connections to the existing structure and proper door support are discussed.

CONCLUSION

The examples provided in this article demonstrate some of the possible uses for CLT products in buildings instead of the standard exterior bearing walls. Using CLT materials to create elevator shafts can help increase the stiffness of light-frame construction methods. The use of wall segregation, where portions of the wall are assigned the lateral capacity of the entire wall, can provide more design flexibility in construction and lead to more open building concepts. CLTs can also provide protection from tornado and storm debris. Clearly, there are many more concepts that this material can use to help create more innovative buildings.

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Shake Table Testing of a 10-story Mass Timber Building with Nonstructural Components

Keri L. Ryan, Shiling Pei, Tara Hutchinson

[1]Associate Professor, Civil and Environmental Engineering, University of Nevada Reno, 1664 N. Virginia St., Reno, NV 89557; klryan@unr.edu
[2]Associate Professor, Civil and Environmental Engineering, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401; spei@mines.edu
[3]Professor, Structural Engineering, Jacobs School of Engineering, UC San Diego, La Jolla, CA 92093; tara@ucsd.edu

ABSTRACT

To advance the wood products market, new design solutions for tall wood buildings using mass timber products are being developed. In particular, post-tensioned cross-laminated timber (CLT) rocking walls have been proposed as a seismic resilient lateral system. To advance the seismically resilient CLT rocking walls for tall buildings, a comprehensive shake table test of a 10-story building with CLT rocking walls is planned for 2021 on the NHERI@UC San Diego outdoor shaking table. An essential aspect of building resilience is assurance that nonstructural components (NCSs) sustain minimal damage or are easily repairable; however, a number of aspects specific to rocking wall systems and their impact on NCSs are not well understood. This test is the culmination of the NHERI TallWood Project that aims to develop seismic design methodology for resilient timber buildings. An essential aspect of building resilience is assurance that NCSs sustain minimal damage or are easily repairable; however, a number of aspects specific to rocking wall systems and their impact on NCSs are not well understood.

In this paper, preliminary plans for a seismic shake table test of a 10-story mass timber building are described, and a vision for incorporating NCSs into the test program is presented. Due to the lack of shake table test data of exterior skin systems with glazing, a key objective is to characterize the response of a variety of curtain wall and light-framed window wall type systems, and to validate industry standard racking tests as predictors of seismic performance. In addition, detailing improvements for stairs, interior partition walls, and suspended ceilings are proposed. The project team is actively seeking industry and academic collaborators for testing of various NCSs to capitalize on this opportunity.

1.0 INTRODUCTION

Typical light frame wood stud walls sheathed with wood structural panels are limited to low or mid-rise construction. To expand the wood products market, industry aims to develop and promote the application of new tall wood buildings built from mass timber products. The greatest challenge to taller wood construction is the development of a reliable lateral load system that can produce predictable response and minimal damage when subjected to strong seismic shaking. Recent research aims to enhance the seismic performance of these buildings through use of a cross-laminated timber (CLT) rocking wall lateral system that accommodates the seismic deformation demands by rocking about the base. These promising CLT systems use post-tensioning rods anchored from the top of the wall to the foundation for restoring force and recentering capability, with external energy dissipation devices to reduce drift demands.

To advance seismically resilient CLT rocking wall systems for tall buildings, a landmark shake table test of a 10-story building with CLT rocking walls is planned for 2021 on the NHERI@UC San Diego outdoor shaking table. This test is the culmination of the NHERI TallWood Project that aims to develop a seismic design methodology for resilient timber buildings. An essential aspect of building resilience is assurance that nonstructural components (NCSs) sustain minimal damage or are easily repairable; however, a number of aspects specific to rocking wall systems and their impact on NCSs are not well understood. The NHERI@UC San Diego shake table facility is in the process of being upgraded to allow 6-degree-of-freedom (DOF) input motions. The planned CLT tall building test program in 2021 will be the first tall building tested on the newly upgraded facility.

Uniquely, the 10-story building specimen will incorporate a variety of NCSs, such as facades and egress (stairs). Architects and engineers envision mass timber buildings to be clad with lightweight façades, such as curtain wall, storefront, and light-framed window wall type systems. Glass facades have not been evaluated under rigorous shake table testing. The inclusion of several different systems through industry stakeholder participation is envisioned. The height of the test building allows testing of stairs with a variety of connection details, including expansion joints that better accommodate floor-to-floor interstory movement. Additional NCSs will be strategically located in the building so that they are subjected to variable demands; for example, NCSs at lower levels are subjected to larger drifts while NCSs at upper levels are subjected to larger accelerations. The objectives of this paper are to discuss the basic configuration and preliminary gravity and lateral design of the 10-story building specimen, explain the test objectives and test plan, and present a vision for the inclusion of NCSs. The project presents an opportunity for collaboration with other academic and industry partners.

2.0 DESCRIPTION OF 10-STORY TEST BUILDING

2.1 Configuration

The preliminary design of the 10-story building was completed by the second author in collaboration with structural engineers and architects from KPFF, Holmes Structures, and Lever Architecture. Several considerations dictated the plan configuration of the 10-story test building. First, the structural base is required to sit completely on the shake table with its 25’ x 40’ footprint, to avoid the need to build an outrigger platform (Fig. 1(a)). However, to maximize the floor plan area, cantilevered floor slabs are utilized on all floors above the base (Fig. 1(b)). Story heights are assumed as 13’ for the first story and 11’ for all other floors.

The inclusion of realistic architectural layouts was a high priority. Based on the fact that real buildings are rarely designed to be perfectly rectangular, the plan incorporates some insets and angled walls. (Fig. 1(b)). Further to this goal, beams, columns and walls are arranged based on a vision for the building architectural layout with mixed-use occupancy. As frequently seen in practice, usable floor space surrounds a centrally located stair core. Figure 2 illustrates a concept for how the test building floor plan might be used on an office floor (Floors 3-6, Fig. 2(a)) and a residential floor with 2 units (Floors 7-9, Fig. 2(b)). Floors 1 and 2 are envisioned as open lobby, while Floor 10 is envisioned as a penthouse unit.

The main lateral system is composed of two post-tensioned CLT rocking walls in each direction. The central stair core is utilized for the placement of one of the walls. The other three walls are located on the building perimeter, which increases torsional resistance, and allows for the rocking walls to be part of the building architecture and on display from the street level. The wall placement then determined the placement of the gravity system composed of glulam beams and columns. All rocking walls have boundary columns on each side; thus columns are spaced 11’ o.c. when used as rocking walls. The remaining column spacing is

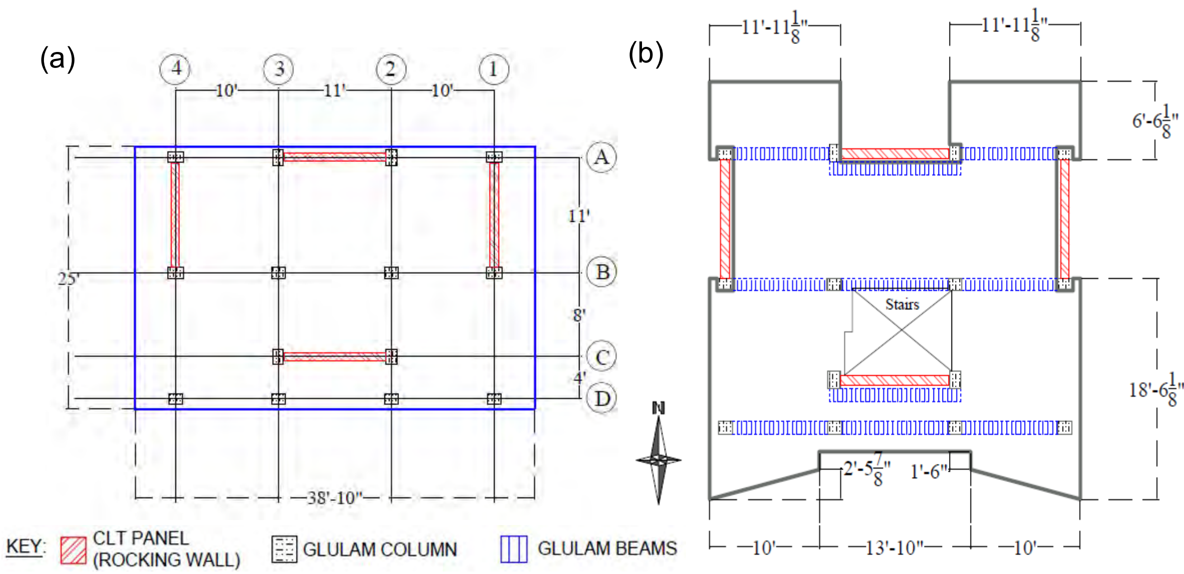

Figure 1. Structural plan layout of 10-story test building: (a) base level on shake table (table outline in blue), (b) typical floor plan (floor panel edge boundary in gray).

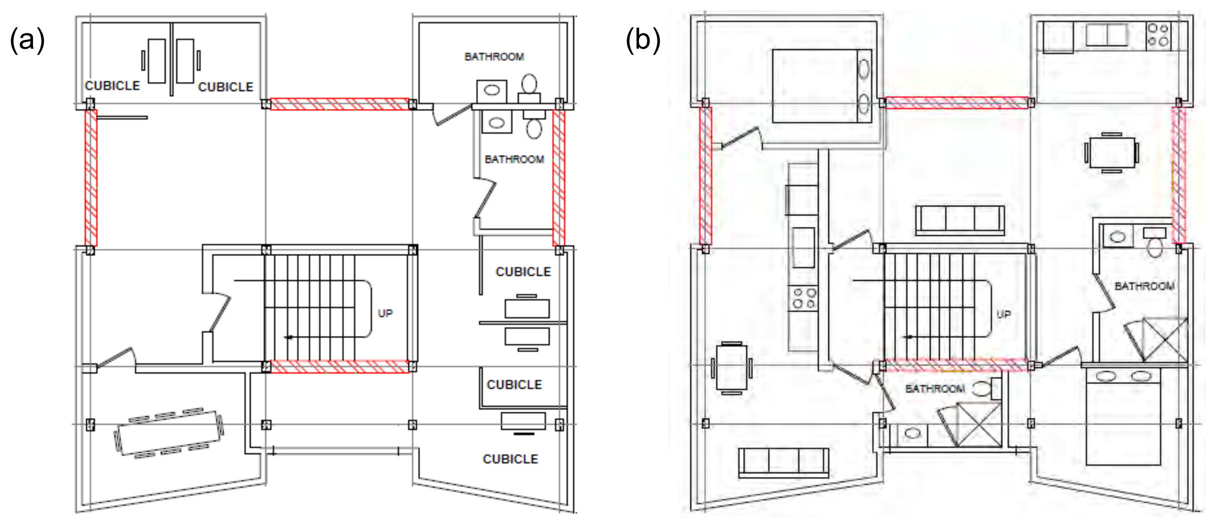

Figure 2. Representative architectural floor plan layout for (a) lower story office occupancy, and (b) upper story residential occupancy.

dictated by the geometric constraints (Fig. 1(a)). Glulam beams are utilized in the E-W direction only, between all columns except offset as needed at rocking wall locations (Fig. 1(b)). A 3D rendering of the structural system is shown in Fig. 3.

2.2 Gravity Design

The gravity system was designed according to the National Design Specification for Wood Construction (AWC, 2015), using Allowable Stress Design. The gravity members are designed for 60 psf dead load for all floors and 50 psf live load for office occupancy or 40 psf live load for residential occupancy, plus 15 psf partition load, for all floors excluding the roof. The seismic mass to be applied during testing is 70 psf, which will be achieved by adding steel plates. In addition, all columns and beams are designed with sacrificial layers ensuring 2 hour fire rating (@ 3.6 inch/hr char rate on all exposed surfaces).

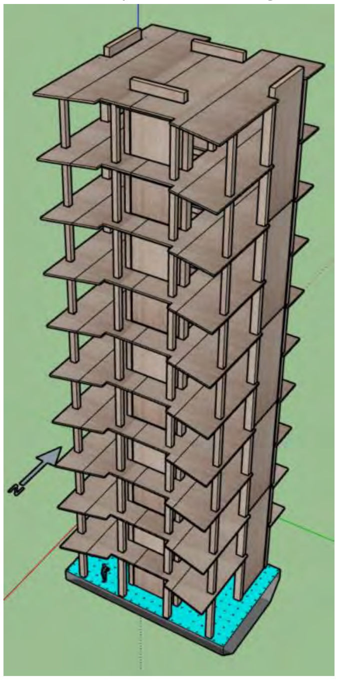

Figure 3. 3D rendering of 10-story building structural system

Beams and columns are assumed to be glulam Western Species 24F-1.8E stress class or equivalent. The floor diaphragms are 3 Ply CLT (4.125") PRG320 – compliant panels. The 3-ply floor panels satisfy the requirements for gravity design, but the team is anticipating upgrading to 5-ply to accommodate exterior skins hung from the cantilevered edges. The CLT floor panels will be fabricated in 6 pieces per floor with strategic geometry that will allow them to be moved into place around the columns.

Table 1. Structural system member dimensions

Member	Cross-Section Dimension or Thickness (in)
Columns (Floor 1-2)	12.25 x 15
Columns (Floor 3-6)	12.25 x 13.5
Columns (Floor 7-10)	12.25 x 12
Rocking wall boundary columns (All Floors)	12.25 x 18
Beam (All)	12.25 x 13.5
CLT floor panel (3-ply)	~4-1/8
Rocking wall Panel (9-ply)	~12-3/8

2.3 Lateral Design

As mentioned previously, the lateral resistance is dominated by two post-tensioned CLT rocking walls in each direction. The walls are designed to rock up off the base, while each wall is post-tensioned through the center to provide a restoring force. The post-tensioning rods are designed to resist the moment that develops at the base of the wall. In addition, each wall is encapsulated by boundary columns. The wall and columns are connected by U-shaped flexural plates (UFPs) at every other story that dissipate energy when subjected to relative motion between the wall and the columns. The UFPs are designed to transmit the vertical shear that develops from the relative vertical displacement between the rocking wall and the bounding columns. Sample connection details for post-tensioning rods and UFP dissipaters are shown in Figs. 4(a) and 4(b), respectively. These details were utilized in a prior shake table test of a 2-story building with CLT rocking walls and performed adequately (Pei et al., 2019a). A floor-to-wall tongue connection at the center of the wall is utilized (Fig. 4(c)). Walls are attached to the floor diaphragms by a vertically slotted shear key that allows movement of the wall relative to the diaphragm. This detail, used in the 2-story building test (Pei et al., 2019a) was effective to prevent diaphragm distortion during wall uplift.

The preliminary CLT panel design has been validated by response spectrum analysis using SAP 2000, and based on ASCE 7-16 specifications. A design spectrum and maximum considered earthquake risk-targeted (MCE_R) spectrum assuming a location in downtown Seattle are utilized. The seismic weight is estimated assuming an area dead load of 70 psf on each floor that includes the floor diaphragm, and self-weight of the structural framing. For this analysis, the CLT walls are modeled with thin shell elements and CLT E1M5 structural laminated wall panel material. The preliminary design for drift is based on an equivalent linear elastic analysis of a fixed base shear wall subjected to unreduced forces. A strength design check is also

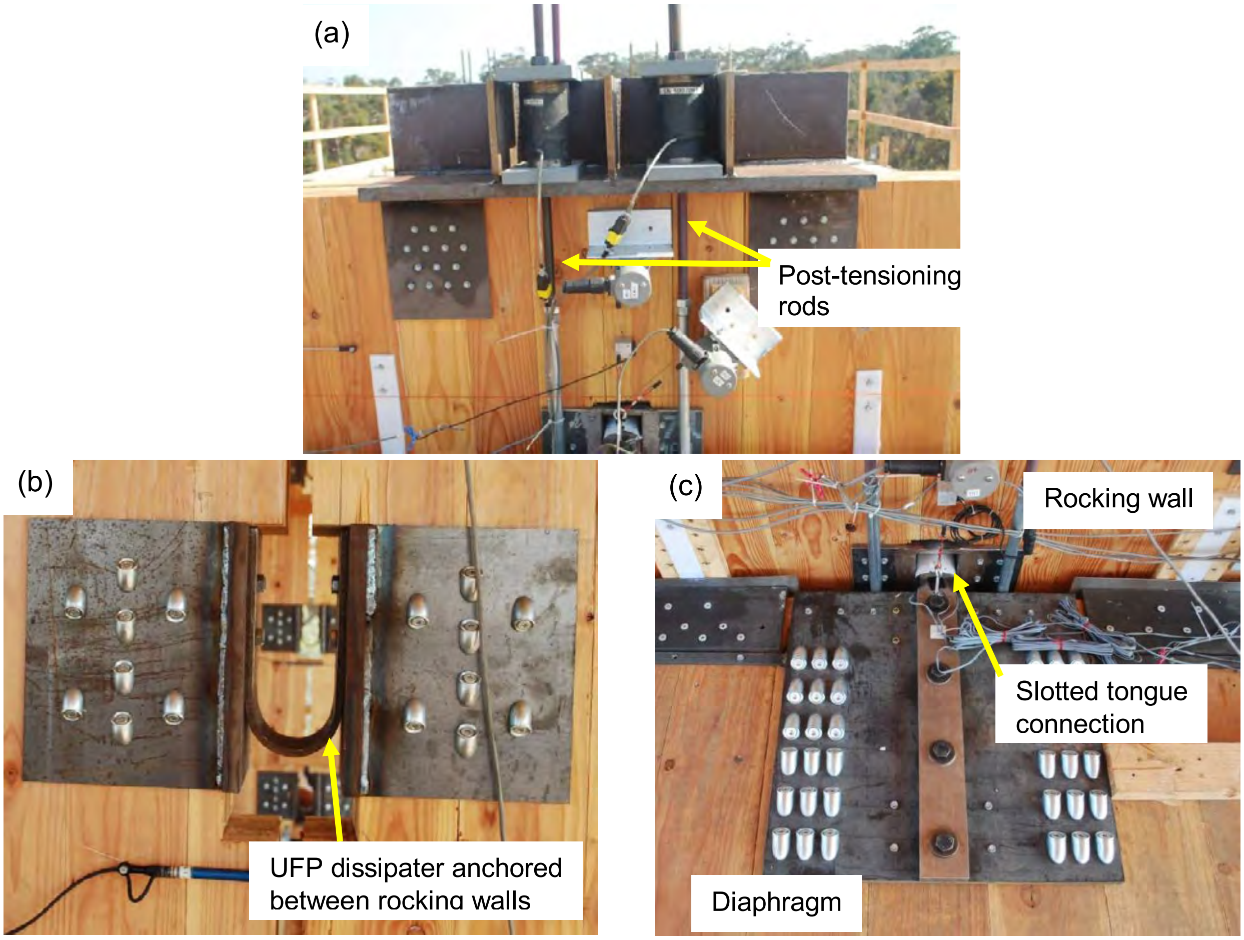

Figure 4. Details of CLT rocking wall lateral system: (a) post-tensioning rod connection at top of wall, (b) U-shaped flexural dissipater between rocking walls, and (c) floor-to-wall slotted connection at wall center. (Pei et al., 2019b).

performed, using the story shear envelope and base overturning moments evaluated via elastic analysis. The forces are calculated based on a design spectrum reduced by R = 6, and scaled up to meet the code minimum design base shear coefficient. These preliminary forces will be used in the design of the post-tensioning rods and UFPs, and the design will be refined by inelastic response history analysis.

3.0 OBJECTIVES AND TEST PLAN

As mentioned earlier, the TallWood project seeks to validate the resilience-based seismic design (RBSD) methodology for tall wood buildings using the 10-story test. Although final testing program is still in development over the next year or so, it is envisioned that the building will be constructed with a variety of NCSs, including different facade types and egress (stairs) in particular, and subjected to different levels of seismic ground motions considered in design. The building performance will be evaluated according to the following qualitative performance target metrics.

- The building and its components should remain damage-free for small earthquakes.
- The building and components should see very limited damage during design basis earthquakes (DBE), which is an event with a 475 year return period. The level of damage during DBE events should be limited to minor NCS damage that can be repaired quickly, resulting in little loss of

functionality after earthquakes. In other words, the minor repair work can be completed without significant interruption to occupants.

- At the MCE level, which is associated with a 2475 year return period event, the building is expected to experience some repairable structural damage (such as yielding of post tensioning bars) and moderate NCS damage, which may correspond to a relatively short downtime for the entire building to be inspected and repaired.

The research team will compare the actual test performance to the intended resilience design targets used in the design of the building. The central idea of the validation is to achieve controllable downtime at different intensity levels through RBSD. Furthermore, the test serves as a great opportunity to expand the database for development of fragilities for NCSs, and to evaluate the drift compatibility and resilience of NCSs that use both traditional and improved details.

The program will also include a number of small intensity tests for building dynamic characterization, followed by a few DBE level tests to demonstrate resilience of the structural system and possibly very limited NCS damage. The research team will collect data along the way to help develop damage and repair fragilities for NCSs installed in the building. Finally the test will be concluded with 1~3 MCE level tests to examine the building performance in rare earthquakes. It is expected that the test program will take advantage of the 3D excitation capacity of the UCSD shake table to be added in 2020.

4.0 VISION FOR NCSs

4.1 Facades

Architects and engineers envision mass timber buildings to be clad with lightweight façades with a high degree of transparency. The architectural vision is to display the rocking walls and much of the structural wood so that the building is perceived as a timber high rise from the street level. Examples of suitable facades are curtain wall and storefront, as well as light-gage steel or timber framed with metal panel skin, and a high percentage of window opening (e.g. window wall system).

Figure 5. 3D rendering of Framework Building that utilizes several different types of exterior skins. (Source: Lever Architecture, 2016).

The design of the Framework Building in Portland, Oregon exemplifies the architectural vision for tall mass timber buildings (Fig. 5). Framework was conceived as a mixed-use building that combines retail, office space and affordable housing, and utilized CLT rocking walls for lateral resistance. The primary skin is an aluminum composite metal (ACM) with fiberglass windows, but storefront was utilized in the lower lobby space, and curtain wall in the middle of the transverse edge up the elevation of the building displays the rocking wall to viewers from the street (Fig. 5). A shift in ACM panel geometry at mid-height differentiates lower office floors from upper residential floors. Unfortunately, the Framework Building project was cancelled due to permitting and funding issues.

4.1.1 Research Needs and Objectives

Buildings in earthquake zones generally absorb the earthquake accelerations by relative movement of the structural frame between the stories; exterior skin systems are also subjected to this interstory movement, and thus must "go along for the ride". Design codes require demonstration (e.g. racking tests of exterior skin mockups) that curtain walls and other glass-infill systems can sustain the design lateral interstory drift without glass fallout. However, such systems are routinely damaged (Evans et al. 1988; Filiatrault et al. 2001; Miranda et al. 2012; Baird et al 2012). For example, glass damage was extensive in the 1994 Northridge Earthquake, despite other NCS damage being limited (Reitherman and Sabol 1995). Notably, rubber gaskets in mechanically captured systems were dislodged and caused a consistent breach in water tightness in buildings (Harter 1994). Recently, following the 2011 Christchurch earthquake, 25% of curtain wall systems were non-operational (Baird et al. 2012). Reconnaissance data does not elucidate why glass damage is so common in spite of the robustness of modern designs. The majority of failures may be in vulnerable systems or affected by boundary details with adjacent systems, however, details of individual failures are not known or well understood.

Industry standard in-plane static and dynamic racking tests of full-size curtain wall and storefront mock-up specimens are used to validate seismic drift capacity. This static test (AAMA 501.4) is the industry standard for serviceability, and specifies a sequence of tests including air and water penetration before and after 3 cycles of static loading (racking) to a target drift level, e.g. 1% (AAMA 2018a). The displacement sustained without glass fallout, or $\Delta_{fallout}$, can be experimentally determined using the AAMA 501.6 dynamic racking protocol (AAMA 2018b). ASCE 7-16 (2016) specifies that for any glazed system, $\Delta_{fallout} \geq 1.25 D_{pl} I_e$, where D_{pl} = design relative story displacement and I_e = importance factor. Given the high rate of glass cracking and failure in the field, the AAMA testing protocol may not represent the seismic response of curtain walls and other glazed systems in field conditions. Seismic performance of curtain walls may be affected by: interaction between in-plane and out-of-plane movement, interaction between panels, flexure or vertical vibration at structural attachment points, high frequency vibrations or diverse frequency content of motion inherent in a multi-modal system, and boundary conditions between different façade types. Large-scale 3D shake table testing offers the opportunity to incorporate some of these more realistic field conditions, but shake table tests of curtain walls and glazed systems are extremely limited (Ma and Yan 1998, Wang et al. 2002, Lu et al. 2010). Thus, a performance comparison of similar specimens tested under the AAMA 501.6 loading protocol and shake table testing is needed. Equally important, ASCE 7-16 does not have a serviceability requirement, but California Building Code Section 2410 (CBSC 2016), used for critical emergency response buildings, requires that structurally glazed systems demonstrate serviceability at the design drift. Confirming that an AAMA 501.6 compliant design can maintain serviceability after a shake table test is important for continued functionality in the proposed new immediate occupancy performance objective (Sattar et al., 2018).

The research objectives related to façade testing in the present program are: (1) Evaluate the seismic performance of glazed facades in the context of the design methodology and performance targets to achieve seismic resilience; (2) evaluate the relative performance of glazed systems with different details, including any proposed detailing improvements, to identify systems best suited to meeting performance targets for seismic resilience; (3) validate AAMA 501.4 and 501.6 racking protocols for system qualification to represent the seismic performance of curtain walls and other glazed systems.

4.1.2 Preliminary Plans

The vision for this project is to clad portions of the building with a variety of different skin systems provided by different industry suppliers, i.e. the "patchwork quilt" approach. Suppliers may select a portion of the exterior to install their systems. Suppliers are encouraged to put forth innovative details that may improve the seismic performance. As a priority objective is to understand and evaluate the performance of individual systems/details, interactions between varying skin systems will be avoided. Thus, the building will not be fully clad and will not need boundary joints between different skin systems. Based on story height, footprint dimensions and rocking wall locations, the building will have about 10,000 sf of usable exterior skin area. Individual subassemblies on the order of 500–2000 sf are considered desirable. Figure 6 illustrates different possible configurations for individual skin subassemblies that vary from about 200-250 sf per story.

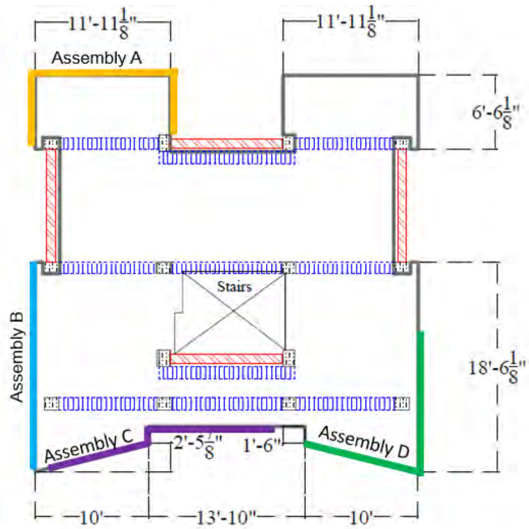

Figure 6. Potential subassembly configurations for testing different skin systems

Table 2 provides a list of general type of skin systems and detailing variations that are desired to be incorporated into the test program. The desired facades can be classified into one of two basic types of systems: glazed curtain wall, and light-frame systems with windows. With regard to curtain walls, stick-built and unitized are constructed distinctly and have the distinct mechanisms (rack versus sway) for accommodating the inter-story drift; thus comparing their performance is of great interest. Among light-frames systems, steel stud framing with metal panel finish are of great interest, with recognition of the myriad of options available on the market for metal panels. One of the unique aspects of this project is assessing the performance of the glass during 3D shaking, including the ability of the system to resist glass cracking or fallout under intermediate and large drift levels. As such, the proposed glass variations with regard to aspect ratio, glass treatment and glass type can be pursued across both curtain walls and light-framing with window openings. The research team is actively pursuing material donations and other in-kind contributions to support investigations of each of these types of promising systems.

The plan sketches (Figs. 1 and 6) show that the CLT floor beams are set back from the plan edge and that floor diaphragms are cantilevered over the edge of the floor beams for the skin subassembly regions denoted in Fig. 6. Thus, the CLT floor diaphragms will be utilized for anchoring the exterior skins. As mentioned in Section 2.2, 5-ply (6.875" thick) CLT is anticipated for this purpose. A top of slab lag bolt anchor is envisioned for hanging the curtain walls. Platform framed systems are easily supported between the floor diaphragms, while a balloon framed system could be supported by installation of perimeter joists.

Table 2. Skins systems and detailing variations desired for the test program

Basic Skin System	**Class of Variation**	**Variations Considered**
Storefront	Glazing method	Mechanically captured vs structurally glazed
Curtain wall w/ glazing	Glass aspect ratio	Varied from 1:2 to 2:1
Stick built curtain wall	Glass treatment	Heat strengthened vs. fully annealed
Unitized curtain wall	Glass type	Laminated and insulating glass units (IGU)
Light-framed with windows	Framing style	Balloon vs platform framed
Light gage steel stud framing	Finish material	Metal panel, wood shingle, and stucco
Wood stud framing	Window type	Fixed or operable, variable size
	Window framing	Metal or wood framed
	Glass variations	Same variables as for curtain walls may be applied

4.2 Stairs

In the event of power loss during an earthquake, stair systems serve as the sole means of human egress and ingress. Moreover, the continued function of the stairs during the shake table test program will be critical to support access to all floors of the building to inspect damage after each test. The proposed building layout (Fig. 2) includes one scissor staircase per floor, stacked up on all floors of the building. The architectural vision for the tall mass timber buildings would utilize lightweight prefabricated stairs built from steel, wood, or a hybrid combination of the two for an aesthetic match to the building architecture.

4.2.1 Research Needs and Objectives

Scissor stairs are susceptible to twisting as their structural form rises in elevation. Steel stairs tend to be lighter and more deformable than other commonly used reinforced concrete stairs. Although stairs are assigned an importance factor $I_p = 1.5$, catastrophic behavior has been documented in past earthquakes (e.g. Roha et al. 1982; Bull 2011; Kam and Pampanin 2011; Li and Mosalam 2013). For example, collapse of stair systems in New Zealand during the 2011 Christchurch earthquake precluded occupant safe egress from three high rise buildings in the business district. The most prominent mechanisms that have led to stair failure are described in Bull (2011). Appreciable interstory drift along the strong axis of the stair system may lead to: 1) compression or shortening of a straight stair system resulting in an opening 'knee failure' or 2) extension, which can lead to stairs sliding off their support if insufficient width is provided. Interstory drift transverse to the stair primary axis causes bending and shear in the plane of the stairs, which also has led to significant damage observations in the field. Finally, scissor stairs are especially susceptible to twisting and torsional displacements due to their mid-height landing and high asymmetry. The experience in Christchurch prompted immediate changes to New Zealand design provisions for stairs (SESOC 2011) that require fixing a stair's top connection, and allowing a sliding base connection or sliding at mid-height in the case of scissor stairs, where sliding displacements are to be designed for 1.5 times the ultimate limit displacements. These modern design and detailing guidelines have not been tested to validate their effectiveness.

Numerical studies have been focused on quantifying the influence of stair systems on the overall building response (e.g. Cosenza et al. 2008; Tegos et al. 2013), while coupled numerical analyses involved comparisons of response with and without stairs to elicit the impact of the presence of stairs. Such simulations have been limited to considering elastic response of the stairs, though inelastic response could occur under large earthquakes. A few experimental programs have been conducted on stair subsystems (Higgins 2009; Black et al. 2017). In the latter test program, stairs fixed at one end, and partial freedom at the opposing end were tested and demonstrated promise to minimize drift induced damage. While these tests do offer understanding of the stair subsystem performance, they do not elicit interaction with their supporting structure. However, a few full-scale building tests have incorporated stairs. In a previous large scale building test, prefabricated steel stairs were damaged at interstory drift levels well below the building design performance targets (~0.75%), including weld fracture at flight-support locations (Wang et al. 2015). The design details in these tests were intended to provide ductility, but rather demonstrated inadequate load path continuity precipitated by premature weld failure.

The research objectives related to stairs testing in the present program are: (1) Evaluate the seismic performance of stairs in the context of the design methodology and performance targets to achieve seismic resilience; and (2) further develop and validate approaches to protect stairs from drift-induced damage. Evolving solutions isolate the stairs from the drift demands through a free connection at one floor level.

4.2.2 Preliminary Plans

Donations from industry are sought to incorporate a variety of lightweight stairs built from different materials and with different support conditions. Desired stair support systems utilize wood carriages and stringers or steel stringers. The treads may be finish wood flooring over plywood, steel pan treads with concrete fill, flat plate treads with textured top surfaces, or bar grating treads; paired with wood or steel risers. Open riser configurations are also of interest.

Solutions that are under development for stairs aim to isolate the stairs from the drift demands through a free (slotted or sliding) connection at one floor level. To test these solutions, a fixed connection may be utilized for the stair to top landing connection, while a free or deformation compatible connection may be incorporated at the stair to bottom-landing connection. Thus, it is envisioned that new deformation compatible bottom landing connections (fixed-free) are compared with traditional fixed-fixed connections. These configurations should be dispersed throughout the building to capitalize on the variation of drift and acceleration demands. Table 3 presents a possible selection matrix to combine the different possible variations for the stairs. Fixed-free connections are utilized on the stories with the largest expected drift demands (predicted to be the lowest stories) to minimize damage and preserve building access throughout the test program.

Table 3. Selection matrix for stair detail variations

Story	Stair Support	Tread and Riser	Boundary Conditions
1	steel	steel treads with concrete-fill	fix-free
2	steel	wood	fix-free
3	wood	wood	fix-free
4	steel	steel treads with concrete-fill	fix-fix
5	steel	wood	fix-fix
6	wood	wood	fix-free
7	steel	steel bar grating treads	fix-fix
8	steel	steel flat plate treads	fix-free
9	steel	wood, open riser	fix-fix
10	steel	wood, open riser	fix-free

4.3 Other NCSs

Also of interest to the team are interior partition walls, suspended ceilings, and piping/mechanical equipment. The performance of these NCSs is impacted by their interactions. Unlike stairs and facades, extensive experimental and analytical research has already been conducted on many of these NCSs, such that their performance has been rigorously quantified, and the major vulnerabilities have been identified. Thus, this test is an opportunity to test detailing improvements that have potential to eliminate or reduce some sources of component damage in small to moderate level shaking.

4.3.1 Research Needs and Objectives

Interior partition walls are drift sensitive and incur significant damage at relatively low levels of drift (Retamales et al. 2013). One study (Almufti and Willford 2013) concluded that preventing damage in non-load bearing walls is the key to resilience for low-to-mid seismic hazard levels. Damage-reducing details have been developed, such as including the gaps at wall boundaries, sliding “slip-track” or friction connections, and enhanced strength connections for weaker structural systems (Araya-Letelier and

Miranda, 2012, Retamales et al. 2013, Tasligedik et al. 2013, Swenson et al. 2015). Even walls with the slip track detailing incur damage at intersecting walls, because the attached intersecting wall cannot slip in the out-of-plane direction, or at wall ends when sheathing over the slip-plane. Fire-rated detailing, which is an important design consideration in tall timber buildings, generally requires that exposed steel and timber be covered. This requirement, unfortunately, is at odds with many of the current ideas for resilient nonstructural walls that aim to somewhat isolate the partition wall from the interstory drift as well as accommodate some deformation in the wall through gapping.

Nonstructural walls with improved details were recently tested in bidirectional subassembly tests at Lehigh University. In the first test, a planar wall with double deflection or telescoping slip track (nested top tracks with a vertical gap usually used for accommodating vertical deflection) was compared to an identical wall with conventional slip track detailing (Fig. 7(a) and (b)). In the second test, the response of two C-shaped walls with different gap details were evaluated: a corner gap detail at the intersecting walls, and a distributed expansion gap detail (Figs. 7(c)). The gaps were intended to reduce damage at the wall intersections. While the results are still being analyzed, preliminary observations suggest the following. The telescoping detail improves performance over the traditional slip track, especially at wall ends where the studs and track can become disconnected under deflection. Both the distributed gap and corner gap details delayed the onset of damage to about 1% drift (with the exception of one distributed gap expansion joint that suffered some premature cosmetic damage). With the distributed gap detail, the small gaps directly adjacent to the intersection are the most effective at absorbing relative drift, thus, lengthening these gaps might further delay the onset of damage. One drawback of the gap strategy is the risk that the gaps open completely at large drifts, thus allowing for portions of the wall to separate. This could lead to isolated wall segments being at risk of collapse under large drifts, which could outweigh the gains of delayed damage onset.

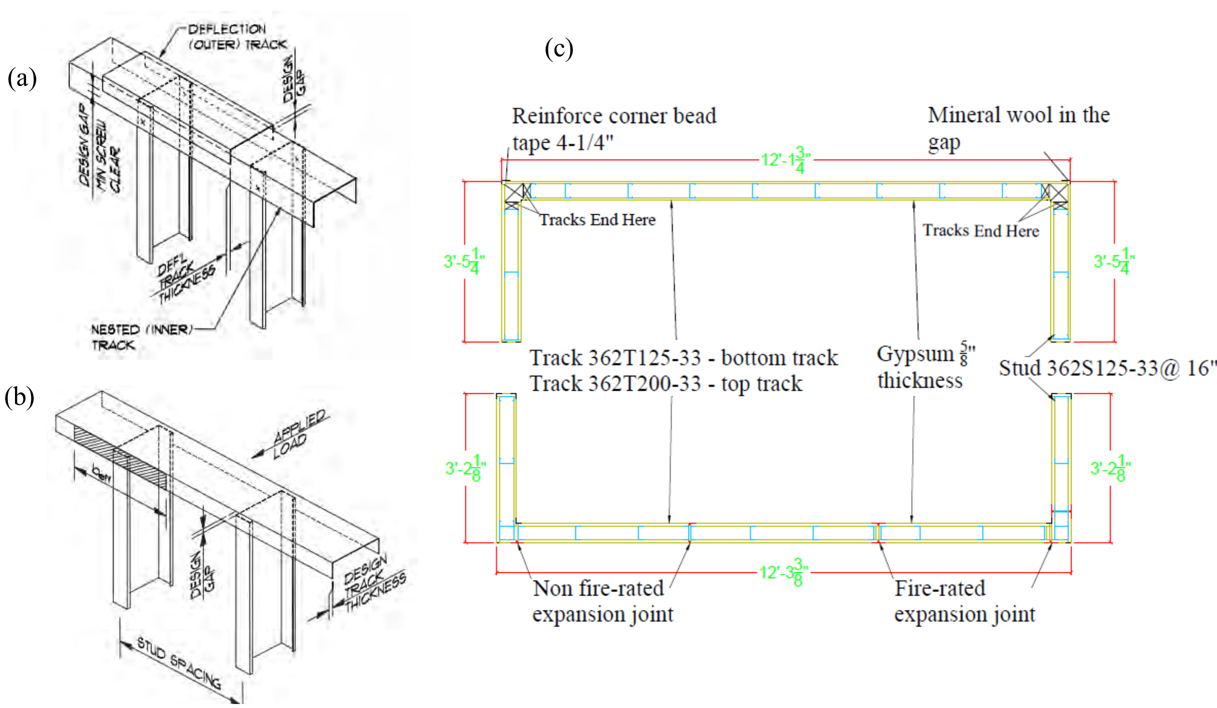

Figure 7. (a) Telescoping connection detail, (b) slip track connection detail, (c) C-shaped wall with corner gaps (top) and distributed gaps (bottom).

Fire protection of the CLT rocking walls is another issue of importance. Building code regulations will typically require that some CLT walls be sheathed with gypsum wall board (GWB) for fire protection, to limit the total amount of exposed wood. In this case, standard architectural detailing would involve sheathing directly over the wall and boundary columns with three or four layers of GWB. However, this detail would not accommodate wall uplift and rocking, and relative movement between the walls and boundary columns. It is expected that the GWB would tear apart and induce significant damage. The project team has discussed other fire protection detailing, such as introducing a gap with a fire retardant impregnated foam.

Suspended ceilings are frequently used in commercial buildings to provide soundproofing, fire protection, and cover mechanical equipment, wiring and plumbing in the plenum region. Suspended ceilings consist of a horizontal grid system of main tees and cross tees with lay-in tiles, and supported at select locations by vertical hanger wires. In the U.S., suspended ceilings covering more than 1000 sf area between boundary walls are required to have seismic bracing, which consists of compression posts and diagonal splay wires. As typical boundary conditions, the ceiling is fixed to the perimeter walls along two adjacent edges, and floating with a small gap on the opposite two edges.

Typical damage to suspended ceilings is discussed in Soroushian et al. (2016), as determined from 3 major experiments. During large intensity shaking, ceiling panels are routinely dislodged and some panels may fall to the floor. As shaking intensity increases, several grid connections may fail in a localized area causing portions of the ceiling to collapse. This behavior is often instigated by pounding of the ceiling system at the wall boundaries. Pop rivets and seismic clips installed at the boundaries suffer failures at relatively low levels of shaking. In addition, a shake table test at E-Defense led to the conclusion that suspended ceilings with seismic bracing are very susceptible to damage from the vertical component of shaking, because the rigid bracing drives the ceiling grid system to move with the floor above (Soroushian et al. 2015).

To improve the resilience of suspended ceilings, Pourali et al. (2017) have proposed the concept of a floating ceiling. Compared to the conventional fixed-floating boundary, the floating ceiling is installed with a sizable gap between the ceiling edge and perimeter walls on all sides, and no seismic bracing so that the ceiling is a fully suspended system that vibrates as a pendulum, with vibration frequency determined by the length of the hanger wires. A series of tests on floating ceilings were conducted at University of Canterbury (Pourali et al. 2017), and the specimens were subjected to both sinusoidal and earthquake loading. It was shown that maintaining a completely floating ceiling is unrealistic due to large displacements that led to perimeter gap closure, and subsequent significant acceleration amplifications of the ceiling. As a result, another configuration with an acoustic isolation foam placed between the ceiling and the boundary walls was tested. The foam was effective to mitigate the effect of pounding and reduce the seismic displacements, but acceleration amplification actually increased. The concept may have some potential for a resilient ceiling system if a balance can be achieved between utilizing the pendulum behavior while controlling the displacement demands.

The project team proposes another low damage solution for ceiling systems for consideration in the test program. Dislodged ceiling tiles are generally observed at relatively low shaking intensities, before any other damage. While dislodged tiles are easily restored, the temporary dislodgement disrupts the integrity of the suspended ceiling system, leaving the grid framing susceptible to other damage states. One idea is to explore the use of magnets to secure the ceiling tiles to the grid members as a defense against dislodging. Also, as mentioned above, the authors observed that under current detailing (Fig. 8(a)), rigid seismic bracing caused the ceiling system to move rigidly with the floor in the vertical direction, which led to dislodgement

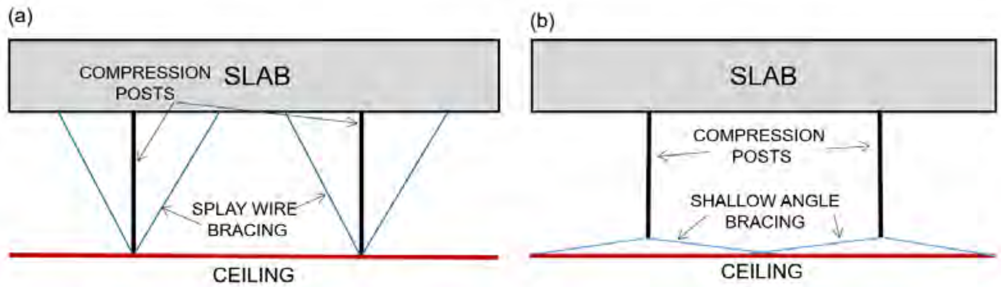

Figure 8. (a) Current and (b) proposed seismic bracing detail for suspended ceilings (Soroushian, 2019)

of numerous ceiling tiles. A new detail for seismic bracing is proposed that uses shallow angle splay wires to connect the compression posts to the ceiling grid (Fig. 8(b)) (Souroushian 2019). This detail is envisioned to maintain the function of the bracing in the horizontal direction while separating the suspended ceiling from the floor above in the vertical direction, and thus reducing the vertical demands to the system.

Several tests have been conducted on suspended ceilings integrated with sprinkler piping (Soroushian et al. 2015; Jenkins et al. 2017). However, a knowledge gap exists with regard to mechanical equipment in the plenum region. Dynamic response of above-anchored equipment such as air handlers should be quantified under realistic 3D shaking. Furthermore, displacement compatibility of main equipment units and connecting HVAC ducts should be evaluated. These lightweight ducts are often installed with very limited bracing. Finally, the compatibility of the seismic response of the mechanical equipment and suspended ceiling system should be experimentally evaluated for undesirable interactions, leading potentially to new solutions that consider the integrated design of the systems.

4.3.2 Preliminary Plans

Preliminary plans are to fabricate and test partition walls on a minimum of two floors and suspended ceilings on a minimum of two floors. This would permit some of the detailing variations discussed above to be explored while limiting the required resources for testing. Two options will be considered: 1) integrated partition walls and suspended ceilings on the same floors, or 2) partition walls and suspended ceilings installed on separate floors. The decision depends on the test objectives for each system. For instance, if the main focus of the suspended ceiling tests is to evaluate new detailing, omitting partition walls to allow for larger open plan area best supports this objective. However, partition walls should be installed around the plan boundary in the absence of exterior skins. Under option 1 (integrated partition walls and ceilings), it is proposed to install these NCSs on one lower level (subjected to higher drift demands) and one upper level (subjected to higher acceleration demands). Under option 2 (separate partition walls and ceilings), it is proposed to install the partition walls in adjacent lower floors (subjected to similar and larger drift demands) and the ceilings in adjacent upper level floors (subjected to similar and larger acceleration demands).

Piping and/or mechanical equipment may be added as resources permit. Again, these systems may be integrated with suspended ceilings or installed in isolation depending on the determined objectives. New details for suspended ceilings or equipment installation should first be tested in isolation. However, an integrated design and test to evaluate interaction between components is desirable if the response of the components in isolation is well-established.

5.0 SUMMARY

Preliminary plans for a seismic shake table test of a 10-story mass timber building have been described. The building is constructed with glulam beams and columns, CLT floor diaphragms, and post-tensioned CLT rocking walls. The overall test objective is to validate the design methodology for seismically resilient timber buildings. The response of NCSs are critical to resilience, and the timber specimen offers a testbed to evaluate existing and improved detailing strategies for many types of NCSs. This is an exciting opportunity to advance the state-of-the-art in NCS analysis and design. A vision for NCS testing has been presented; however, payload projects to advance alternative objectives will be entertained.

The testing will take place at the NHERI@UC San Diego outdoor shaking table after its upgrade to allow input of 6 degree-of-freedom input motions. Construction of the specimen will commence in spring of 2021, and testing is planned over the summer of 2021. The project team is actively seeking industry and academic collaborators for testing of various NCSs. Currently, the following types of contributions are needed: material donations; fabrication and disassembly; and in-kind engineering design, analysis and data synthesis.

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The Potential of Additive Manufactured Housing

Joe Colistra[1] and Paola Sanguinetti[2]

[1]Associate Professor, Department of Architecture, School of Architecture & Design/University of Kansas, 1465 Jayhawk Blvd., Lawrence, KS, 66045. 720-203-5678, jcolistra@ku.edu
[2] Professor, Department of Architecture, School of Architecture & Design/University of Kansas, 1465 Jayhawk Blvd., Lawrence, KS, 66045. paolas@ku.edu

ABSTRACT

This paper will present emerging trends in additive manufactured housing (3D printed concrete) techniques that allow housing units to be delivered sustainably and affordably. Through case studies, we explore the potential for 3D printing Net Zero Energy housing units.

Building envelope assemblies are compared to analyze the insulating capacity of concrete 3D printed walls and their predicted impact on energy consumption. The pros and cons of this emerging construction technique are discussed, including: speed of construction, energy efficiency, flexibility in housing module, constructability of complex geometries and associated layout limitations, code and inspection implications, incorporation with conventional building envelope components and systems, and marketability.

INTRODUCTION

This paper explores the possibility of using additive manufacturing (3D printing) to achieve affordable net zero energy housing units. Additive manufacturing, the process of building something one layer at a time has the potential to transform the design and construction industry. It offers speed, accuracy, complex geometries, and replicable automation. (Linke, 2017) The design configurations presented here test the notion that a hybrid construction process might be utilized that optimizes both site-built construction as well as off-site prefabrication techniques. In this way, the construction process can more closely resemble the optimization utilized in advanced manufacturing. That is, components and systems can be selected based on performance criteria rather than perceived ease of subcontractor coordination.

SELECTING SYSTEMS AND ASSEMBLIES

We challenge the traditional construction industry practice of selecting materials and assemblies most efficient for the construction of a single stand-alone building. Rather, greater flexibility can be achieved in selecting more innovative and higher-performance systems if buildings are able to utilize a combination of prefabrication, automation, and assembly-line processes. This assumes that the means of projection is able to reach a critical mass that allows the housing industry to reach an economy of scale enabling innovation in the manufacturing process of high-performance energy efficient homes. The goal is to achieve superior energy efficiency without significant first-cost increases by optimizing the manufacturing process.

For example, in examining a 3-4 story mixed-use building, one of the most cost-effective systems for ground floor exterior walls could be 3D printed concrete. Additive manufacturing allows for an automated construction process that is superior in durability, resists moisture and bugs, and can be left unfinished without the need for cladding systems.

While these walls achieve the much-desired durability at the ground floor to resist the wear of foot-traffic, snow drifting, moisture penetration, etc. they introduce several logistical issues when trying to achieve walls higher than 10' – 12' high. They also offer challenges for portions of wall located above doors and windows. The incorporation of a steel or reinforced concrete lintel adds a complexity not typically required in wood-framed construction. For walls above the first level, the most cost-effective wall assembly for our target climate region would be a prefabricated composite sandwich panel comprised of expanded polystyrene insulation with an exterior sheathing adhered directly to the insulation. The sheathing has a factory-applied fluid vapor barrier. These panels also have 2x wood framing adhered to the insulation. This allows mechanical and electrical subcontractors to install conduit without having to rout out channels in the insulation. The panels also arrive on site with high-performance windows and doors installed and flashed in factory conditions to minimize air infiltration. The primary manufacturer of such an assembly that we have explored is produced by BuildSmart. (BuildSmart, 2019)

Traditional construction means would dictate that the interior walls also be 2x wood framing in order to utilize the same framing contractor and to be able to achieve economies of scale. However, the most efficient interior wall framing system, again utilizing the philosophy of optimized manufacturing, would lead us to light-gage steel framing. These systems, right-sized for loading and shear conditions are fabricated and sent to the site with RFID tags allowing them to be sorted and set into place. The system illustrated here is produced by Prescient. (Prescient, 2019)

In the example described here, it would also make sense that the framing subcontractor would also set joists and sheathing for the floor/ceiling assembly. This systematized construction method that we would like to introduce could utilize a more innovative and sustainable system such as cross laminated timber (CLT) or steel where jurisdictions and site specificity require noncombustible assemblies. For these instances we are developing a rapidly constructible and reconfigurable modular steel floor system utilizing two-way members stabilized with a thin sheet metal diaphragm. (Boadi-Danquah, Robertson, Fadden, Sutley, & Colistra, 2017) These modules can be shipped on trucks, craned into place and lend themselves to various efficient air-delivery systems by providing a plenum space. They are inherently sustainable in that they can be disassembled and reconfigured when a building has reached the end of its useful life.

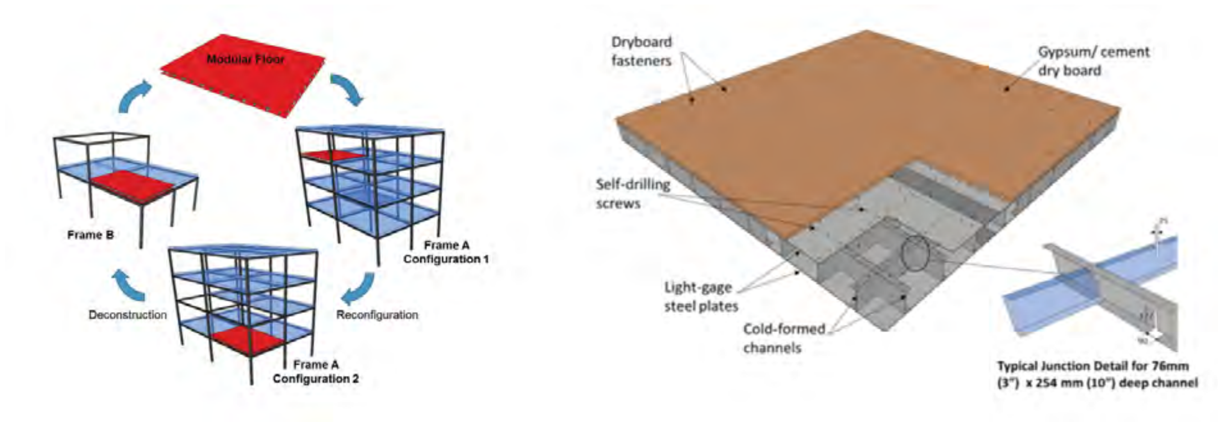

Figure 1. Rapidly Constructible and Reconfigurable Modular Steel Floor/Ceiling Assembly. (Boadi-Danquah, Robertson, Fadden, Sutley, & Colistra, 2017)

ANALYSIS OF THERMAL RESISTANCE QUALITIES OF 3D PRINTED WALLS

Summarized here is an analysis of the 3D printed wall insulative qualities. Colleagues at the University of Kansas were engaged by a Kansas City developer, 3 Strands Neighborhoods (O'Dell, 2019) to investigate the viability of incorporating 3D printed walls into an affordable housing development. Aspiring to create net zero energy affordable homes, the group charged us with establishing the barriers to achieving the necessary R-factor in a 3D printed concrete wall. It is documented that 3D printed concrete homes are built as a cost-effective solution. (Bos, Wolfs, Ahmed, & Salet, 2016)

In this case, net zero energy homes are defined as a home that produces as much energy as it consumes using renewable energy sources. Such research has been promoted by the US Department of Energy in the development of homes that combine both architectural as well as engineering research. (Solar Decathlon, 2019) Affordability is defined by the US Department of Housing and Urban Development as paying less than 30% of your household income on shelter. (HUD, 2019)

Speed of construction is typically one of the primary factors in citing affordability and some companies tout the ability to print and cure a 3D printed home in as little as 24 hours. (Nadarajah, 2018) The speed of large-format 3D printers and advances in curing time have accelerated delivery time of such walls to the point where they are not a viable building component. However, there has not been much analysis conducted on the performative aspects of such walls nor much exploration of assembly configurations to achieve the desired R-factors and resistance to moisture. (Hager, Golonka & Putanowicz, 2016)

Three variations of 3D printed concrete wall assemblies were compared to a typical 2x6 wood-framed exterior wall. The three concrete walls were configured in an assembly illustrated in Figure 1. The three walls were examined using THERM software (Huizenga et al., 2017) to determine R-value.

To summarize, the results were not unexpected. The uninsulated 9” thick 3D printed concrete wall (See Figure 2.) with no added insulation in its cavity was found to have an R-value of 7.6. (Sanguinetti, Almazam, Humaidan, & Colistra, 2019). This indicates significant insulation (batt, foam, or other) would need to be added to the wall assembly in order to meet energy efficiency goals.

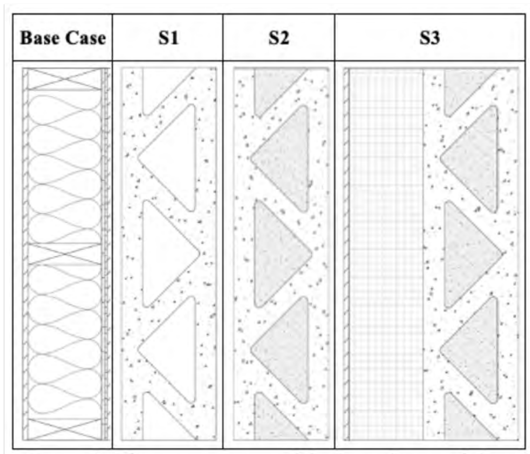

Figure 2. Plan view of 3D printed wall assemblies. (Sanguinetti, Almazam, Humaidan, & Colistra, 2019)

3D PRINTED HOME DESIGN EXERCISE

3 Strands Neighborhoods next asked us to participate as advisors in a design competition that would illustrate the design potential of utilizing 3D printed walls for net zero energy affordable housing solutions. The company engaged an architectural firm, Overland Partners to provide various single-family or duplex designs that demonstrate the design opportunities of such a construction process.

Working with Icon Build, a 3D printed concrete home company, the advisory group selected a series of designs that balanced marketability, sustainable features, and a geometry that would highlight the additive manufacturing capability of their Vulcan II printer that rides on rails and can quickly and accurately lay concrete layers. (Icon, 2019)

The AZA team’s solution incorporates 3D printed concrete on the ground floor with prefabricated wood panels at the second story. Deep overhangs shade outdoor spaces and an asymmetrical roof-line optimizes solar panel areas.

Figure 3. Proposed 3D Printed home. (Team: AZA, Courtesy Overland Partners/3 Strands Neighborhoods, 2019)

Similarly, the design solution submitted by the Fluid & Formless team also utilizes 3D printed concrete walls at the ground floor. The ability for the printer to achieve curved forms are accentuated and a prefabricated CLT housing “box” is place on top of the concrete structure.

Figure 4. Proposed 3D Printed home. (Team: Fluid & Formless, Courtesy Overland Partners/3 Strands Neighborhoods, 2019)

The final competition entry shown here by the team ITB is designed with numerous curved walls showing the ability for the printer to execute complex geometries. The second level is described as being constructed out of traditional 2x framing. The heavy structure of the ground floor allows for future additions to be added easily at the second floor.

The concept of the ITB scheme is that the house is able to grow with the family needs with minimal structural work to the foundations or first floor walls in the future.

Figure 4. Proposed 3D Printed home. (Team: ITB, Courtesy Overland Partners/3 Strands Neighborhoods, 2019)

CONCLUSION

3D printed concrete offers great potential to the design and construction industry. The relative speed with which a durable ground floor can be printed could be transformative to housing. Also, the ability to print complex geometries with little to no upcharge from orthogonal walls opens enormous opportunities to architects.

Understanding the limitations of 3D printing also leads to several necessary explorations. First, the printed concrete printed wall, even with current advances in admixtures, does not provide the thermal resistive qualities to be able to stand on its own as an acceptable exterior assembly. Only through the addition of insulation will 3D printed concrete walls provide a viable exterior wall configuration.

Due to weight and the limitations of unreinforced concrete printing, the greatest potential for 3D printed walls may be to serve as a stout and durable ground floor exterior wall. This requires a hybrid construction in which the upper walls are able to be built out of prefabricated systems such as unitized metal stud wall systems and prefab wood panels.

Results of the design competition shown here illustrate such a hybrid system in which the 3D printed concrete walls are left exposed at the ground floor with insulation installed later into the printed cavity and/or installed into furring on the interior. The upper levels have been constructed of various framed wood scenarios.

Despite the trade-offs of constructing a viable exterior assembly with 3D printed concrete walls and the complicated assembly connections required, the designs appear to be able to achieve an articulation that is decidedly residential in scale and articulation. These homes that aspire to be both affordable and net zero energy would contextually fit into most single family home neighborhoods and be an asset to their communities.

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The Challenges of Creating Resilient Housing at Affordable Cost – A 'Lessons Learned' Report on The Field of Dreams EcoCommunity

Jörg Rügemer

Associate Professor, School of Architecture, College of Architecture and Planning, University of Utah, 375 S 1530 E, Salt Lake City, Utah 84112. +1 801 585 8951, ruegemer@arch.utah.edu

ABSTRACT

The Field of Dreams EcoCommunity [FoD] was conceived as a collaborative effort to re-imagine the affordable housing typology in the Southwestern States of the US. FoD consists of twenty, 1,500 SF units in ten duplex buildings, the first two units of which were recently constructed on an abandoned baseball field in close proximity to Salt Lake City, Utah. As part of the development process, underlying principles of how we live and the types of spaces we need to accommodate these desires were re-examined, challenging the contemporary notion that quantity of space supersedes quality of space and design clarity, with the goal of providing a high quality of living within an optimized, moderate footprint that is sensitive to both the inhabitants and the local environment. To achieve these goals, FoD was planned to be the synthesis of modern technology and vernacular principles – unlike traditional modern buildings, FoD *utilizes what is immediately available onsite* as the primary energy source in the form of passive winter solar heat gain; it supplements only what cannot be generated onsite to meet modern standards of comfort through technological means. To become net-zero, the remaining energy requirements can be offset through an optional photovoltaic (PV) solar system. Traditional ideas of *orientation, passive energy design, thermal massing* and *aspects of daylighting* are key elements in the outward expression of the building's massing. *This strategy creates an energy-efficient building with* ***a high resilience factor****, thus making survival in extreme conditions possible without external energy sources.* This is also reflected through the idea of supporting a family with it's own food supply by offering produce production onsite.

This paper describes the development and design process of the Field of Dreams EcoCommunity, to continue with a 'lessons learned' section that focuses on the construction-specific challenges encountered when the contractor, who is also the client and owner of FoD, constructed the first two units, units 9 and 10, in a duplex building between the summer of 2017 and the spring of 2019.

Keywords: Affordable and High Performance Housing, Resilient Building, Structural Insulated Panels, Lessons Learned

1. INTRODUCTION

The collaborative design and research project Field of Dreams EcoCommunity (FoD) in Kearns, Utah has been described in greater detail in previous publications [Rügemer, 2017, 2018]. The project came to life when the author approached Salt Lake Valley Habitat for Humanity (SLVHFH) with the proposal to develop and design better performing buildings for Habitat's clientele, who come from a low-income demographic background. According to SLVHFH, 60% of its clientele are single women with an average of two children, with the mothers working full-time to ensure the family's survival. Most money saved by such families is redirected into educational support for their children, to provide them with better future opportunities in their lives. To be eligible for the SLVHFH housing program, each low-income applicant must complete a minimum of 225 sweat equity hours with the non-profit organization, working alongside other volunteers from the community that support SLVHFH's mission. Each applicant must also participate in homeowner education classes and workshops to prepare for homeownership, before a Habitat house is then purchased through an interest-free, 30-year Habitat for Humanity loan [Salt Lake Valley Habitat for Humanity 2019]. As reported by SLVHFH, this enables families to disengage from rental dependencies to advance into a mortgage ownership situation, where mortgage rates are usually lower than the previously paid monthly rental fees. The families can then take pride in, ownership of and responsibility for their very own building and small community, which undoubtedly stabilizes the lives of the entire family, and especially those of the children.

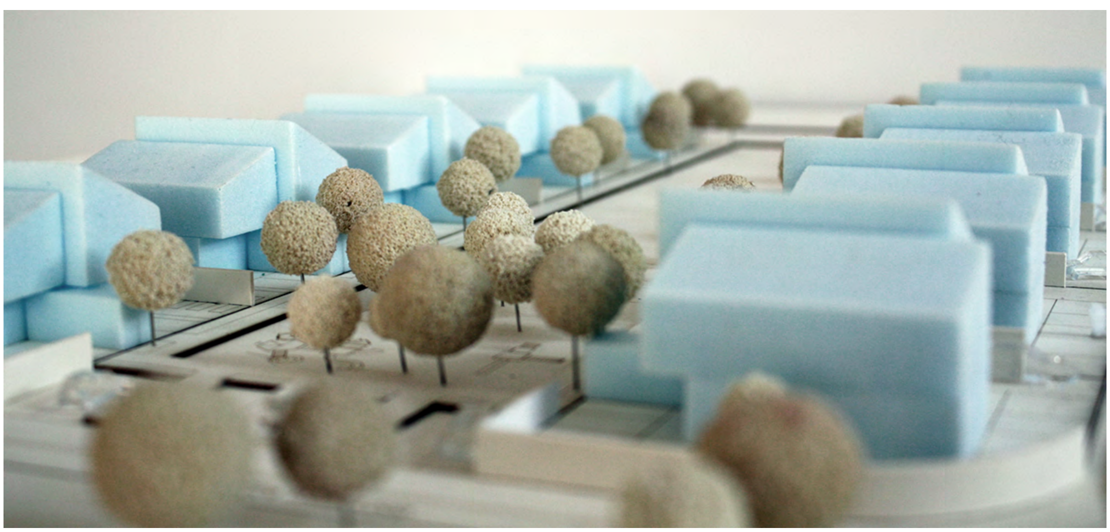

Figure 1: Field of Dreams EcoCommunity model showing the Common Center Green.

To date, the typical SLVHFH house supported these families with minimum-quality, code-standard buildings that provided satisfactory shelter for their inhabitants. Their layouts followed outdated, single-story design guidelines, with an emphasis on fast and inexpensive construction, and therefore a lack of *efficiency, resilience and sustainability*. In 2014, SLVHFH purchased the former *Kearns American League Western Boys Baseball training field* in the township of Kearns within the Salt Lake

Valley, which had been falling into disrepair over many years. The applicable R-1-6000 zoning allowed for the subdivision of the land into ten, 6,000 square feet (sq.ft.) parcels, which legally allowed for a maximum density of ten single-family detached residences on said premises.

2. DESIGN AND DEVELOPMENT PROCESS

2.1 Design Philosophy

Albert Einstein once said: *"Everything should be made as simple as possible, but not simpler."* In today's world, we have lost this kind of approach in many regards, including the ability to concentrate on the essence of things. This applies to architecture, too, and, with few exceptions, is well documented in the built environment with which we surround ourselves in many places. Especially in the field of residential design and construction in the US, architectural design is repeatedly confused with the functional organization of large quantities of spaces, which, at their best, conform to code, but lack spatial, architectural and daylight quality. Often, the results are pricey, poorly performing buildings with a low spatial and indoor air and thermal quality, as well as a limited expected lifetime. To find a way back to the essence of good architectural design, the author based the FoD design philosophy on the following four pillars:

1. *Simplicity* is the key to successful design, sustainability and high performance in architecture and urban design;
2. A *holistic*, interdisciplinary approach leads to superior architectural design;
3. The *quality* of the detail and its execution determines the level of quality of the overall work; and
4. Successful architecture and urban design include aspects of both *regional and global* contexts.

2.2 Project Goals

To make the Field of Dreams EcoCommunity a successful case study development, the project team, consisting of the author as the project architect and leader and SLVHFH as both client and contractor, defined the project's goals as listed below:

- Development of a resilient, sustainable and affordable micro-neighborhood.
- Exploration of higher than recent-zoning density in an existing part of the township of Kearns.
- Each unit to be designed to a three bedroom, 1½ bathroom, 1,500 sq.ft. house.
- Maximum hard cost not to exceed $150,000, including cost of land for the future homeowner.
- Daily energy consumption to heat and cool the house and to provide domestic hot water (DHW) shall be less than or equal to $1.50 (this does not include metering and general utility fees).

- Design and construction of the buildings to the U.S. Office of Energy Efficiency & Renewable Energy Solar Ready standard and the National Renewable Energy Laboratory NREL's Solar Ready Buildings Planning Guide, which requires a building to be designed and built with integrated electrical and mechanical features that will streamline a future integration of photovoltaic panels [NEL 2009].
- Use of robust and durable construction and construction materials, to protect low-income homeowners from increased maintenance cost during the lifetime of the building.
- The process of building the homes would be suitable for integrating volunteers from the community and students at the University of Utah in their Design+Build Salt Lake program.
- Innovative design to be reproducible to serve other Habitat chapters and low-income families, and to help the local residential construction market move towards better-performing, more affordable homes.

Consequently, the author decided to design the buildings as close to the Passive House standard as budget would allow, with each unit originally designed to consume about *80% less energy* then a typical code-standard building in the same location. These benchmarks were to be achieved through a highly insulated and airtight enclosure made of panelized Structurally Insulated Panels (SIPs). As it is part of the author's university research, the project's performance was planned to be Post-Occupancy monitored over 24 months.

2.3 Densification as Strategy

FoD was planned on the former Kearns American League Western Boys Baseball field, which is located in the township of Kearns, about 11 miles south of downtown Salt Lake City. It was a Kearns community epicenter before falling into disrepair until 2014, when it was purchased by SLVHFH for $190,000. Typical, suburban, 1.5-story tall, single-family residential buildings surround the parcel. The neighborhood consists of a mixed White (60.2%) and Hispanic or Latino (31.7%) population, with an average age of 29.5 years [United States Census Bureau 2019] – it therefore represents an ideal community for simple, affordable starter homes and typically attracts first-time home buyers, even though the target group for the typical Habitat house differs from that described above. The parcel is about 87,000 sq.ft. or roughly 2 acres in size. Originally zoned to R-1-6000, it allowed for a maximum density of 10 single-family detached residences, which would have provided an acceptable setting for the typical single-story SLVHFH homes. However, to get closer to the cost goal of a maximum hard cost of $150,000 per home for each unit alone, the 'business-as-usual' strategy would have subtracted $81,200 from an already tight budget for land and land development costs, leaving a cost of $68,800 for the actual building itself.

Figure 2: Unit 9 & 10 close to completion in late fall 2018, with the overall development with doubled density superimposed onto the site.

Proposing a 100% higher density in two-story buildings organized in duplexes, property-related cost could be cut by 50%, leaving roughly a $110,000 hard cost for each unit, an amount that was much more realistic to reach the project goals. In working closely with Salt Lake County Development Services (SLCDS), which is the legal jurisdiction that manages zoning changes and is responsible for zoning and building permits in Kearns, the author was able to rezone the land to an R-1-3000, which allowed for 20 units on 3,000 sq.ft. individual parcels. With Utah anticipating one of the fastest population growths among all states within the US, the Salt Lake metropolitan area along the Wasatch Front is under enormous pressure to provide more affordable housing over the coming decades. By providing homes for twice as many families, the FoD strategy makes a small contribution to reducing stress on the market and, more importantly, now provides a research-based case study project that documents the rather difficult and time consuming process of rezoning and urban densification for affordable housing.

2.4 Ownership model

With SLCDS requiring building permit project documentation at the construction document level, the design and rezoning process took more than 2.5 years. However, the architect-client team was able to utilize project hurdles in said process to the project's advantage, developing an ownership model in which each of the 20 units is individually owned to the exterior walls. The space in direct adjacency around the buildings, which includes the front and back yards and the driveway, are defined as a *Limited Common Area*. These areas are still under direct ownership responsibility of each individual owner, but also under the influence of the Home Owner Association's (HOA) rules, the so-called Covenants, Conditions and Restrictions (CC&Rs), to be established by SLVHFH as the project developer towards the finalization of the first units. Similar rules apply to the access loop road on the outer edges of the development, which is also part of each individual 3,000 sq.ft. parcel, but is established as a legal, binding easement to ensure continuous access to all buildings in the future, also under the legal rules of the CC&Rs.

This rather complex ownership model strategy is justified through a large, FoD community-owned Community Central Green space located between the north and the south row of duplex buildings (Figures 1 and 2). Once finalized, the space provides a 12,000 sq.ft. open playing field for sports, recreating and community activities, two bocce courts, a picnic area with pavilion and two playgrounds for toddlers and children. The central green area will be open to people beyond the FoD community, thus also providing a neighborhood recreational space for people in the immediate surroundings of the site.

3. CONSTRUCTION PROCESS

3.1 Overview

As part of the passive design approach towards higher energy-performance in each FoD unit, common construction methods on the Utah residential market were analyzed for their feasibility to achieve Passive House standard. Wooden platform framing, as Utah's predominant construction method, offers a variety of advantages, including cost-effectiveness, speed of construction and knowledge among trades. However, energy-performance and air-tightness – two of the most important criteria to construct a high-performance building – are not amongst the advantages of standard wood-framed buildings. Even though insulation value inefficiencies can be overcome by doubling up wooden stud walls, offsetting studs to minimize thermal bridging and using blown-in blanket (BIB) fiberglass or cellulose insulation to minimize the problem of air pockets in the assembly, FoD would have not allowed for the additional square footage required by these thicker walls. Due to the number of seams, gaps, nail holes and other construction inefficiencies of wood-framed walls, it is also more challenging to achieve superior air infiltration rates towards a Passive House performance of equal or better than 0.6 ACH @ 50 pascals – this especially challenging with a builder who is not familiar with such a construction approach. Finally, with the project partly constructed by volunteers, the double stud assembly would have been too complicated for unskilled workers.

As a result, the author decided to propose 8 3/8"-thick graphite-infused Structural Insulated Panels (SIPs) as the predominant envelope material, offering an insulation value of R-40.3 Btu/(hr ºF sq.ft.) at 4" lessened thickness compared to a regular 12" SIPs panel, or 6" lessened thickness compared to a double-stud wall, which at the same time facilitates better airtightness and a dew-point-free wall assembly if installed to the manufacturers' recommendations.

During the very meticulous design development process, the client and contractor were present at all meetings and well integrated in all decisions, resulting in a very comprehensive Construction Document (CD) set. The CD set addressed all items necessary for this rather complex case study endeavor; furthermore, it integrated the challenges anticipated, such as buildability by volunteers, material cost, durability and project operations and maintenance. After it was agreed on by all parties, FoD was successfully granted a rezoning, subdivision and building permit in the summer of 2017.

3.2 Challenges Anticipated

The first two units were constructed between the summer of 2017 and the spring of 2019, with an overall duration of roughly 18 months. Even though the team had a very successful and smooth design and development phase, the process changed considerably when it came to the actual construction of the project. This came as a surprise since one would expect that the general project setup – the client being the contractor, with all stakeholders and the actual site supervisor present at all design and development meetings – would constitute a perfect basis for a successful project execution. Even though many construction steps were executed '*close enough*' to expectations, there was a considerable number of imperative steps where the client/contractor disregarded what had been agreed on and put 'into writing' (meaning the commonly agreed Construction Documents), ignoring their very own decisions that had been made during the previous design process.

As a *lessons learned report*, the following discussion focuses on the envelope-related challenges that occurred during the construction phase of units 9 and 10, and especially on those decisions that compromised aspects of quality, long-term durability, performance and indoor air quality. In a future paper, the author will discuss additional issues with the building's heating, ventilation and air conditioning (HVAC) and Energy Recovery Ventilation (ERV) systems, as well as the Post-Occupancy monitoring setup. This future paper will also report on experiences of the occupants when spending their first year in the units.

3.3 General and Administrative Challenges

After an overall planning process of more than 2.5 years, the team members were enthusiastic when actual the groundbreaking approached in July 2017. In contrast to the very open, transparent and interdisciplinary design and development phase of FoD, it quickly became evident that there was a severe lack of communication between SLVHFH's leadership and the contractor, who is an employee of SLVHFH. Often diverging from what was agreed on and documented in the drawings, the contractor took his own decisions onsite, falling back on familiar construction habits, resulting in many mistakes, low construction quality and unacceptable results. Furthermore, the site organization was lacking management competencies, which, among many other issues, resulted in considerable amounts of wasted time due to a constant lack of materials, repeated and daily material runs and therefore a very slow construction progress. The site supervisor's denial of a recommended, free product training offered by the SIPs manufacturer created additional execution and quality issues throughout the process, with the panels being exposed to weather for more than a year, resulting in severely weakened structural components (Figure 3), with those panels still being used for the next two units and another SLVHFH project in Salt Lake City itself.

Besides the weekly site visits, the author, for legal and professional insurance reasons, had to spend considerable time to constantly document these shortcomings, admittedly without any tangible impact on the non-profit organization's behavior. Finally, the contractor's failure to order building inspections at required intervals added another level of complexity to the already challenging process, as depicted further below.

Figure 3: Deteriorated SIPs due to prolonged weather exposure.

3.4 Concrete Form Work Tolerances and SIPs

SIPs are factory-made building components that are manufactured to a high level of precision, usually within an 1/8 to a 1/4 of an inch. As structural envelope components, they rely on sitting on a concrete foundation with both interior and exterior (structural) Oriented Strand Board (OSB) surfaces resting on the concrete, which is especially important since Salt Lake City is located in a seismic zone D. In a high performance building, the concrete slab on the ground, stem walls and foundation have to be detailed in a way that any thermal bridging between the radiantly heated slab and the exterior is eliminated. For FoD, this problem had been solved by placing the 8 3/8" wide SIPs on 9" wide stem walls that would elevate 6" above the finished ground, with the slab-on-ground poured after the first floor SIPs wall had been erected, to allow for insulation around the entire slab. A similar detail had been developed for the firewall section between the units (Figure 4).

Due to inaccurately installed formwork without subsequent dimension control, the measurements and actual location of the poured foundation and stem walls was off by 3" to 6" along the perimeter of the building, resulting in compromising the structural strength of the envelope because the SIPs would not rest on the concrete on both sides any more (Figure 5). Simply double-checking and correcting the formwork before installing the concrete would have avoided this initial and severe issue – a measure that is common practice on construction sites and would have taken less than a day for the relatively small building footprint.

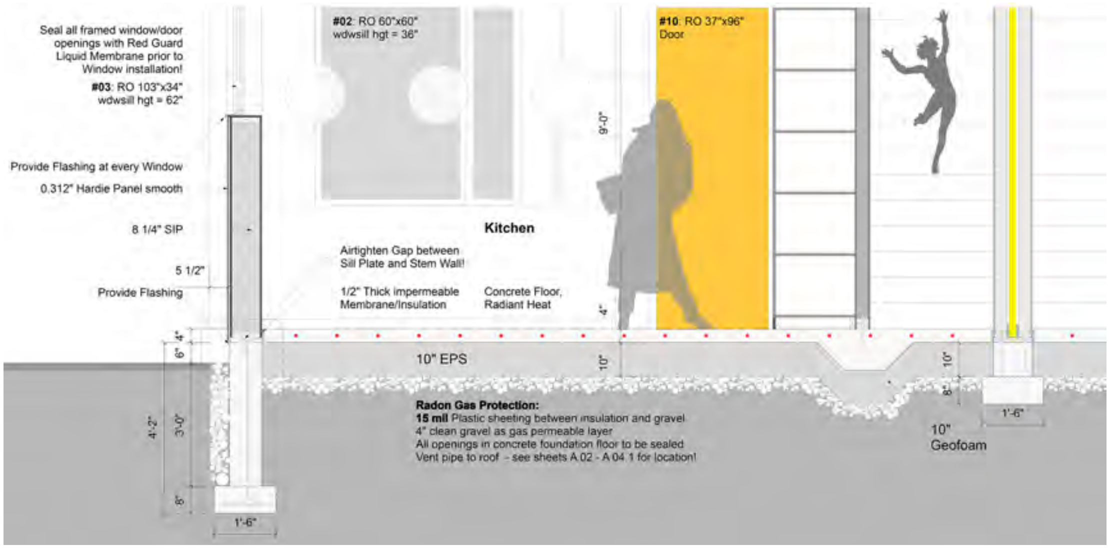

Figure 4: Thermal-bridge free floor slab to stem-wall detailing.

A missed commission of a required framing inspection before installing the main floor SIPs onto the sill plates resulted in the inspector being unable to examine the required anchoring bolts at a later time – in contrast to a standard framing process, in which those connectors are visible until insulation has been installed into the wall cavities, the SIPs cover up those connectors when installed. Consequently, the building official required the installation of heavy metal brackets to secure the frame to the foundation, which then resulted in a detail that catches rain water inside the façade due to improper flashing (Figure 6).


Figure 5: SIPs sit considerably off of stem walls due to inaccurate concrete formwork and concrete pour.

Figure 6: Building officials requested additional brackets as a result of ignoring required building inspections, leading to a flashing detail that directs water behind the façade. Note the considerable concrete ledge at the bottom of the SIPs, where the concrete was supposed to be flush with the exterior OSB above, which would have also allowed using simple seismic strips instead of the heavy brackets.

3.5 Compromised Insulation and Air Tightness

An airtight and continuously insulated building envelope is one of the most important, yet easy-to-achieve and relatively inexpensive, measure for a building designed and constructed in line with the Passive House strategy, with the insulation and air-sealing work becoming critical for the building's successful performance. During the construction of units 9 and 10, this had been repeatedly challenged, resulting in a low final blower door test performance of 3.1 ACH @ 50 pascals instead of the target number of 0.8 ACH @ 50 pascals (Figure 7). Considering the amount of work that went into the improvement of the envelope by volunteers and School of Architecture students, and three subsequent blower door tests with groups of 8 students onsite to find and seal additional air and insulation leaks, this effort can be regarded as useless in retrospect: the achieved final air infiltration barely meets 2012 IECC standards of equal or better than 3 ACH @ 50 pascals for climate zone 3-8, with Kearns being in climate zone 5 [U.S. Department of Energy 2019].

The identified problem sources of the unexpectedly high air infiltration include both insulation as well as air-sealing measures. Starting with the floor slab, the contractor decided on processing leftover foam for the under slab insulation that left large gaps between the pieces, allowing concrete to flow all the way down to the gravel, thus creating significant thermal bridging (Figure 8). A sufficient measure would have been to foam the gaps before pouring, including the perimeter around the concrete slab, which was ignored, leading to linear air gaps between slab and fire walls.

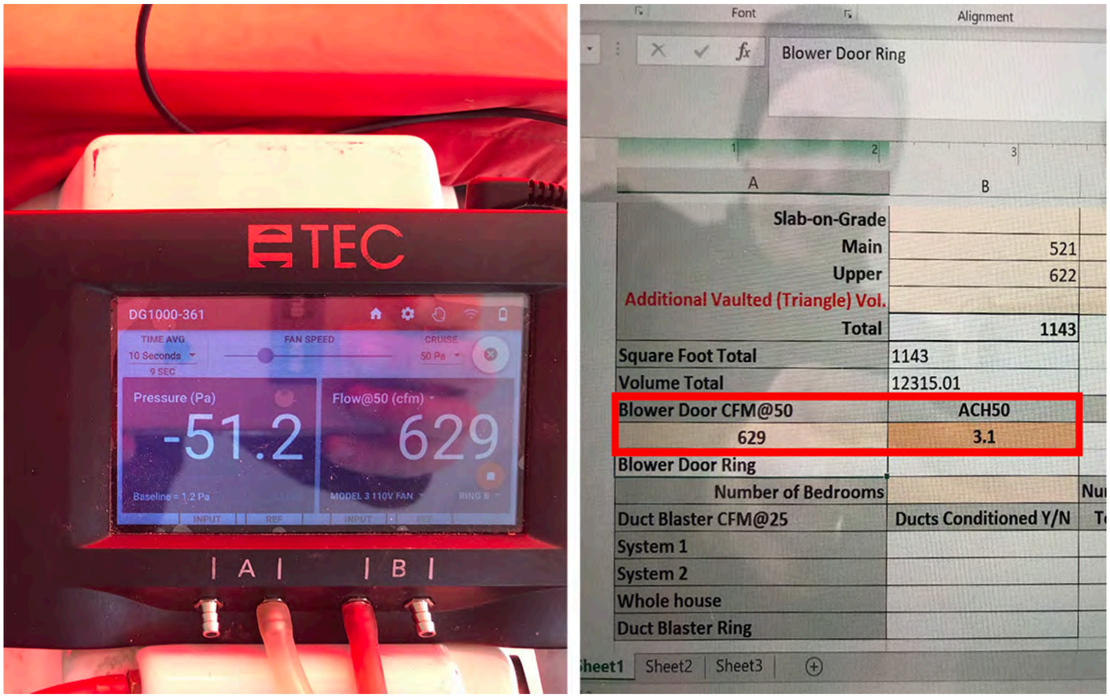

Figure 7: Final Blower-Door test results of 3.1 ACH @ 50 pascals, missing the required target value of 0.8 by large.

Another challenge resulted from the contractor's early refusal to hang the floor joists from the inside OSB board of the SIPs, which constitutes a structurally sound and generally applied method. Instead, the joists were rested on top of the entire SIPs width, creating a 12" break in the exterior insulation layer along the vertical wall, making air sealing very difficult in the area of the rim boards. By choosing this more traditional path, a layer of closed-cell Icynene had been specified to successfully air tighten and insulate these areas, which also addressed the expected insulation and air-sealing challenges around the fire wall between the two units. Instead, the pockets between the joists were filled with hand-cut layers of rigid foam insulation, with the various gaps spray-foamed with canned expanding foam, a method that is not only much more expensive due to intense labor, but also unsuccessful in closing all leaks, which became apparent when conducting the following blower door tests. A similar approach was used for the firewalls, leading to unsolvable air leakage issues in the rest of the process.

Another common air-sealing method for Passive Houses is to use Passive House-approved sealing tape that is applied to the outside of the building. In doing so, part of the issues described above at the rim board and in other areas could have been minimized. Instead, a cheap tape that was available onsite was applied, and, when it was not adhering well to the outside of the building due to sun exposure, the decision was made to tape the inside only, where many critical areas where not captured (Figure 8). Due to the tape's quality, it came off after several weeks, and was simply drywalled over.

Another issue that became insoluble was the installation of different, less expensive windows to the product and brand originally specified, with the author not being informed about this move. The original windows, on which the project's Passive House Planning Package PHPP and Sefaira energy modeling relied, had a specified average U-value of 0.24, with different Solar Heat Gain Coefficient SHGC according to their orientation (0.5 for the south-facing windows, 0.25 for all others). The windows installed showed a U-value of 0.28 and an average SHGC of 0.18, which cuts out a considerable amount of passive solar heat gain on the south façade during the winter, and an air leakage of less than or equal to 0.3 as per ASTM E283. The high air infiltration rate in particular became literally tangible during the blower door tests, when the team could hear and feel the air coming in through all windows, even those that had fixed glazing installed.

Figure 8: Compromised insulation and air tightness measures. Left: non code-compliant usage of left-over XPS pieces; upper right: hand-cut EPS used to fill the rim board cavities instead of using closed-cell Icynene; lower right: improper tape used on the inside of the SIPs to achieve better air tightness.

To further compromise performance *after* the final blower door tests had been concluded, the contractor installed regular exhaust dryers instead of the specified condensing dryer, adding an intentional 4" leak in form of an open duct to the outside, therefore weakening the building's performance even more.

3.6 Façade Durability

For aspects of long-term durability and fire safety in times of increased wildfires in the Salt Lake area, FoD facades had been designed and specified to a rain screen system that uses larger scale, pre-painted cement boards with ¼" air gaps with insect screens between each panel, to allow for proper ventilation as well as thermal expansion and contraction. For no specific reason, the contractor deviated from this simple and easy-to-install system, and instead added aluminum T-profiles and angles between all panels, without accounting for the reduction in expansion joints between the panels. This added both considerable cost and complexity to the façade installation, leading to unacceptable results when the panels were finalized. In many areas, especially around windows, at the metal sun blades and at the transition between metal roof and vertical façade, proper flashing has been left out, leading to water entering the inside of the buildings right after occupation in early 2019. Inward-sloping metal components support this effect, with the overall assembly presumably resulting in early deterioration of the building envelope (Figure 9).

Figure 9: Façade construction as originally designed (upper right image of a mock-up) and as executed by SLVHFH. Lower right image: note the missing flashing at the rooftop, with wood directly exposed to the weather, as it appears in many other locations on the façade.

4. CONCLUSION

As proven in previous residential projects and research conducted by the author, the most powerful tool to reach ambitious project goals is a *highly collaborative, integrated design, development and construction process*, which, in tandem with energy modeling and a close collaboration amongst the architect, contractor, subcontractors and structural and mechanical engineers, can deliver high performance buildings at market rate or affordable costs, even in the overheated markets that the Architecture/Engineering/Construction AEC industry is currently facing. Similar to a design-build process, the close collaboration and communication needs to be continued throughout the construction process, which was when the FoD project began to fail. The experiences made during construction show the importance of an earnest and trustworthy project buy-in of everyone, including the contractor and sub-contractors. Even though the original project setup appeared to be ideal, and the 30-month-long design and development process went very commendably, most of the original efforts, ideas and goals were severely compromised during the subsequent construction process of units 9 and 10. With the duplex achieving a Home Energy Rating System (HERS) rating of 39 (61% better than the comparable code-standard building), one could argue that the buildings still outperform the standard, built-to-code SLVHFH or other residential structures, but the author is very concerned about the building's originally agreed indoor air quality, thermal comfort and its long-term performance and durability, which were all vital measures and goals established by the entire team. Meeting with the new occupants over several months, the author realized that many of the issues are severe (e.g. the ERV in the west unit was erroneously installed in one of the bedroom's galleries, which is against both the code and the original plans, as the ERV was intended to be installed in the mechanical room; due to the resulting noise issues, SLVHFH permanently disabled the unit, telling the occupant that it is only a fan that is not needed). Even after six months of occupancy, most issues have not been addressed, creating additional challenges with the impending arrival of the first winter of occupancy.

Being very involved in the FoD construction process, the author is convinced that most of the issues could have been avoided by closely following the project's designs and specifications, as well as the author's recommendations and repeated advice, and by addressing and discussing issues in a timely and honest manner. Due to SLVHFH's specific work procedures, time was no issue during most of the construction process, which would have allowed for the building the units with the appropriate care, and would have facilitated the analysis of possible mistakes to avoid a repetition when erecting the upcoming 18 units. However, due to SLVHFH's decision to ignore most challenges, Field of Dreams units 9 and 10 became a questionable, low-quality case study that already faces considerable performance and durability problems and will continue to do so during its shortened expected lifetime. However, it is the author's hope that SLVHFH will use their new knowledge and experience gained to construct the remaining units closer to the design specifications and recent code.

Figure 10: Staged interior image of the living room to the architect's original spatial intend.

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"Integrating Flexible Human-Activity in Modular Space Design for Affordable Mass Housing in Asia"

ATUL KUMAR BILTORIA[1], DR. UTTAM K. ROY[2]
e-mail: archi.atul@gmail.com

Abstract

In the contemporary fast changing world, with urbanization as an inevitable process for economic development of nations, it is often forgotten that Housing is one of the basic human rights. Migration of people to urban centers occurs in search of better career opportunities, in lieu of which citizens are forced to live in sub-standard housing. Due to increased demand of affordable housing, Governments in Asia needs to provide livable shelters to its people urgently. Livability leads to activity spaces, like behavioral pattern and flexibility. A design of housing space, which compliments its users with healthy spaces is the quest. Psychological and social needs of people living in urban multi-storied buildings need to be taken care of, by design intervention and integration of robust system of modular grid planning, capable of assembling various components of housing construction. Modular construction with prefabricated materials has the enormous capability of reducing the ever increasing gap between supply and demand of affordable mass housing due to faster construction process. Primary and secondary case studies were conducted to gauge such activity spaces. Interesting plots on space and time matrix, which reflects usage of space by each family member are obtained. These results correlates to research gap found earlier in literature study, as evident by primary survey conducted on urban population as respondents. This Paper aims to understand patterns of urban living in urban housing through Time-space matrix and links it with flexible housing design.

Keywords: Prefabricated Construction, Standardized Modular Design, Modular Grid Planning, Healthy Urban Housing

[1]PhD Research Fellow [2] Assistant Professor,

Department of Architecture and Planning

Indian Institute of Technology

Roorkee, Uttrakhand, India

1. Introduction: Status of Urban Housing in Asia

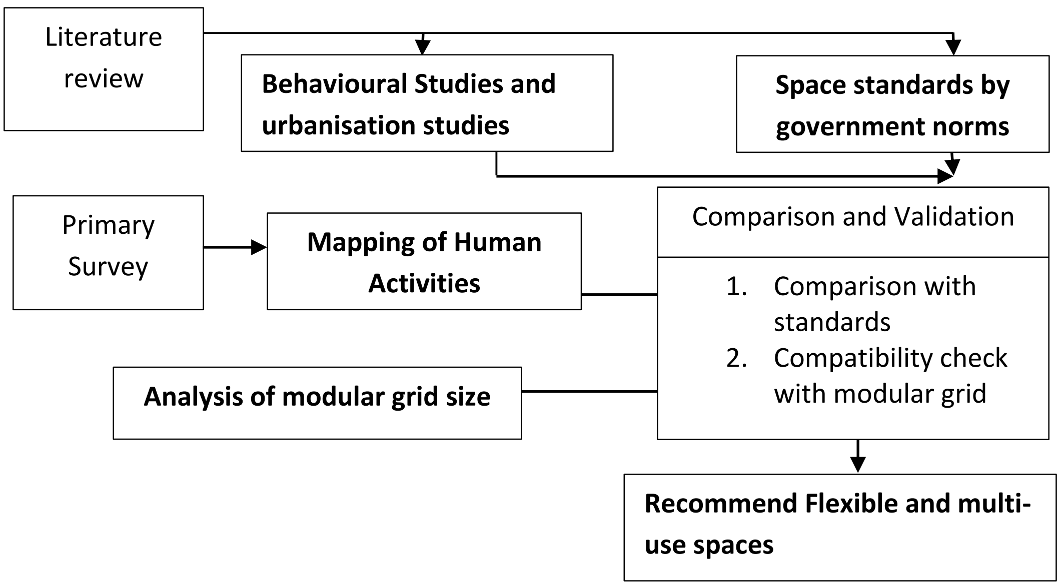
Urbanization in World Post-Industrialization has been consistent from 1950-2018, The urban centers due to better job opportunities have been preferred choices throughout this phase for the migrating population from rural areas to urban areas. However, the population increase in Asia has been unprecedented and contributes to major fragments when compared to other regions of the world. According to a report by United Nation on World Urbanization Prospects UN DESA (2019), Asia accounted for 40 percent of annual average increment of world population growth. Future projections suggest that it will account for 57 percent of world population growth alone. Therefore, it is important that we genuinely concern about the living conditions of this huge fragment of world's population, which will demand housing majorly in Urban areas. Housing is considered a human right and a basic necessity, the exponential increase of population in urban global south has severely diminished the hope of affordability in dwelling units specifically in Asia for economically weaker section (EWS) and low income group (LIG). (Bredenoord, *et al.* 2014) has described that more than 50 per cent of slum dwellers in the world live in Asia, and 61 per cent of the Asian population lives in slums and informal settlements, a fact that has contributed to Asia's leading position in innovative slum upgrading projects: for example, the Indonesian Kampung Improvement programme and the Baan Mankong programme in Thailand. Both focus on social, economic and environmental factors of slums and informal settlements (Un-Habitat, 2011). "The housing affordability issue of low-income disadvantaged groups, particularly rural-to-urban migrants, has been largely neglected in the Chinese urban housing policy so far" (Shi, *et al.* 2016). Similarly, The Indian Government is looking to close-in the gap of housing requirement through its mission of Housing for All (HFA) with the help of new technology and building materials by the year 2022 (MoHUA, 2015).

Government and Housing authorities in Asia are looking forward for alternative solutions besides linear approach of providing housing to the people. In this regard, many housing projects are done in the last few decades to decrease the housing deficit for urban poor. Such housing projects are often multi-story buildings on urban fringes. Although, it does correspond to the urgent need of Housing, it is studied in primary surveys that these people when shifted from urban centers to the city fringes they lose their employability. The fact behind this as studied in primary surveys, is that these people were working in low end jobs and require a supporting urban population and infrastructure for their employment. Secondly, it is also found through analysis of data that their living pattern included a social gathering space, which was absent in these newly built housing projects. It leads to depressing attitude of the users for their new home.

In this paper, activity spaces of urban dwellers are studied through primary surveys, and activities are mapped on a time line to comprehend the patterns of urban living. Since, governments and housing authorities have opted for partial prefabrication in the developing nations as evident from a case study from India, this paper aim to suggest a modular grid system with environmentally sustainable material like Autoclaved Aerated Concrete (AAC) Blocks. These blocks use waste materials such as fly ash as one of its constituents, and are already produced and adapted in industry setting for mass housing projects by government authorities and builders such as Mumbai Metropolitan Region Development Authority (MMRDA) and Delhi Development Authority (DDA). Secondary studies were done to comprehend use of such materials and technology, and it is found that adapting to a modular grid will reduce the construction time of such housing projects as well as support integration of activity spaces for healthy spaces.

2. Methodology

In order to comprehend activity spaces of Urban Housing, specifically in affordable mass housing projects, a through literature survey was done to understand the psyche and behavioral pattern of the residents. It is found that human living in healthy spaces can be sub-divided into three sub-sections namely physical, psychological and environmental needs. Further primary and secondary case studies along with surveys helped to gauge upon the behavioral patterns of urban living. These results from surveys are analyzed to identify research gap in the housing market as evident in the delivered housing projects. Contemporary practices adopted by the government and housing authorities to improvise the physical housing delivery system are also studied in detail, in order to integrate these new construction methods with psychological and environmental needs of human habitation for healthy living spaces. This required synthesis of social science, environment friendly aspects of construction and urban living.



3. Importance of Activity Spaces and Modular Grid in Mass-Housing

3.1 Activity Spaces for Human Body

At the very basic step of understanding activity spaces, Human Body requirements needs to be studied systematically as well as thoroughly. It is not just the physical security that a home provides, it also includes the emotional and psychological aspects. Bell *et al.* 2018, suggests that "If the large and growing body of work on therapeutic landscapes is to be effectively mobilized within relevant public health discourses and strategies, there is a need for robust and innovative empiricism that is legible both to other geographers and across relevant disciplines within and beyond academia" (Bell, Foley, Houghton, Maddrell, & Williams, 2018). One of the core outcome of their work is the effect of gathering places on Human psyche to rejuvenate through the careful inclusion of nature in designing places. It is found in the study done by Akpinar & Cankurt, (2017) that Prevalence and impacts of physical inactivity, which leads to psychological disorders, can be treated with providing urban green spaces in the close proximity to the place of residing. Also Seo & Kim, (2013) argue that within the housing unit "Any pre-determined, or rather pre-fixed program of built structure cannot cope with the changing needs of human behavior, and thus, at some point, has to restrict the freedom of body". It is suggested by them that some degree of flexibility within the housing unit should be provided to suit the individual needs of the user. Thus it is put forward for consideration that activities should be mapped and documented through primary survey.

For this study, a primary survey was conducted for a small sample size including 20 families who were recently shifted to a multi-story housing unit through government subsidized project. The following observations were found as reflected on graphs.

The scatter graph used for mapping of Time-Space matrix shows patterns of urban living as per user preference of space and duration of time. Interestingly the graph indicates that in the 1 bedroom, hall and kitchen apartment, hall is the most preferred and most time spending zone by all the age groups of the respondents. An adult female spends about 5 hours in kitchen while an adult male has negligible presence in kitchen, this reflects the socio economic society of this region of case study where adult males are the employed and adult females manage the homes. While an adult male remains outdoor for employment purposes, it shows even senior citizens like to spend considerable time outside in social gathering instead of remaining inside. Children had maximum usage of balcony space, reflecting their curious behavioral pattern.

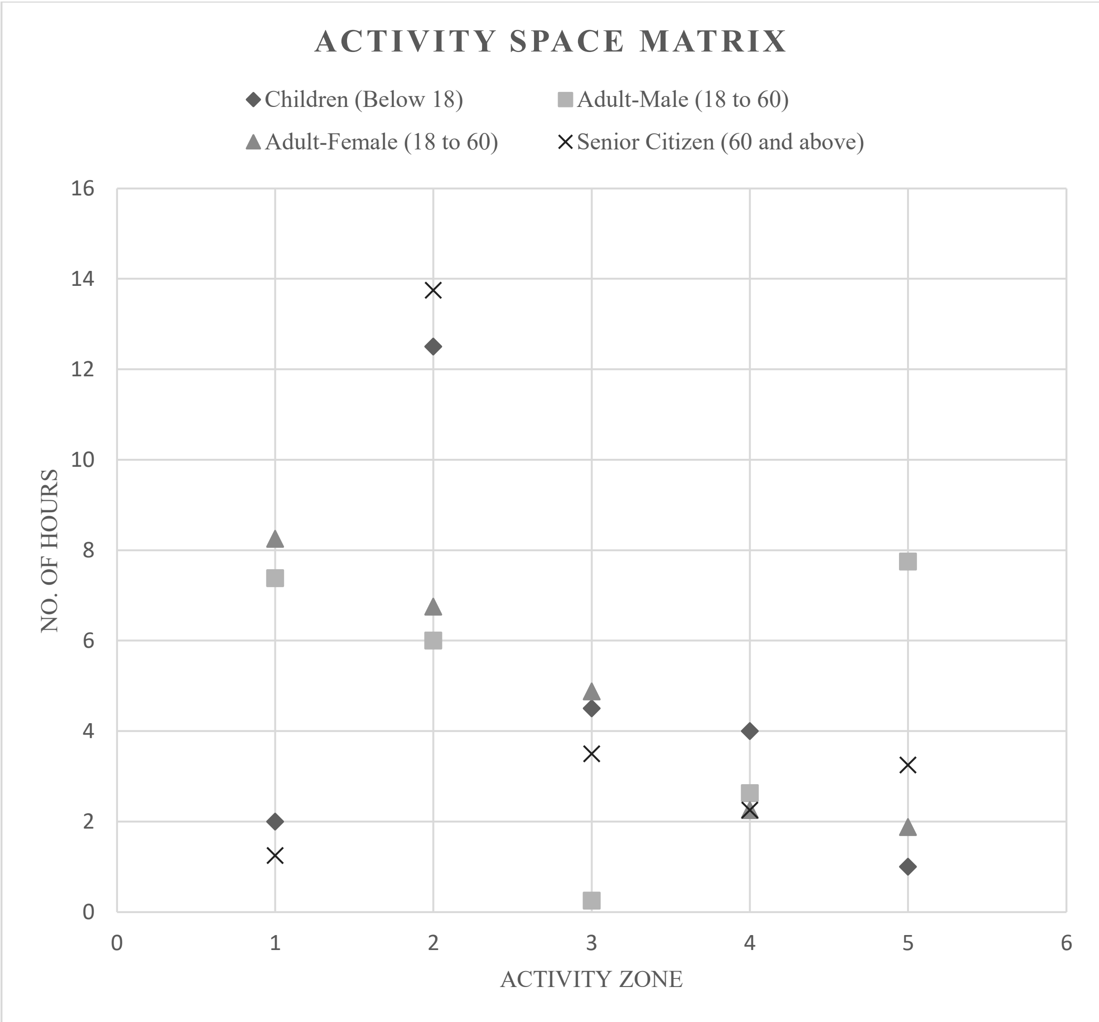


Figure 1. Scatter graph showing the preference of space by individuals 1 Bedroom, 2 Hall, 3 Kitchen, 4 Balcony and 5 Outdoor

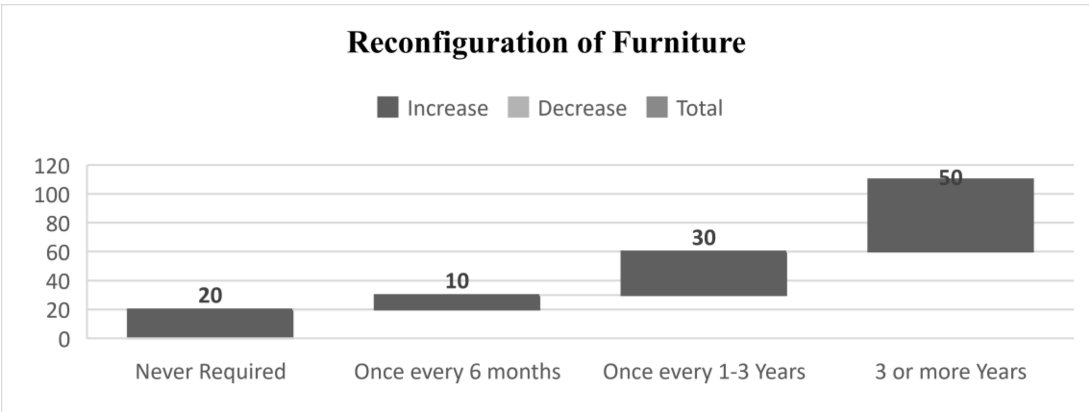


Figure 2. Graph representing flexibility required within housing unit by respondents in percentage

This survey required respondents to mark how often they altered the position of the furniture within a housing unit. The results are compiled to represent percentage of reconfiguration of furniture as a measure of flexibility within last 3 years. It is noticed that at least 80 percent of users would like to have flexibility of reconfiguration within the dwelling unit. This clearly suggests for a holistic design approach, which can support such psychological requirement.

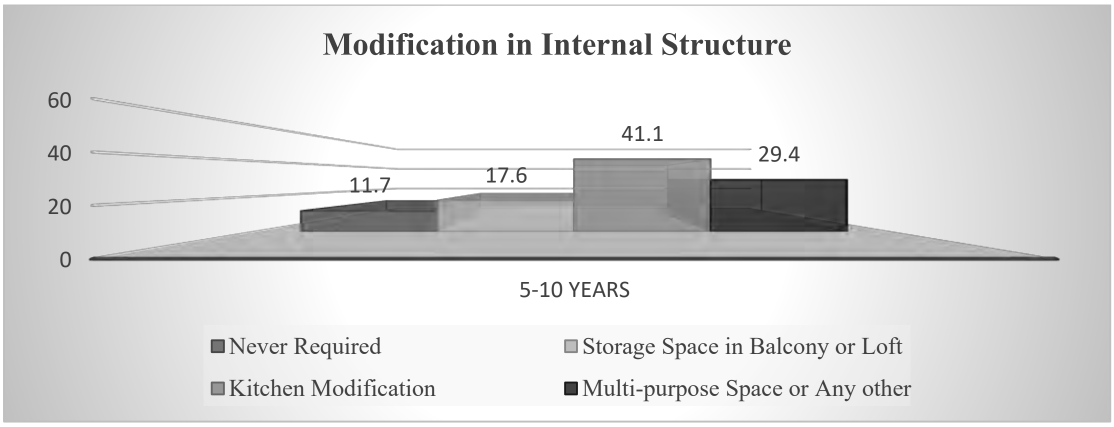


Figure 3 Frequency of modification required within housing unit for evolved functional needs overtime

Respondents also provided information related to their evolving needs and weather they modified the built structure to suit their personal needs in the last 5 to 10-year time. It is evident from the analysis of data that 88.3 percent of respondents required to alter the built structure. Interestingly, this might not be supported by the existing by-laws as there was no flexibility based plans developed at start of the project. It is observed 41.1 percent of the user in this study, reflected their choice of modification in the kitchen area. This highlighted the user need that kitchen zone needed the most of the flexibility.

Based upon the literature study and survey on Activity Spaces, it is felt that since human habitation cannot be devoid of flexible spaces, the initial planning stage of such housing project can be built upon a standard modular grid, which will have capability to not only support faster construction process but also assist in later modification of the built structure. The stakes holders and housing boards should realize that housing is a continuously evolving process and not a onetime task. Families grow, their income level grows, and therefore their basic necessities also increase accordingly.

3.2 Modular grid system to support faster construction of mass-housing projects

In contemporary practices within the last decade, China has been investing and using prefabricated components for the construction of affordable housing. India also is actively participating from 2014 onwards to climb up the ladder of partly prefabricated structures to more optimum construction technologies. Global Housing Technology

Challenge (GHTC) was launched in year 2019 by the government of India to achieve its ambitious target of Housing for All (HFA) by the year 2022. It will require constructing 30 million houses in affordable housing segment. This is a huge number and this will affect a large number of families who are going to live in these houses. China and India are the major countries of Asia and are home to the first and second largest human population. It is in the interest of these major countries as well as other smaller countries to adopt to cleaner and faster ways of construction for these ongoing and future housing projects. Future projections suggest that Asia will account for 57 percent of world population growth alone UN DESA (2019) this growth is going to demand for more stocks of Housing in a relatively shorter period of time. Therefore, it is utmost important to switch from conventional housing construction technologies to more contemporary effective technologies.

While discussing role of modularity in sustainable design (Sonego, *et al.* 2018) suggest that "permeating the benefits and limitations linked to the product architecture, it is also important to consider user behavior and its influence in the product life cycle". While comparing conventional methods to modular construction (Hammad, *et al.* 2019) pointed out that "The overall sustainability advantages of modular construction compared to on-site conventional construction comprises of shorter construction times, higher quality control and less environmental breaches compared to conventional methods".

Prefabrication of building components for Industrialized Building System (IBS) comprises of various levels of adaptation of pre cast components levels. As given by (Sarja, 2003) it could range from "Industrial material and equipment plus manual assembly on site" to "open building system from network of companies, total design thinking and development of design, Assembly and finishes" where "closed building concept means that it does not allow for flexibility for the user and open system ensures flexibility for users as well as increased supply of housing units" (Roy & Roy, 2016). "Modular construction has the potential to shorten project design and engineering time, reduce costs and improve construction productivity" (Generalova, *et al.* 2016). However, it is important that various construction components correspond to each other with similar dimensional standards. Therefore, a modular grid size is required such that all construction components correspond to the same grid size. Suppose we adopt to a grid size of 300 mm; then dimensions of all the components should be in multiple of 300mm. This will bring universal adaptability to the grid. Various construction components are studied in detail to suggest this grid size, as it is corresponding to the manufacturer design codes as well as it is suitable to adapt small building components like switchboards. When various categories of construction materials are designed as per modular grid, it will reduce the manual assembling time on site, and therefore support faster construction of mass-housing projects.

4. Analysis and Findings

4.1 Human behavioral pattern and need of flexibility within a housing unit

Suggested by the literature study that it is not just the physical security that a home provides, it also includes the emotional and psychological aspects, the primary survey results adhere to these aspects of human behavior and are matching with literature study. Further, the patterns of urban living are analyzed by plotting the data gathered by the respondents for their usage of space in a dwelling unit. This lead to findings of their preferred choice of activity zones according to the age group. Various daily and routine activities were mapped in the survey. Among all age groups, hall remains the most preferred activity zone in one room apartment. Also, frequency of reconfiguration of furniture and modification of built structure are evidences of requirement of flexibility. These findings correlate with literature study findings that human beings require social gathering spaces and physical activity is directly proportional to the proximity of urban green spaces. These findings can be utilized to develop policy guidelines of healthy housing living spaces for the huge influx of population that is going to come to urban centers.

4.2 Need of integration of activity spaces with modular grid system

Prefabricated structures are catching up in developing countries of Asia, and this provides an opportunity to fine tune it to suit the modular coordination through constant modular grid size of 300 mm. Further, psychological disorders for human habitation can be avoided mainly by designing healthy spaces. As evident in the already published literature, examining the links between indoor and built environment along with nature will give better health to the user. In the simulation of various components of building structures, it is established that prefabricated structures with modular grid gives economic benefits when compared to conventional structures. This economic benefit should alternatively be utilized for designing green space in close proximity. It also suggests that human habitation needs to have social gathering spaces as a community. Also, the individual floor patio provisions could be given at initial stage or later stage to gather government incentives. Government should encourage these green spaces in the form of floor patio as these will contribute positively on urban air quality index as well as health index of the inhabitants. Since the buildings will follow modular grid, a uniform space can be added repeatedly to achieve scale of economy, just to make sure any undue burden should not come on user, it is recommended a future provision be left for components.

5. Discussion

The information gathered through literature and primary survey can be utilized by the designers to allocate sufficient flexibility to the user, such that reconfiguration of furniture and modification of built structure to some extent few years after the possession of the housing unit can be made possible. As per the survey results, since hall in the one-bedroom apartment is the most preferred space by all age groups, it can be designed as a multi-functional space. Since all construction materials are made up of modular sizes starting from 300mm and then sizes in multiples of 300 mm further. It also includes proposed floor patio, which will be like a gathering space for the entire floor of cluster. It is to be noted that since it is an affordable housing project, the cost of urban green space like floor patio needs to be covered either by government subsidy to maintain air quality index in urban areas or by tax incentive given to the builder if he agrees to construct such urban green spaces. Alternatively, to maintain low initial cost of housing units, it is suggested to provide for provisions for future amenities, such that modular components like extra toilet, floor patio, extra room etc. van be attached few years later when the house hold income of each family unit is able to support it.

The building materials that are environmentally favorable and are available in modular sizes are suggested to be used for affordable housing projects. Since modular grid size of 300mm is being followed as discussed earlier in the paper, Autoclave aerated concrete (AAC) blocks will be the preferred choice. Quan & Yang, (2011) suggested that one of the main constituent in AAC is fly ash, which itself is a waste product. Also it is available in sizes of 600 mm lengths, which is a suitable for the grid size.

6. Conclusion

This paper attempted to link activity spaces within housing units of urban population with the ongoing research and development of new housing construction technologies. The purpose of this integration is that while modular space design is capable of providing mass housing through faster construction, it is also important that these new houses support flexibility for human activities. For this purpose, modular grid is proposed, which can support existing demand of component based modular construction as well as it can support multi-purpose flexible spaces, reconfiguration options and later modifications. Since the construction will be done on modular grid it will bring flexibility to the end user such as modification of existing unit design, multiple use of space. Urbanization prospects of Asia are among the best, it will be done by the Urban population, and they should have the right to live in healthy spaces.

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Performance of PCMs in Different Building Envelope Configurations, Climate Zones and Building Operating Scenarios

Hyejoo Koh[1] and Fitsum Tariku[2]

[1]Graduate Student, Building Science Centre of Excellence, British Columbia Institute of Technology, 3700 Willingdon Avenue, Burnaby, BC, Canada, V5G 3H2. 778-689-7146, hyejooamykoh@gmail.com

[2]Director and Supervisor, British Columbia Institute of Technology, 3700 Willingdon Avenue, Burnaby, BC, Canada, V5G 3H2. Fitsum_Tariku@bcit.ca

Abstract

Buildings contribute to 30% of the total global greenhouse gas emissions and 40% of the total energy usage worldwide. It is essential to reduce the overall building energy usage required to maintain general day-to-day building operations and occupants' comfort. This paper presents an innovative material, called phase change material (PCM). This material has been introduced in building construction but additional guidance is needed within the industry for selecting and installing PCMs. There are several factors influencing PCM performance in energy savings such as, its characteristics, the weather, the type of building envelope it is integrated with and the building operation type. In fact, inappropriate installation can result in increases in building energy consumption.

The report provides the results of numerical simulations with mat type PCMs installed within a wood framed wall assembly and presents the most effective PCM configuration for energy savings under different climates and mechanical system schedules. The PCMs with several melting points in the range of 21 to 27°C have been simulated under the climates such as, Vancouver (mild), Toronto (cold), and Houston (hot) on different building operation schedules. In most scenarios, the PCM performance is maximized when it is located near the indoor control space and its melting point is within the range of the indoor temperature in the control space. With the non-mechanical scenario, a single PCM can't provide the best performance all year around, indicating PCM performance changes as outdoor temperature fluctuates. With mechanical system operating scenarios, the maximum energy savings can be achieved when the indoor temperature fluctuates within the PCM melting point range. Vancouver has the maximum mechanical system energy savings during summer and fall while Toronto has them in shoulder seasons and Houston in winter and fall. A wall with PCMs does not save energy in extreme weather conditions since the PCMs do not experience a cycle of phase change.

1. Introduction

Buildings contribute to 30% of the total global greenhouse gas emissions and 40% of the total energy usage worldwide [Natural Resources Canada, 2011]. It is essential to reduce the overall building energy usage required to maintain general day-to-day building operations and occupants' comfort. Phase Change Material (PCM) is one of the technologies that can potentially contribute to buildings energy use reduction. PCM performance is climate-dependent [Nghana (2016), Hu (2018), Graciade (2015)]. The factors such as solar radiation, precipitation, wind speed, and outdoor temperature variances can partially or fully affect its performance and benefits in buildings energy saving. As the PCM in a building is mostly installed permanently and run during an entire year, it is essential to comprehend the climate that it is installed in.

Mechanic system operation schedule and indoor set points can also influence the overall PCM performance and efficiency as they may have a direct effect on the PCM charging and discharging cycles. As part of phase change process, any excessive heat stored in PCM must be released to prepare for the next cycle [Marani (2018), Olsthoorn (2017), and Karlessi (2011)].

PCM characteristics affect its overall PCM performance in energy savings, such as PCM melting point, orientation, quantity, thermal storage capacity, conductivity, different PCM application and indoor zonal condition. Some of the characteristics closely corelates with indoor zone set point [Karlessi (2011)].

Many researchers have completed experiments and simulations to understand PCM performance in different application types. A research has been experimented and simulated in a concrete chamber filled with rice bran distilled fatty acid PCM at the melting point of 29°C [Muthuvel (2015)]. This application reduced the maximum indoor temperature of 2°C as opposed to the conventionally constructed concrete chamber, eventually reducing the overall cooling load in hot climate. Another research has been completed with concrete walls with macro encapsulated PCM. PCMs were positioned externally bonded, laminated within, and internally bonded and compared for results. They provided different indoor temperature trends, as internally bonded PCM walls benefitting the most in temperature reduction while the laminated PCM walls shifting the temperature peak load away from the demand times[Shi (2014)].

This paper intends to investigate the performance of a mat-type PCM in wood framed-wall systems under different scenarios using energy simulation tool, and provide a guidance for selecting and installing a mat-type PCM. Four PCMs with melting point in the range of 21 to 27°C, and different climates, building operating scenarios, PCM positions and orientations in the building envelope are considered in the study. The performance of these different combinations of factors are compared based on the resulting heating and cooling energy consumptions. DesignBuilder is used for energy modeling with EnergyPlus weather input data.

2. Building Description

The model building is a single story wood-framed construction built on the concrete foundation slab. It has floor to ceiling height of 3.5 m and floor area of 100 m2. The four facades are identical in its shape and size with a fixed window (height of 1.5 m and width of 2.6 m) on each facade. Window to wall ratio is 12 %.

As the research aims to find PCM thermal performance and its relation to energy savings in heating and cooling, energy consumptions from lighting, plug loads, and indoor equipment, etc. are not modeled in simulations. The heat balance in the simulation includes heat gains from solar energy, sensible & latent heat from two occupants and all building construction components and the mechanically generated HVAC system. The building is assumed to have a unitary heat pump for heating and cooling, and a mechanical ventilation system fueled by electricity to maintain the minimum required fresh air per person during the occupied hours.

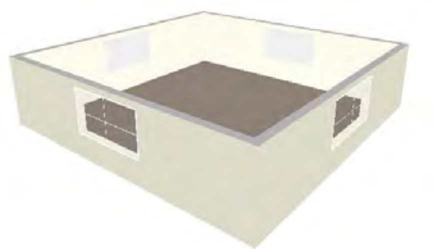


Figure 1 Visualized building simulation model

2. 1. Simulation Inputs

2.1.1 PCMs considered in the study

Four PCMs in a range of melting points between 21°C and 27°C are selected which they all have the similar maximum enthalpy when fully charged.

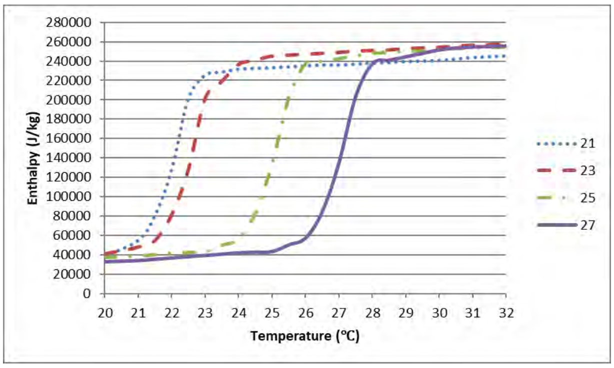
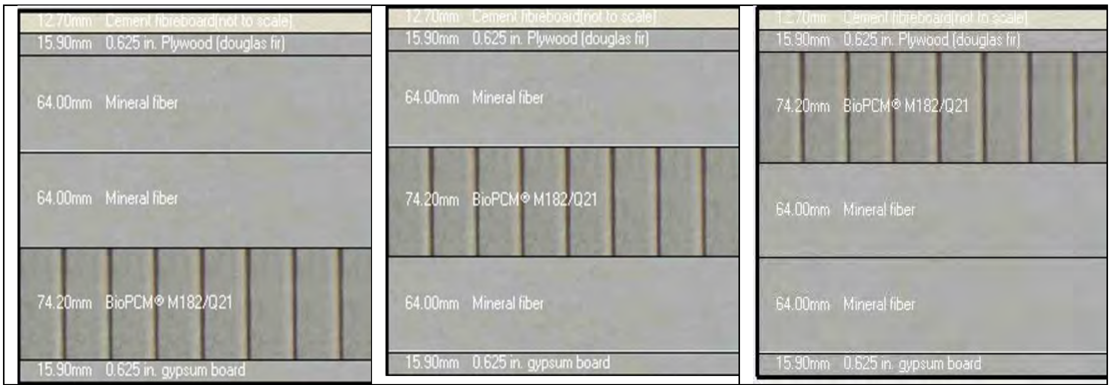


Figure 2 PCM enthalpy vs temperature graph

2.1.2 Envelope assembly

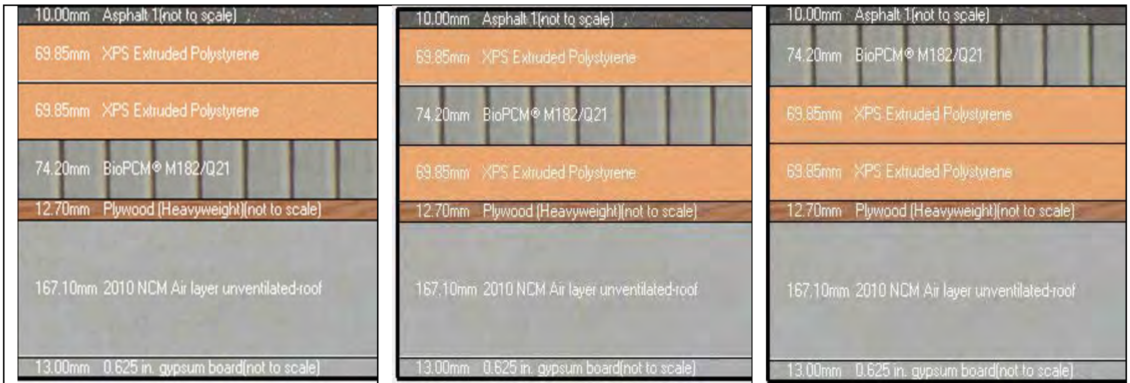
In this study, 2 x 6 wood framed-wall assembly with layers from exterior to interior: cement board, plywood, mineral wood, and interior gypsum board is considered as a base wall. Three wall systems with PCM layer added at the front, center or back of the insulation layer, making up the four wall systems were investigated in this paper, Figure 3. All four constructions have the same overall U-value of 0.248 W/m^2.K. The base wall has a slightly thicker mineral wool insulation than the PCM walls to achieve the same U-value.



PCM wall - interior facing PCM wall configuration	PCM wall - center, PCM wall configuration	PCM wall - exterior facing PCM wall configuration

Figure 3 Wall Assemblies

Similar to wall systems, a reference roof with no PCM and three roof systems with PCM installed at different positions in a flat roof system are considered in the study. The reference roof layer is comprised of asphalt layer on the exterior followed by XPS, plywood, engineered wood joist, and gypsum board layers. In the three roof systems that incorporate PCM, PCM layer is placed between the sheathing and asphalt shingles, more specifically at the bottom, above or in between two XPS insulation layers as shown in Figure 4. The thickness of the XPS layer in the base roof is adjusted so that it has the same U-value as the roofs with PCM, 0.203 W/m2.K.



Interior facing PCM wall configuration	Center, PCM wall configuration	Exterior facing PCM wall configuration

Figure 4 Roof Assemblies

The concrete slab on grade assembly has wood flooring, concrete, urea formaldehyde foam and effective U-value of 0.25 W/m2.K.

2. 2. Mechanical system operations

Four mechanical system schedules are modeled: unconditioned, conditioned during night time, conditioned during day time, and conditioned all day. In cases with air conditioning, the indoor temperature is set to free-float between 21℃ and 24℃. The mechanical system will only operate when the indoor temperature falls below 21℃ or exceeds 24℃ during the occupied hours.

Un-conditioned; reference case setup

The reference building does not operate any mechanical system including heating, cooling, and ventilating nor have occupants. This is modeled to monitor free-floating indoor temperature which is affected by the outdoor condition.

Conditioned during night time; residential building setup

The residential building operates mechanical systems between 8 pm and the next day morning 8 am while the building is occupied with two occupants. The occupants have mild indoor activity until midnight and sleep after midnight. During the un-occupied hours, the indoor temperature is not controlled and fluctuates as the outdoor climate changes.

Conditioned during day time; office building setup

The office building operates mechanical system between 7 am till 7 pm during the weekdays while the building is occupied with two occupants working full-time. There is no economizer or free cooling by natural ventilation at night. The occupants have mild office work activity. During the un-occupied hours, the indoor temperature is not controlled and fluctuates in response to outdoor climatic conditions.

Conditioned all day; residential building setup

This building has 24 hours 365 days mechanical system schedule. The building is occupied with two occupants performing mild activity.

2. 3. Weather Data

To investigate the performance of PCM in different climates, Vancouver, Houston, and Toronto are selected to represent mild, hot, and cold climatic conditions. Vancouver (Zone 5C) has mild climate throughout the year. The average summer and winter temperatures are 16℃ and 4℃ respectively. The rest of the year is rainy. Toronto (Zone 6) is hot and humid in summer and cold with frequent snow in winter. The winter in Toronto is usually below 0℃. The average summer and winter temperatures are 19.5℃ and -4.6℃ , respectively. Houston (Zone 2A) has mild winter climate with the average winter temperature of 11.9℃ and temperatures below 0 ℃ for 13 days per year. The average summer temperature for Houston is 27.84℃, and in general, it is very hot, long and humid. The weather data is imported from EnergyPlus. Table 1 presents the average winter and summer seasonal temperatures and the temperature range within the seasons for the three cities.

Table 1 Outdoor temperature profile

	Vancouver, BC	Toronto, ON	Houston, TX
Zone	5C	6A	2A
Winter Temperature Range (℃)	-4.48 ~ 12.2	-19.4 ~ 13.03	-6.1 ~ 27.52
Winter Average Temperature (℃)	3.94	-4.61	11.9
Summer Temperature Range (℃)	8.9 ~ 25.58	5.52 ~ 32.34	16.37 ~ 39.4
Summer Average Temperature (℃)	16.38	19.47	27.84

3. Analysis and results

The abbreviations below are used to name each simulation. The building without PCM is named as the basic.

- H : HVAC system operating
- N : No-HVAC system operating
- O : PCM located near exterior
- C : PCM located in the center
- I : PCM located near interior
- 21, 23, 25, 27 : Each PCM melting point

3.1 Un-conditioned; reference case setup

Figure 5 shows the ten days indoor temperature of the building in the month of May for the case with PCM melting point 21ºC. As can be seen in the figure, the walls with PCM reduce the peak indoor temperature when compared to the basic walls. PCM absorbs excessive heat while solar energy is abundant and releases the absorbed heat when indoor temperature drops below its melting point. Amongst the three PCM positions, the walls with interior PCM configuration outperformed the other two configurations as shown in the figure, i.e., yielding a lower peak indoor temperature and a narrow fluctuation range. Figures 6, 7, and 8 present how much walls with interior PCM configuration can reduce the indoor peak temperature, when compared to the basic wall. The performances of the four PCMs (melting point 21, 23, 25 and 27℃) in the three climate zones are presented for different times of a year. The left y-axis is the sum of the indoor temperature difference between the basic wall and the PCM wall for the month. The right y-axis represents the monthly average outdoor temperature of the city. The higher the left y-axis number is, the better the PCM wall reduces the indoor temperature fluctuation.

PCMs performs differently in each season. In Vancouver, while NI-21 and NI-23 performs better in the shoulder seasons, NI- 25 performs better in summer. The performance of all PCMs are low during winter as they do not experience phase change.

The temperature difference noticed during winter is due to its high thermal mass and the sensible heat being stored in PCM. In Toronto, while NI-21 and NI-23 performs better in May and June, NI-27 performs better in July and August. In Houston, NI-21 and NI-23 works well in winter while NI-25 and NI-27 work well in shoulder seasons.

The result indicates that a single PCM doesn't perform the best all year around, indicating PCM performance changes as outdoor temperature fluctuates. The indoor temperatures, affected by the climates, fluctuate throughout a year, resulting in PCMs to be exposed to a wide range of temperature variance. Each PCM has the month periods when its performance maximizes. In general, PCM walls maximizes its performance during moderate to mild weather, such as summer in Vancouver, shoulder seasons in Toronto, and winter in Houston.

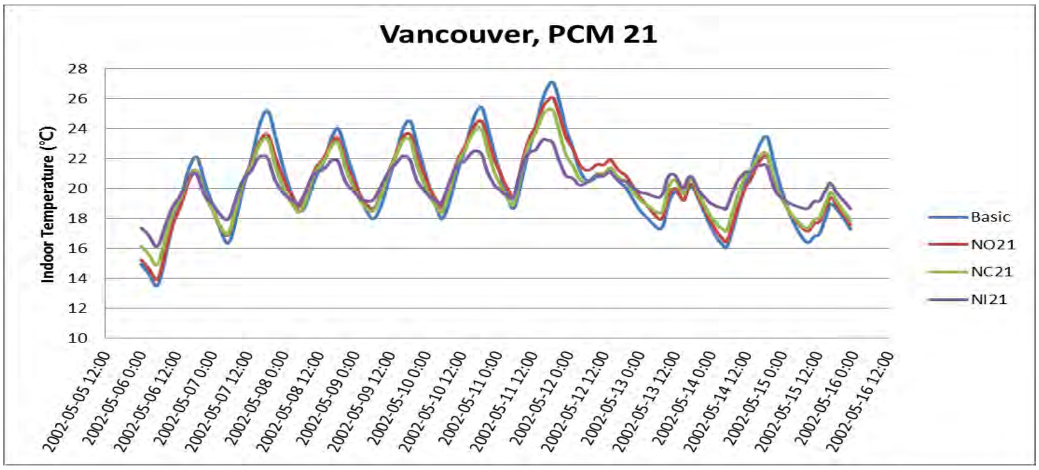


Figure 5 Basic wall and PCM-21 walls indoor temperature results

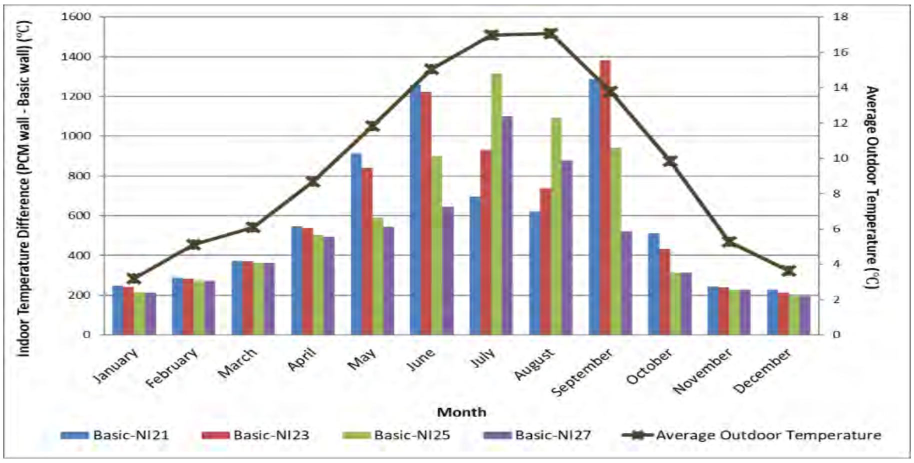


Figure 6 Vancouver, Indoor temperature difference between the basic wall and the PCM wall (NI)

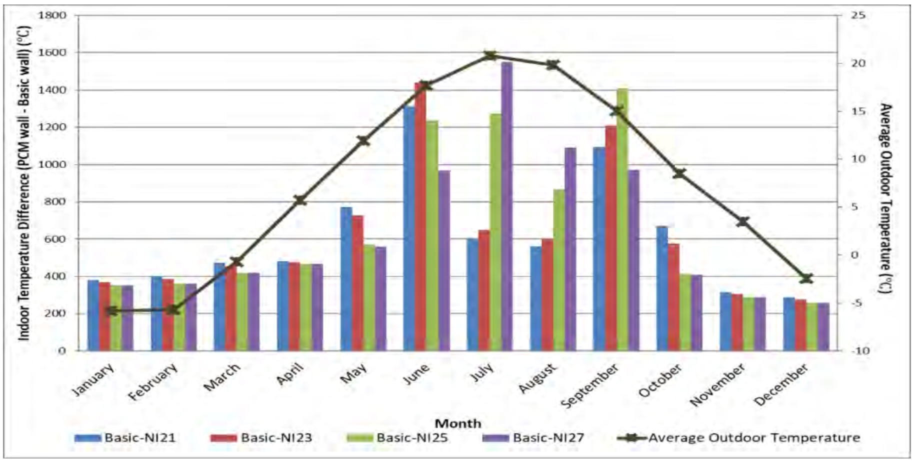


Figure 7 Toronto, Indoor temperature difference between the basic wall and the PCM wall (NI)

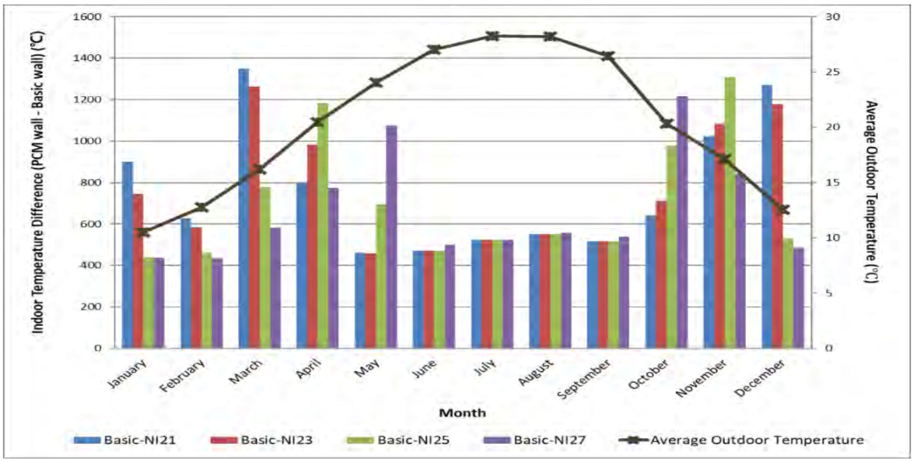


Figure 8 Houston, Indoor temperature difference between the basic wall and the PCM wall (NI)

3.2 Cases with Air Conditioning

The scenarios with mechanical system operation are analyzed in each season to provide better understanding of PCM behavior and its performance. The time periods of each season referred in this paper are described in Table 2.

Table 2 Season Table

Month	Season
December – February	Winter
March – May	Spring
June – August	Summer
September – November	Fall

3.2.1 Conditioned during night time; residential building setup (A setup)

In 'A' setup, the mechanical system is scheduled to operate between 8 pm till the next morning 8 am while the building is occupied. The indoor temperature fluctuates between 21 and 24℃, and the heat pump operates when the indoor temperature is below 21 ℃ or above 24 ℃.

Toronto and Vancouver have shown similar pattern in energy consumption. Generally, there is more heating and cooling energy required in Toronto to keep indoor temperature within the set point temperature range due to more extreme outdoor weather condition during summer and winter.

In Vancouver and Toronto, the heating energy usage with PCM walls are higher throughout the entire year especially in fall and winter. During winter, PCM absorbs mechanically produced heating energy during occupied hours (between 8pm and the next day 8am) and discharge the energy during un-occupied hours (between 8am and 8pm) as the indoor temperature reaches below its melting point. In fact, the indoor temperature during un-occupied hours is between 12 and 15℃ in winter, which is lower than all PCM melting points. Thus, PCM being present within a wall assembly eventually increases heating load when the building is occupied at 8pm and the heating system operates. Installation of PCM on the interior resulted relatively high heating energy usage (poor performance) when compared with its installation at the center or exterior. A substantial cooling energy saving in both Vancouver and Toronto, 88.8% and 37.6%, respectively, are achieved by incorporating PCM in the walls. The optimal PCM location for cooling load reduction is in the interior, which is a position that rather increases heating energy usage during winter and fall as discussed above. Although the cooling energy saving is substantial, on annual basis, the heating energy demand in these cities is significantly higher, and thereby makes the energy benefits of PCM in these cities minimal (0.87% and 0.19% in Vancouver and Toronto, respectively). For the simulation scenario presented here (Setup 'A'), PCM with melting point 21℃ installed in the interior perform better in Vancouver whereas in Toronto a PCM with melting point 25℃ installed at the middle of the wall is better when compared with other PCM types and configurations.

Houston has shown very different patterns than Vancouver and Toronto as its climate is hot throughout the year and mild in winter. PCM walls in Houston have shown significant heating energy saving during winter, while cooling energy saving is negligible than the basic wall. PCM walls with interior configuration can exchange energy with the control space more efficiently than other PCM wall configurations. Thus, generally PCM-HI walls can contribute to more mechanical heating or cooling energy saving than other walls if there is an excessive energy in the control zone. However, in some cases where PCM walls require extra cooling or heating load from heat pump during extreme weather condition, having more efficient PCM configuration can become a disadvantage as this will trigger higher energy load from the heat pump. In summer, PCM walls absorb solar radiation entered in the indoor space during unoccupied hours (between 8am and 8pm) and become fully charged. The indoor temperature fluctuates between 25 and 32℃ during unoccupied hours in summer. At 8pm, PCM-HI walls require extra cooling energy than the basic wall to readjust the indoor temperature down to 24℃. The mechanical system has to not only cool down the indoor temperature to 24℃ but also extract energy absorbed in PCM during unoccupied hours before 8pm. PCM-HI walls cause the heat pump to use 100 kWh more to cool the indoor space than the basic wall during summer, causing overall cooling load increase. Due to this fact, PCM-HC walls produce better annual energy saving performance than PCM-HI walls in Houston. PCM-HC25 provides the maximum energy savings of 94.62kWh when compared to the basic wall.

Table 3 A Setup - Annual Energy Consumption in Vancouver, Toronto, and Houston (kWh, Energy Saving Increase Percentage)

'A' Setup	Vancouver						Toronto						Houston					
	Heating		Cooling		Total		Heating		Cooling		Total		Heating		Cooling		Total	
Basic	3690		105		3795		5230		296		5526		1049		2365		3414	
HO21	3715	-0.7%	67	36.6%	3782	0.3%	5305	-1.4%	264	10.6%	5569	-0.8%	992	5.4%	2397	-1.4%	3389	0.7%
HC21	3718	-0.8%	46	56.6%	3764	0.8%	5303	-1.4%	236	20.1%	5539	-0.2%	972	7.3%	2366	0.0%	3338	2.2%
HI21	3748	-1.6%	48	54.5%	3796	0.0%	5314	-1.6%	252	14.8%	5566	-0.7%	870	17.1%	2490	-5.3%	3360	1.6%
HO23	3716	-0.7%	65	37.8%	3781	0.4%	5306	-1.4%	260	11.9%	5566	-0.7%	992	5.4%	2396	-1.3%	3388	0.8%
HC23	3719	-0.8%	43	59.1%	3762	0.9%	5304	-1.4%	227	23.3%	5531	-0.1%	971	7.4%	2355	0.4%	3326	2.6%
HI23	3754	-1.7%	35	67.2%	3788	0.2%	5321	-1.7%	236	20.0%	5557	-0.6%	870	17.0%	2464	-4.2%	3335	2.3%
HO25	3717	-0.8%	66	37.2%	3784	0.3%	5308	-1.5%	260	12.1%	5568	-0.8%	999	4.7%	2400	-1.5%	3400	0.4%
HC25	3722	-0.9%	43	58.7%	3765	0.8%	5306	-1.4%	218	26.2%	5524	0.0%	980	6.5%	2339	1.1%	3319	2.8%
HI25	3765	-2.0%	12	88.8%	3776	0.5%	5331	-1.9%	184	37.6%	5515	0.2%	905	13.7%	2422	-2.4%	3328	2.5%
HO27	3718	-0.8%	66	37.1%	3784	0.3%	5309	-1.5%	265	10.2%	5574	-0.9%	1006	4.1%	2409	-1.8%	3414	0.0%
HC27	3722	-0.9%	50	53.0%	3771	0.6%	5306	-1.4%	228	23.0%	5533	-0.1%	995	5.2%	2344	0.9%	3338	2.2%
HI27	3765	-2.0%	30	71.3%	3795	0.0%	5331	-1.9%	235	20.6%	5566	-0.7%	961	8.4%	2505	-5.9%	3466	-1.5%

The highlighted cells represent the maximum saving PCM wall configuration for each scenario.

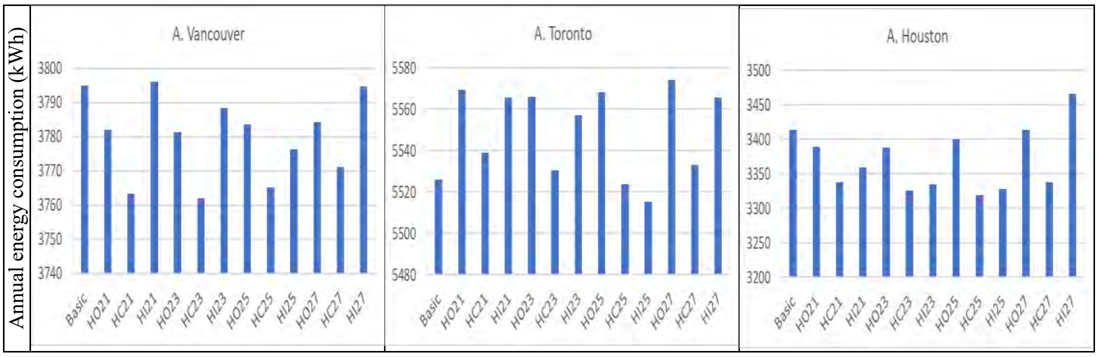


Figure 9 A Setup – Annual Energy Consumption in Vancouver, Toronto, and Houston

3.2.2 Conditioned during day time, office building setup (B setup)

In B setup, the mechanical system is scheduled to operate between 7 am till 7 pm during the week days. There is no free cooling at night. During the occupied hours, the mechanical system maintains indoor temperature between 21°C and 24°C.

In Vancouver and Toronto, both heating and cooling energy savings are observed in summer and shoulder seasons. PCM-HI walls achieve significant energy savings in cooling during summer and consume more heating energy in winter. PCM located near interior will be able to readily absorb and release energy from the control zone. During summer, PCM-HI outperforms other wall configurations by readily absorbing solar energy during peak hours (i.e., between 12pm to 2pm) and shift the peak load to the evening. This results in total cooling energy saving during the peak hours. In winter, at

7am, the heat pump operates not only to adjust the indoor temperature to a set point but also to charge PCM. The stored energy in PCM will be released to the indoor space after 7pm as the heat pump does not operate. As the indoor space will not be occupied after 7pm, the energy being released after 7pm is wasted. Overall heat pump energy usage being wasted during winter is approximately 30kWh in Vancouver and 5kWh in Toronto for PCM-HI walls. However, the overall annual energy consumption is lower with PCM walls as opposed to the basic wall as there is significant cooling energy saving during summer and heating energy saving during shoulder seasons. PCM-HI23 provides the maximum energy saving in both Vancouver and Toronto.

In Houston, all PCM walls save both annual heating and cooling energies approximately 50kWh to 100kWh. The energy savings are observed throughout the entire year. In winter, heating is required between 7 to 10 am while cooling is required between 2 to 7pm to maintain indoor temperature within the set point range. Excessive solar energy is absorbed in PCM between 2 to 7 pm and released to the indoor space when the temperature drops below the set point after 7pm. This not only reduces heating load between 6 to 10am, but also reduces cooling load after 2pm, providing cooling and heating saving. In summer, no heating energy is required at any time. Energy saving is very minimal and can be negligible. In fact, PCM located near interior consumed more cooling energy compared to the basic wall. PCM-HI walls are exposed to indoor condition, between 24 and 32 °C (24°C during occupied hours, fluctuate between 24 and 32°C during unoccupied hours). PCM melting points 21 and 23 are in a liquid form without phase change. However, PCM melting points 25 and 27 experience a significant enthalpy change, resulting in increased cooling load due to excessive energy saved during unoccupied hours. Mechanical system pumps out the energy reserved in PCM during unoccupied hours as well as provide cooling to maintain the indoor space within the setpoint temperature. Overall, walls with PCM provide annual energy saving in Houston as its winter heating and cooling saving is significant which can make up for extra cooling energy consumption during summer. The maximum total annual energy saving is with HI23 of 269 kWh (heating 146.1 kWh and cooling 96.15 kWh).

Table 4 B Setup - Annual Energy Consumption in Vancouver, Toronto, and Houston (kWh, Energy Saving Increase Percentage)

'B' Setup	Vancouver						Toronto						Houston					
	Heating		Cooling		Total		Heating		Cooling		Total		Heating		Cooling		Total	
Basic	3320		206		3526		4954		424		5378		643		2461		3104	
HO21	3244	2.3%	168	18.2%	3412	3.2%	4877	1.6%	386	9.1%	5262	2.2%	582	9.6%	2384	3.1%	2966	4.5%
HC21	3227	2.8%	153	25.8%	3379	4.2%	4847	2.2%	371	12.6%	5218	3.0%	547	14.9%	2372	3.6%	2919	5.9%
HI21	3262	1.7%	116	43.6%	3379	4.2%	4865	1.8%	338	20.4%	5203	3.3%	497	22.8%	2322	5.6%	2819	9.2%
HO23	3245	2.3%	170	17.5%	3415	3.1%	4878	1.5%	387	8.8%	5264	2.1%	583	9.3%	2387	3.0%	2970	4.3%
HC23	3228	2.8%	154	25.0%	3382	4.1%	4847	2.2%	370	12.8%	5217	3.0%	560	13.0%	2372	3.6%	2931	5.6%
HI23	3262	1.7%	103	50.1%	3365	4.6%	4866	1.8%	329	22.4%	5195	3.4%	520	19.1%	2315	5.9%	2835	8.7%
HO25	3254	2.0%	176	14.5%	3430	2.7%	4885	1.4%	393	7.3%	5278	1.9%	593	7.8%	2403	2.4%	2995	3.5%
HC25	3240	2.4%	162	21.1%	3402	3.5%	4856	2.0%	378	11.0%	5233	2.7%	575	10.7%	2381	3.2%	2956	4.8%
HI25	3306	0.4%	112	45.7%	3418	3.1%	4896	1.2%	334	21.2%	5230	2.8%	571	11.3%	2311	6.1%	2882	7.2%
HO27	3257	1.9%	178	13.4%	3435	2.6%	4889	1.3%	398	6.2%	5287	1.7%	598	7.1%	2417	1.8%	3015	2.9%
HC27	3245	2.3%	167	18.9%	3412	3.2%	4864	1.8%	386	9.0%	5250	2.4%	582	9.5%	2392	2.8%	2974	4.2%
HI27	3328	-0.2%	143	30.4%	3471	1.6%	4923	0.6%	375	11.6%	5298	1.5%	596	7.4%	2454	0.3%	3050	1.8%

The highlighted cells represent the maximum saving PCM wall configuration for each scenario.

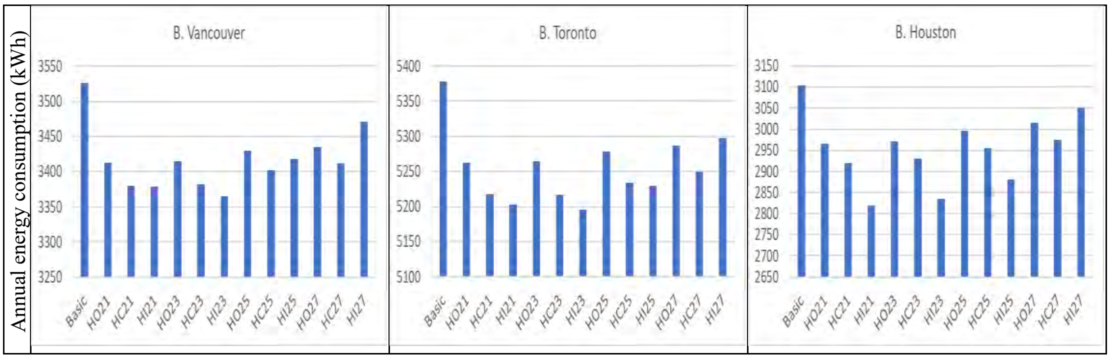


Figure 10 B Setup - Annual Energy Consumption in Vancouver, Toronto, and Houston

3.2.3 Conditioned all day, residential building setup (C setup)

In this scenario, the mechanical system is scheduled to operate all days, keeping the indoor temperature between 21°C and 24°C.

In Vancouver and Toronto, the walls with PCM save significant mechanical energy usage all year around. Not like the other simulations (A setup and B setup), PCM in a wall assembly does not result in heating load increase in winter. PCM at A and B setups have experienced energy charging or discharging periods during un-occupied hours, which required extra heating or cooling load during occupied hours. However, the PCM in this scenario does not experience the charging and discharging period, as the indoor set point is between 21 and 24°C all year around. Further, solar energy entering through windows is captured in PCM and helps to reduce the overall heating load. All PCM configurations provide energy savings as PCM walls absorb solar radiation during the day, reducing cooling load and release the absorbed energy at night, reducing heating load. The PCM walls with melting point 23°C experience phase change cycle while the indoor temperature fluctuates between 21 and 24°C all year around. As such, PCM-HI23 has the most energy storage capacity with higher enthalpy difference within the indoor set point, which can result in the maximum energy saving. PCM with melting point 23°C installed in the interior performs better in Vancouver and Toronto as opposed to other PCM types and configurations.

In Houston, most of the PCM walls provide energy savings in heating and cooling than the basic wall as seen in Table 5 and Figure 11. Especially significant heating energy saving is observed in winter, spring and fall. During summer, all PCM walls consume more energy than the basic wall approximately 20 to 25kWh. Houston summer is hot and the average outdoor temperature is 27.84 °C which is higher than any PCM melting point simulated. The heat pump works to control indoor temperature and pump the heat absorbed in PCM during all days. Both significant cooling and heating energy savings are observed in winter. Excessive solar energies during day time are absorbed in PCM, reducing overall cooling load. When outdoor temperatures drops at night, the stored energy in PCM is released to the indoor space, reducing heating load with significant energy saving (approximately 150 kWh savings from heating). In Houston, the maximum total annual energy saving is with HI23 of 445.9 kWh (heating 256 kWh and cooling 189.9 kWh).

Table 5 C Setup - Annual Energy Consumption in Vancouver, Toronto, and Houston (kWh, Energy Saving Increase Percentage)

'C' Setup	Vancouver						Toronto						Houston					
	Heating		Cooling		Total		Heating		Cooling		Total		Heating		Cooling		Total	
Basic	5361		333		5694		7284		685		7969		1235		3880		5116	
HO21	5234	2.4%	254	23.8%	5488	3.6%	7159	1.7%	606	11.6%	7765	2.6%	1123	9.1%	3829	1.3%	4951	3.2%
HC21	5213	2.8%	224	32.7%	5437	4.5%	7138	2.0%	572	16.5%	7710	3.3%	1083	12.3%	3786	2.4%	4869	4.8%
HI21	5234	2.4%	242	27.5%	5476	3.8%	7063	3.0%	528	23.0%	7590	4.8%	948	23.3%	3715	4.3%	4663	8.9%
HO23	5234	2.4%	254	23.6%	5488	3.6%	7158	1.7%	605	11.8%	7763	2.6%	1124	9.1%	3831	1.3%	4954	3.2%
HC23	5213	2.8%	225	32.5%	5438	4.5%	7135	2.0%	567	17.3%	7702	3.3%	1089	11.8%	3782	2.5%	4872	4.8%
HI23	5105	4.8%	143	57.0%	5248	7.8%	7049	3.2%	500	27.1%	7549	5.3%	945	23.5%	3688	5.0%	4633	9.4%
HO25	5243	2.2%	261	21.5%	5504	3.3%	7164	1.6%	610	11.0%	7774	2.4%	1135	8.1%	3845	0.9%	4980	2.7%
HC25	5226	2.5%	235	29.5%	5460	4.1%	7145	1.9%	574	16.3%	7718	3.1%	1113	9.9%	3783	2.5%	4897	4.3%
HI25	5162	3.7%	147	55.8%	5309	6.8%	7088	2.7%	487	29.0%	7575	4.9%	1034	16.3%	3712	4.3%	4746	7.2%
HO27	5245	2.2%	264	20.8%	5509	3.2%	7168	1.6%	616	10.1%	7785	2.3%	1142	7.6%	3857	0.6%	4999	2.3%
HC27	5234	2.4%	242	27.5%	5476	3.8%	7157	1.7%	587	14.4%	7744	2.8%	1129	8.6%	3795	2.2%	4923	3.8%
HI27	5205	2.9%	197	40.7%	5403	5.1%	7130	2.1%	557	18.8%	7687	3.5%	1103	10.8%	3805	1.9%	4908	4.1%

The highlighted cells represent the maximum saving PCM wall configuration for each scenario.

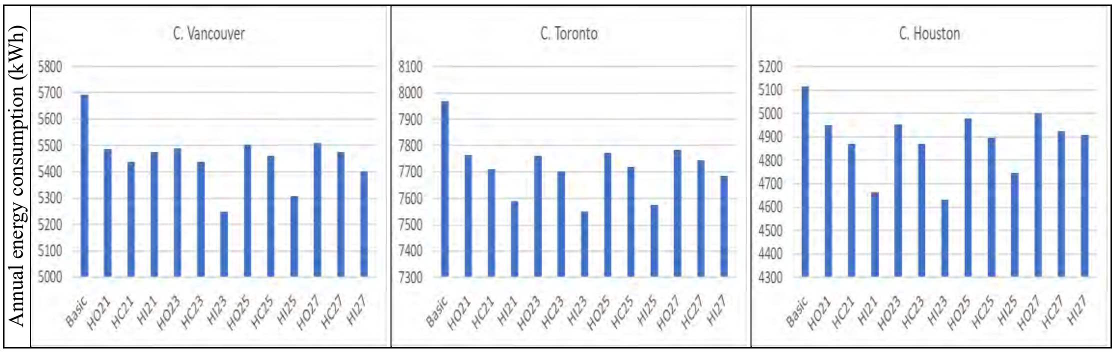


Figure 11 C Setup - Annual Energy Consumption in Vancouver, Toronto, and Houston

4. Conclusions

This paper presents the results of numerical simulation on a simple PCM application (a mat type) in wood framing walls under different scenarios. The main conclusions are as follows:

- The PCM-HI provides the maximum energy savings in most case scenarios except in extreme weather condition such as Houston summer or Vancouver and Toronto winter. However, the annual energy savings are achieved as PCM-HI has significant energy saving in other seasons.

- With the non-mechanical scenario, a single PCM can't provide the best performance all year around. Each month has a different best performing PCM. In the hotter seasons, PCM-27 reduced the temperature fluctuations the most while in the shoulder seasons, PCM-21 & 23 reduced the temperature fluctuations the most. Further research can be investigated in the benefits of installing multiple PCMs under free-floating indoor temperature condition.

- In Vancouver and Toronto A and B setup, PCM-HI walls cause additional heating energy load during winter. As the heat pump provide energy for keeping the indoor temperature within the setpoint as well as for charging PCM within the wall assemblies.

- In Houston A setup, PCM-HC performs better than PCM-HI as PCM located near interior contribute additional cooling load from the heat pump during summer.

- In Houston B setup, PCM walls can consume extra cooling energy than the basic wall during summer. However, the annual energy saving can be achieved from substantial heating energy saving during mild winter.

- In Vancouver and Toronto C setup, most PCM walls save significant energy usage all year around. Not like the other simulations (A & B), the PCM walls can provide energy savings in winter as they do not experience charging and discharging cycle which resulted in additional heating load in A and B setup.

- With mechanical system operating scenarios, the maximum energy savings can be achieved when the indoor temperature fluctuates within the PCM melting point range. Vancouver has the maximum mechanical system energy savings during summer and fall while Toronto has them in shoulder seasons and Houston in winter and fall.

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CHARACTERISTICS OF TYPICAL OCCUPANCY SCHEDULES FOR RESIDENTIAL BUILDINGS IN THE UNITED STATES

Debrudra Mitra[1], Nicholas Steinmetz[2], Yiyi Chu[3], Kristen Cetin[4]

[1] Department of Mechanical Engineering, Iowa State University, Ames, Iowa 50011-1066; email: dmitra@iastate.edu
[2] Department of Mechanical Engineering, Iowa State University, Ames, Iowa 50011-1066; email: nstein@iastate.edu
[3] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, Iowa 50011-1066; email: yiyichu@iastate.edu
[4] Assistant Professor, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI; email: cetinkri@msu.edu

Abstract

The overall energy performance of the residential building sector highly depends on the presence of occupants and their interaction with the energy consuming systems in buildings. In order to predict the energy performance of a residential building, it is important to utilize an occupancy profile that accurately represents occupants' presence in a space. In current practice, most building energy simulation tools for residential buildings assume a standard 24-hour schedule, regardless of the home's known characteristics. This demonstrates that there is room for improvement in modeling occupancy schedules. In order to better represent the unique characteristics of residential occupancy profiles, 12 years of American Time Use Survey (ATUS) data was analyzed. Major classifiers that impact the variations among schedules were obtained and compared. It was found that there are two classifiers that significantly impact occupancy schedules: (1) age of the occupant, and (2) type of day, i.e. weekday or weekend. To further explore variations among these groups, cluster analysis was performed on the daily occupancy profiles. For the age groups, various occupancy schedules can be seen, where two major clusters dominate in both weekdays and weekends: stays in home for the whole time and follow a working schedule. The results help illustrate the variability of occupancy schedules, providing tailored occupancy schedules for every cluster group. Overall, the results of this study provide a better understanding and more tailored prediction of the residential occupancy schedules, based on known occupant characteristics, which benefits both building energy modelers and researchers in sustainable residential building design.

Introduction

Occupant behavior in the building sector is an emerging area of study with potential benefits in areas such as efficient design of building spaces, and heating, ventilating and air-conditioning (HVAC) and lighting system operations, as well as improving thermal comfort control [Saha et al, 2019]. Occupants' behavior and their lifestyle, particularly in residential buildings, significantly influences the building indoor environment and overall energy consumption [Yan et al., 2015; Yu et al., 2011]. A study in 25 households in a residential building in Beijing in the summer showed that the electricity consumption for air conditioning varies from 0 to 14 kWh/m^2 with a mean of 2.3 kWh/m^2 [Li et al, 2014], demonstrating the variation that occurs in energy use due to occupants and their energy-related preferences. It was also shown that, compared to commercial buildings, occupant behavior has more significant impact on residential building consumption [Santin et al, 2009, Wilke, 2013, Popoola, 2018]. Various recent research has also shown that more accurate detection of these occupants can reduce energy use in buildings by up to 30% [Lo et al, 2010] through adjusting controls. Others have shown that variation in occupants' behavior resulted in 87% change in the air change rate using a natural ventilation system [Iwashita et al., 1997]. As such, it is beneficial to work towards better understand occupancy in residential buildings, to support improved building efficiency.

Similarly, in order to evaluate the overall energy savings potential in a residential building, HVAC control strategies need to be designed based on realistic occupancy scenarios of the building under consideration. An occupancy profile of a residential building is highly diverse and stochastic in nature. There is also significant uncertainty in predicting overall energy use [Hoes et al, 2009]. Therefore, it is important to evaluate different types of occupant schedules in a residential building. One method to divide the data into categories is through clustering techniques, which, in this scenario, can be used to find distinctive features among different types of schedules and classify occupant in different categories.

The development and refinement of occupancy schedules has been an ongoing topic research in recent years; however, most studies focus on the development of occupancy profiles for a single building or small subset of buildings. Occupancy prediction based on the data of a single building can predict the profile for that particular building, but it may not necessarily be representative of a broader set of residential buildings, at least not without further validation and comparison of the data. Therefore, it is critical to better understand the characteristics of occupancy schedules to generalize the different profiles occupants have in residential buildings. An "average" occupancy schedule (e.g. [Mitra et al., 2019]), one method of development of occupancy schedules used in building energy simulation software, provides a "typical" schedule of an occupant(s). However, the drawback of this method is that due to averaging the schedule across a period of time, the daily variations in an occupant's schedule can be lost.

However, in commonly used building energy modeling software programs, an "average" schedule is commonly used which includes a, typically hourly, fraction from 0-1 of the occupancy in a particular space. Using this "average" schedule, there are no situations where the occupancy profile is 0. This presents challenged when simulating HVAC control methods that are based on the presence or non-presence of occupants in a space. The modeling method of occupants needs to include a schedule that has both occupied and unoccupied periods of time in order to evaluate the energy savings from such controls. In addition, there have been very few studies to create occupant profiles that represent the U.S. population, rather than a small number of buildings. As such, the main objective of this study is to better characterize the occupancy profiles of residential buildings that represent the U.S. population.

Several recent studies have focused on developing occupancy patterns in buildings. To represent the stochastic nature of occupants, Markov chain-based methodologies have been used in recent literature. One of the pioneer studies in this field, Page et al. [2008], used a discrete time Markov chain modeling, targeted at use for single zone, single occupant situations over a shorter span of absence. Richardson et al. [2008] studied first order Markov Chain models. Based on the data obtained from camera and motion sensors, Markov and Semi-Markov models were used to simulate the occupancy for different spaces during different times of one day [Adamopoulou et. al, 2016]. Two stochastic models were proposed by Chen et al. [2015] for single and multi-zone scenarios with multiple occupants. For the single zone scenario, an inhomogeneous Markov chain model was used. Beyond Markov chain models, other methods such as recursive algorithms have also been used, such as by Schwartz et al [2016]. However, most of these studies focused on specific occupancy scenarios for a single building, thus and it is difficult to translate this data to represent a broader population in the United States.

To study the occupant behavior, occupant presence data is needed, however it is challenging to collect sufficiently diverse data to represent the typical characteristics of occupant behaviors [Hu et al, 2019]. Time Use Survey data can fulfil this data requirement as it statistically represent the overall population of a country. Several countries throughout the world, such as China, Japan, Belgium, the United States, etc. collect and publish time use survey data for their countries. Time use survey data generally includes details about the peoples' demographics and their activities for a 24-hour period.

In summary, occupancy behavior is among the most important parameters in predicting energy consumption in residential buildings yet is also among the least understood. This study, 12 years of American Time Use Survey (ATUS) data (2006-2017) is used with cluster analysis methods to analyze different occupant profiles of the U.S. population. We determine the optimum number of clusters to represent occupants' schedules, then for each cluster, we define the percentage of people who can be represented by each. The results of this work will represent different types of typical schedule patterns occupants have in a residential building, which provides energy modelers with more realistic occupancy-related tools to support the evaluation of the energy performance of the residential building sector.

Dataset

American Time Use Survey data (ATUS)

The American Time Use Survey (ATUS) (U.S. BLS, 2017), supported by the United States Bureau of Labor Statistics, is an annual survey that began in 2003. The results of the survey are intended to evaluate how individuals spend their time, down to the minute level of granularity. The survey results include information on the activity conducted (e.g. sleeping, socializing, traveling…) as well as the location (e.g. home, office, school, etc..). All ages of people are included in the survey; however, if their age is below 15 or over 75, they are designated as being 15 or 75, respectively, in the resulting data. The data is collected through in-person, telephone, or email interviews, in which the respondents supply data about their activity and location, including where they were, with whom they were with, and specific activity they were doing over a 24-hour period. The activity data is then coded in three hierarchical levels to represent the specific activities within the database. However, unlike other time series data published in Europe (e.g. Sullivan et al. 2017), the survey does not ask for activities in specific time intervals. The activity is recorded as being the same until there is a change in the activity designated by the person. The survey also provides details about the day of the week each activity occurs, and the month of the year. To statistically represent the United States, a weighting factor is utilized for interpretation of the results of the survey. The method used to calculate the weighting factor was modified in 2006 and has remained consistent since that time. Due to this modification, only the survey data from 2006 to present was utilized in this study.

Methodology

In this study, ATUS data is utilized to extract people's activity data, specifically in buildings. This section discusses the division of 12 years of ATUS data in several groups based on parameters which have significant impact on the occupancy profile, and the development of different typical occupancy profiles based on the data results.

In the previous studies by the authors, average residential occupancy profiles were studied where the age range of the occupants and whether it's a weekday or weekend were used as two important classifiers to subdivide the data [Mitra et al., 2019]. This research found significant differences in the average residential occupancy profiles for occupants in different age groups. In this study, a similar approach is taken, where the ATUS data is segregated based on age groups and whether it's weekday or weekend. The occupants are then divided into four age ranges: (i) below 25, (ii) 25 to 44, (iii) 45 to 64, and (iv) older than 65. This division is consistent with the previous mentioned study with a slight modification: the multiple age groups between 25 years and 44 year are combined to be in a single age group category, which reduces the total number of age groups from 7 to 4. The dataset is then further subdivided into weekday and weekend data.

Following the data subdivisions, cluster analysis is performed to define typical occupancy schedules for the subdivided data. Cluster analysis is a popular unsupervised learning technique used to group the data in different clusters according to the similarity of data characteristics. For example, Liao et al [2005] and Reddy TA [2011] used clustering to analyze static and time series data. Diao et al [2017] used the cluster analysis and obtained 10 different schedules for people living in New York. Cluster analysis is also commonly used for studying the electricity or energy consumption patterns for different types of buildings. Electricity use patterns were studied for different non-residential buildings in Italy [Chicco et al 2012], China, South Korea, and Finland [Kim et al, 2011, Kwac et al, 2014].

There are different methods which can be used to perform cluster analysis of time series data. Dynamic time wrapping (DTW) determines the optimum profile between time series profiles [Brendt et al, 1994]. In this method, the time series profiles can be grouped according to their patterns even if there is a time lag between them. The main advantage of DTW is the possibility of grouping time series according their patterns or shapes even if these patterns are not synchronized.

In this study, DTW is used, based on the R package *dtwclust* [Sarda-Espinosa et al, 2019]. In this package, the number of clusters must be specified. As such in this work we assess clustering the data into 3, 4 and 5 different groups, then apply a goodness of fit test to the resulting distributions to determine the optimum number of clusters. The average of the silhouette width (*Si*) is used to evaluate the goodness of fit of the cluster results. *Si* (Equation 1) is used to determine whether the data lies in the proper cluster or not and also evaluate the quality of the clusters [Kaufman et al., 1990]. *Si* is defined as

$$Si(i) = \frac{b(i)-a(i)}{\max(a(i),b(i))} \quad (1)$$

Where, *a(i)* and *b(i)* is the average distance of *i* from the specific cluster and from other clusters from the specified one [Reynolds et al., 2006]. An Si value equal to 1 represents data that is "well classified"; a negative Si indicates the data has been classified in the wrong cluster. The higher the average of the Si values of the data, the better the goodness of fit for the clusters. Finally, for optimum clustering, the percentage of people who followed the define profiles is calculated.

Results and Discussion

Following the described methodology, the ATUS data was divided into 8 smaller datasets based on the age group and whether it was designated as a weekday or weekend. 3 clusters for each sub-dataset were used to further subdivide the data, resulting in a total of 24 sets of data for cluster analysis. The types of occupancy schedules are first discussed, with a focus on the most common types of profiles, followed by the goodness-of-fit for different numbers of clusters, including the determination of the optimum number of clusters. This is followed by comparing the characteristics of the final occupancy clusters.

The occupancy profiles obtained from the cluster analysis resulted in 17 different profiles. The descriptors of the different types of occupancy profiles are listed in Table 1. These schedules can be classified into three major categories, working during the day schedules (O), stay-at-home schedules (P) and absence for some smaller timespan or at night (N). These types of occupancy profiles were obtained irrespective of the age of occupants and weekday/weekends. For the (O) schedule, the absence time for residential buildings varies from 6 hours to about 12 hours. Whereas, there are also some occupancy schedules which indicate the person(s) stays at home most the day with minimal (i.e. about less than 2 hours) absence. There are also several occupancy schedules where occupants are away from the home for different time span during daytime and sometimes during night (i.e. N1 to N6). The frequency of occurrence of different profiles are shown in Figure 1. It should be noted that only the most common schedules (i.e. larger than 13% of data) for all of 3, 4 and 5 clusters are shown in figure1.

The most common occupancy schedule in the data is P1, where occupants stay at home for the entire day. Regardless of the number of clusters (i.e. 3. 4 or 5) analyzed, and for all ages and weekdays/weekend datasets, this schedule was among the most common. The schedule representing working for approximately 8 hours (O1) also appeared for all subgroups when using 5 clusters, and often when using 3 and 4 clusters. The other common occupancy profiles are N2, N3 and O4; O2 and O3 also appeared several times.

The goodness of fit for the clusters using the average *Si* value is shown in Table 2. It shows that 3 clusters for each subgroup of data is the best fit, except for occupants who are over 65 on weekdays, where 5 clusters is a slightly better fit. However, it should be noted that for this age group, the average *Si* value for 3 clusters (0.37) is very close to the 4 and 5 cluster scenarios (0.38). As such, in the following sections, the analysis of the results using 3 clusters are discussed since this number of clusters shows the best fit for the distributions.

Table 1. Types of residential occupancy schedules based on cluster analysis

Cluster Type Description	Index
Office schedule, absent from home for ~8 hours	O1
Office schedule, absent from home for ~6 hours	O2
Absent from home for more than 12 hours	O3
Office schedule, absent from home for 10-12 hours	O4
Office schedule; leave home later; absent for 8-12 hours	O5
Office schedule; return later at night; absent for about 12 hours	O6
Office schedule; leave home later; absent ~8 hours	O7
Leave home in morning; return midday; leave for significant time	O8
Stay at home entire day	P1
Stay at home entire day; except a short period in the afternoon (~1-2 hours)	P2
Stay at home entire day; except a short period (~1 hour)	P3
Absent most of the day, including sometimes at night	N1
Absent for a short period in the afternoon (~2 hours)	N2
Absent for a short period in the morning (~2 hours)	N3
Absent for a short period in the early morning (~2 hours)	N4
Absent the entire day	N5
Absent at night; at home during the day	N6

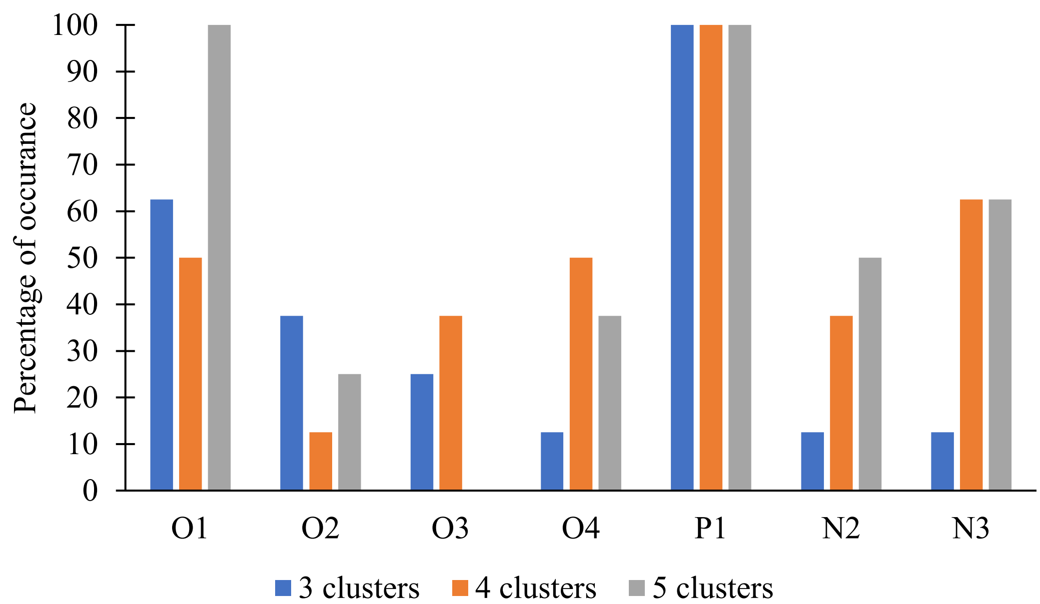

Figure 1. Frequency distribution for different types of occupancy schedules *(Note: O = office-type schedule; P = stay at home type schedule; N = absent for long periods of time type schedule; the numbers correspond to the cluster type as noted in Table 1)*

Table 2. Average silhouette widths for different number of clusters

	Average silhouette width *(Si)*							
	Weekday				Weekend			
Number of clusters	Age: Under 25	25-44	45-64	Over 65	Below 25	25-44	45-64	Over 65
3 clusters	0.38	0.44	0.35	0.37	0.39	0.36	0.41	0.44
4 clusters	0.34	0.26	0.32	0.38	0.33	0.34	0.32	0.36
5 clusters	0.33	0.28	0.34	0.38	0.34	0.29	0.33	0.38

The centroid of the clusters for different groups are shown in Figure 2. Figure 2 (a1) -(a4) show the schedules for occupants who are under 25 years, 25 to 44, 45 to 64 and over 65, on weekdays and weekends. The x axis represents the time of a day, starting from midnight, and ending at midnight of the following day. The y axis represents the binary distribution of presence and absence, where 1 indicates presence and 0 indicates absence in a residential building. There are three typical occupancy schedule clusters based on age and weekday/weekend. People who are older than 65 have similar schedules on both the weekdays and weekends. However, this is not the case for people belongs to other age groups. As shown in Figure 2, the type of profile varies significantly depending on whether it is a weekday or weekend. Some types of profiles are also present for people in certain age groups, which are not common for people in other age groups. It is also interesting to note that the staying at home (P1) schedule occurs across all subgroups.

For people under 25, three major schedules can be seen for weekdays. One is the schedule where people are not at home for approximately 8 hours, where they follow a typical office-type work schedule; in the second cluster they are not present in the home for approximately 10 to 12 hours. The third cluster is similar for both weekdays and weekends, where the profile represents that occupants spent most of their time at home. On weekends, even though the 8-hour office-type schedule is still present, another type of schedule is also common, where occupants leave home in the morning, then return home midday and leave again for the afternoon.

For occupants age 25 to 44, on weekdays the cluster analysis indicates they either follow an approximately 8 hours workday schedule or stay at home for most or the entire day. On weekends, the span of absence can vary, where one typical schedule is leaving for a short period of time (~3-4 hours) and returning home midafternoon. The schedules for occupants ages 45 to 64 are similar to those ages 25 to 44 on both weekdays and weekends. For people over 65, typical schedules do not vary significantly due to whether it is a weekday or weekend; some follow the 8-hour workday schedule; some are absent for about 10 hours, and other stay at home for the entire day.

These profiles represent the different variations in occupancy schedules on both weekdays and weekends. To further understand which schedule types are most common, the percentage distribution of occupants with different schedules in each cluster type are calculated and shown in Table 3.

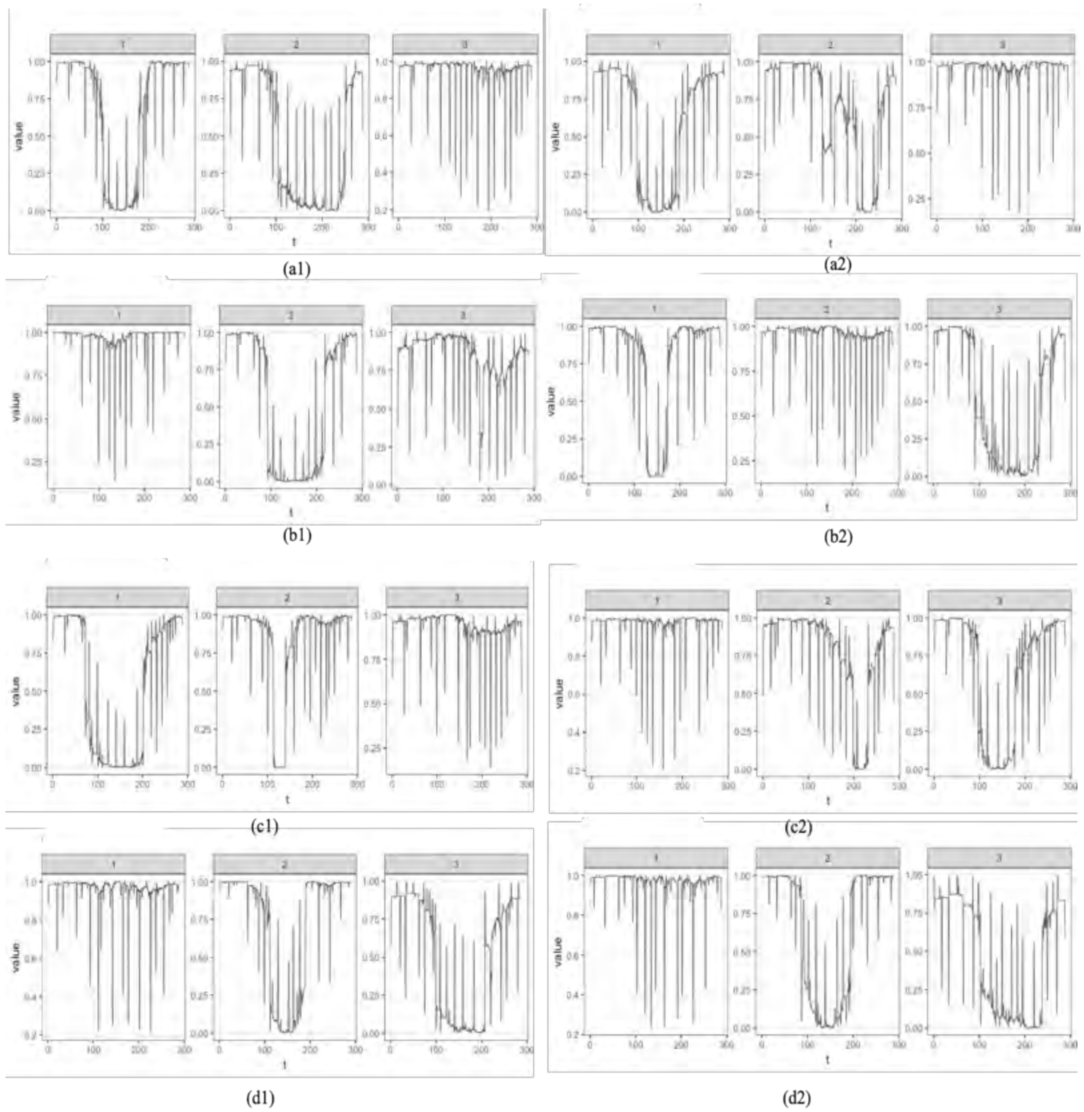

Figure 2. Centroid of the clusters for people who are (a) under 25, (b) 25 to 44, (c) 45 to 64, and (d) over 65 years old, on (1) weekdays and (2) weekends *(e.g. (a1) = under 25 years old, on weekdays)*

For younger people under 25 years of age, the percentage of people who follow schedule types O1 (30.4%, 30.2%) and P1 (51.2%, 46.4%) are nearly the same for both weekdays and weekends. For occupants ages 25 to 44, significant differences can be seen for schedules P1 on weekdays and weekends. On weekdays, 26.4% of people stay at home the entire day, whereas 53.4% do so on weekends. On the other hand, less people follow working during the day schedules on weekends compared to weekdays in that age group. A similar trend for P1 can also be seen for people ages 45 to 64, where 39.7% on weekdays to 53.4% on weekends follow this schedule. In addition, both on weekdays and weekends, 11.7% to 16.4% of people leave home for a shorter period of time, represented in schedules N2. For people over 65, both the schedule types and the percentages of people who follow them are similar, which suggests that whether it is a weekday or weekend does not have a strong impact on the schedule of older people.

Table 3. Percentage of people who follow specified cluster-based schedule types

People's age range	Schedule type and percentage of people in each cluster			
	Weekend		Weekday	
	Schedule type	% of people	Schedule type	% of people
Under 25	O1	30.4	O1	30.2
	O8	18.5	N1	23.4
	P1	51.1	P1	46.4
Ages 25-44	P1	53.4	P1	26.4
	O2	22.8	O1	56.6
	O4	23.8	P2	17.0
Ages 45-64	P1	53.4	P1	39.7
	O1	30.3	O1	48.6
	N2	16.4	N3	11.7
Over 65	P1	64.4	P1	58.0
	O2	20.2	O2	17.6
	O3	15.4	O3	24.3

Note: Please refer to the definitions of the schedule types (e.g. O1, P1, etc…) in Table 1 of this paper.

Comparing the schedules across different age ranges shows that the percentage of people who follows schedule P1 on weekdays is the lowest for occupants belonging to the age range of 25 to 44; this percentage increases with age. On weekends, apart from the 65 and older group, the percentage of people following schedule P1 is similar for all other age groups. On weekdays, the percentage of people who follow working schedule (O) is highest for occupants ages 25 to 44, whereas on weekends, it highest for people below age 25.

Conclusion

As occupancy schedules in residential buildings significantly impact their energy consumption, the characteristics of residential occupancy profiles were studied in this work. 12 years of ATUS data (2006 to 2017) were used, then divided based on the people's age and whether it is a weekdays or weekends. A dynamic time wrapping clustering method was used cluster the time series profiles of occupants in residential buildings. The occupancy profiles were clustered using different numbers of clusters, then the characteristics of these clusters were analyzed. The following conclusions can be drawn from this work:

- A total of 17 different types of occupancy profiles were identified in the data; among these profiles, the most common profile type, both on weekends and weekdays and across all age ranges, is people spending their entire day or nearly their entire day at home.
- Of the 3, 4 and 5 clusters considered for the subdivided data, 3 clusters have the best goodness-of-fit (average silhouette width), indicating that there are generally three main types of schedules of occupants within in each age range and weekday/weekend designation.

- Divided by age, the most common types of schedules vary; occupancy profiles for those over 65 appear to be independent of whether it is a weekday or weekend.
- On weekdays, following an office type work schedule where people absent from home 8-12 hours per day is most common for people ages 25 to 44 (56.6%), and least common for people over 65 (17.6%). The percentage of people who stay at home the entire day is highest for people over 65 (58.0%), and least for people 25 to 44 (26.4%).
- On weekends, the percentage of people who stay at home the entire day is similar for those age 25 to 64 (51.1% to 53.4%) and somewhat higher for those over 65 (64.4%).

In summary, this study provides a broad overview of the type of schedules people follow in residential buildings in the United States. This will help building energy modeler to predict the energy consumption more accurately and help those developing occupancy sensor system and occupancy-based controls to better assess typical occupancy patterns. Moving forward, these schedules will be further studied to create an occupancy simulator tool for residential buildings in the United States.

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An Evaluation of Electrical Energy Usage Comparing Homes Built With and Without Building Code Enforcement

Ben F Bigelow[1], Melina Cedillo[2]

[1] Associate Professor & Director, Hakell & Irene Lemon Construction Science Division, Gibbs College of Architecutre, University of Oklahoma, 830 Van Vleet Oval, Norman, OK, 73019. 405-325-6404, bigelow@ou.edu.
[2] Engineer, Holder Construction, 15455 Dallas Pkwy Suite 350, Addison, TX, 75001. 972-870-4260. melinacedillo@tamu.edu.

ABSTRACT

Homes account for 23% of energy consumption in the United States. However, most homeowners are less likely to invest in energy efficiency upgrades after construction. As a result, current building codes include energy efficiency requirements. The reduction in electrical energy usage because of code compliance has been documented, as well as the lack of any reduction in consumption based on year of construction when a building code is not enforced. This paper compares two studies that measured electrical consumption in homes. Using both data sets, the financial impact of electricity consumption in homes built to code, versus homes built to an older code or built without code enforcement are compared. The research suggests that more recently built homes do not consume less electricity in the absence of code enforcement. Not surprisingly, homes built with a code enforced were more efficient than homes without code enforcement. In fact, homes built without code enforcement in recent years were found to consume more electricity than homes built with a code enforced that were competed in the 1980's.

INTRODUCTION

Energy consumption of homes in the U.S. is changing, as are the perceptions of homeowners, but they may not be changing fast enough. Prior to 1992, consumers and home builders alike had little concern for energy consumption levels (Omer, 2008). While concern since then has increased, homeowners still can't be expected to make energy efficiency upgrades on their own (Suter and Shammin, 2013), and if they do make upgrades, there must be a short term benefit (Meyers, Williams, & Matthews, 2009). Home builders continue to report that, with limited budgets, given the choice between granite countertops or upgraded windows or insulation, the majority of home buyers opt for granite.

The need for a reduction in consumption is highlighted by data from the United States Energy Information Administration. In 2015, homes accounted for 23% of energy consumed, which was a 2% increase from 2013. The increasing consumption of U.S.

homes, and the hesitance of consumers to pay for energy efficiency upgrades have implications relating to power generation needs, and long term home ownership costs.

With consumption increasing, and few homeowners willing to pay for higher efficiency options, building codes are one avenue to ensure a reduction in consumption. Although building codes were originally enacted as life safety measures, they have expanded to encompass energy efficiency as well. Previous research has found that the more recent a building codes is, the stronger the positive relationship with reduced electrical energy consumption they have (Bigelow & Lopez, 2015). However, as building codes have become more stringent, there have also been improvements in construction materials and methods. Cedillo & Bigelow (2018) explored year of construction and electrical energy used, they found that year of construction did not relate to electrical energy consumption, suggesting improvements to materials and methods do not drive increased efficiency.

This paper compares the data produced in those two studies, to compare the electrical energy consumption of homes built to a code with homes built where a code was not enforced. This research sought to identify difference in electrical cost to homeowners based on code enforcement. The specific research question for this study was: 1) What is the annual difference between homes built to a building code and homes built without a code enforced based on kWh/sf.

This study is significant as it provides an empirical look at the cost of ownership for homes built to code and those not. This information is important as it can provide electrical utilities with grounds to support energy efficiency measures as they seek greater efficiency in electrical usage and generation. Further, it should stand as practical evidence that an individual purchasing a home built to code will have more income available each month to put towards a mortgage. Thus loan qualification amounts should vary based on the energy efficiency of the home purchased.

LITERATURE REVIEW

Energy consumption is not a new subject in the literature, however there is limited published research considering actual energy consumption in a sample of occupied homes for any purpose. The literature focuses on three areas; specific improvements that can be made to a home, simulations, or larger scale results considering code changes.

The building envelope, including windows have been the subject of multiple studies. Cooperman et al. (2011) found that envelope measures like window sealing, insulation, and roofing can reduce consumption by as much as 40%. Zhiqiang, et al. (2014) did not considered the building envelope directly, rather they found that 12% of energy use goes to space heating and 12% goes to air conditioning and refrigeration, so ~24% of energy use is directly affected by the building envelope. Thus, controlling or improving it is a means to reduce energy consumption. Sadineni, et al. (2011) reported that moderate improvements to insulation in walls and windows had a payback period of approximately 10 ten years.

Other measures to reduce energy use are varied. McNeil and Bojda (2012) considered the effect of energy efficient appliances and found that there are substantial energy savings available through their use. Suter and Shammin (2013) Tested how much energy was saved by making homeowners aware of their energy consumption. They report that when homeowners were aware of their consumption, and were provided with monetary incentives to keep it low, the greatest reductions in energy consumption were achieved.

On a larger scale, studies have considered specific building codes. Raheem et al. (2012) looked at the 2012 International Energy Conservation Code (IECC) and compared it to the Florida Energy Efficiency Building Code (FEEBC) using a computer simulation. Jacobsen and Kotchen (2013) also considered the effects in code changes in Florida. Both studies report a reduction in consumption from code adoption. Koirala et al. (2013) compared the IECC 2003 and 2006, and Aroonruengsawat et al. (2012) studied the impact of state building codes. These studies all found reductions in consumption from adoption of the codes in question. While these studies considered energy consumption, Home Innovation Research Labs (HIRL) (2015) did a cost comparison for building a home to the 2012 vs. 2015 IRC and found an increase of over $10,000 to do so, indicating that, despite long term savings from greater energy efficiency, code compliance does cost the consumer more up front.

In what are the most relatable studies to this project, Kim et al. (2013) explored the electrical demand savings in Texas from the implementation of the IECC. As expected, it showed a consumption savings, however, the study used a simulation rather than actual homes. In a follow up study, Baltazar et al. (2014) looked at homes just in College Station Texas and the saving possible from the 2001 and 2006 IECC. While they looked at actual consumption in homes, the study only considered the IECC and not the broader building code. Bigelow & Lopez' (2015) study considered electrical usage in Georgetown Texas based on the different codes that have been adopted there. They report as much as a 25% reduction equaling up to $395 a year in savings from the adoption of a new building code. These findings suggest that the $10,000 increase reported by HIRL could require more than 25 years to recover.

While these previous studies form a respectable body of knowledge regarding energy consumption in homes and the impacts that different variables (such as codes) have on them. There was no published research identified comparing energy usage in homes built without code enforcement to code built homes, particularly where a sample of actual homes with occupants living in them is used. This comparison (consumption of code built homes to homes built without a code enforced) is the focus of this study. The authors compared kilowatt hours as a unit of measure, as well as cost to homeowners in dollars.

METHODS

This study used a quantitative approach to empirically compare homes built to a building code and homes built without a building code enforced. Actual user data was obtained from two different electrical utilities. The utility provider usage for homes was provided by month in kilowatt hours (kWh). The raw data is considered highly reliable as both utility providers use smart meters to collect consumption data from their customers.

Data were collected from two different areas representing different time periods. Data on homes built to a code came from Georgetown, TX. These homes were built with the 2000 International Residential Code enforced. While data on homes that did not have a building code enforced came from Montgomery County, TX. These homes were built from 2003 to 2013. Electricity consumption varies greatly based on homeowner habits and occupancy. To mitigate skewed results from those variables, samples of 96, and 100 homes were used and the averages from each sample served as the basis for comparison. Basic descriptive statistics were used to make the comparisons.

The data for each location came from different projects. Data from Georgetown, TX was taken from the study published by Bigelow & Lopez (2015). While data from Montgomery, TX came from a study by Cedillo & Bigelow (2018). Excerpts from the data set in each study were used to make the comparisons for this study. Because the two different data sets under consideration came from different projects, this study faced certain limitations. Chief among those limitations is that this is a convenience sample from two different areas and times. The study is also limited in that the size range of the homes in the sample overlap, but are not the same.

The limitations were accepted for the study, due to the challenge of obtaining actual electrical consumption data. Electrical consumption data is not publically available, so finding a utility provider that is willing to share data is challenging. That difficulty, in obtaining consumption data, was elevated because most utility providers have a defined service area and are unlikely to service both rural customers, where codes are unlikely to be enforced, and urban or suburban customers, where code compliance is enforced. As such, the project would require cooperation from two utility providers. So the convenience sample presented by comparing data from the two previous studies was accepted.

While both samples come from Texas, the locations are not adjacent to one another. The sample of homes built with code enforcement came from the City of Georgetown, which provides utility service to its residents. Georgetown is located in Williamson County, TX. Alternatively, the data collected on homes built without building code enforcement came from Montgomery County, TX. In Montgomery County Mid-South Synergy provides electrical service to rural homes and very small municipalities. Georgetown is approximately 130 miles directly West of Montgomery County. While they are not adjacent, they are nearly identical latitudinally, and are found in the same climate zone, with very similar annual temperatures. Table 1 compares the average annual temperatures between the two locations. With no more than two degrees of difference in average monthly high temperatures and four degrees of difference in average monthly low temperatures the two locations are considered very similar. In general, Georgetown is slightly hotter and slightly colder than Montgomery County. The average annual climatic

Table 1. Average Annual High and Low Temperatures

Month	Georgetown		Montgomery County		Δ High	Δ Low
	Average High	Average Low	Average High	Average Low		
Jan	61°	36°	61°	40°	0°	4° M
Feb	66°	40°	65°	43°	1° G	3° M
Mar	74°	49°	72°	50°	2° G	1° M
Apr	80°	56°	79°	57°	1° G	1° M
May	86°	63°	85°	65°	1° G	2° M
Jun	93°	69°	91°	71°	2° G	2° M
Jul	96°	72°	94°	73°	2° G	1° M
Aug	96°	70°	95°	73°	1° G	3° M
Sep	91°	65°	89°	68°	2° G	3° M
Oct	82°	55°	81°	58°	1° G	3° M
Nov	71°	45°	71°	49°	0°	4° M
Dec	65°	40°	63°	41°	2° G	1° M
Averages	80.08°	55°	78.83°	57.33°	1.25° G	2.33° M

G Indicates Georgetown had higher average temperatures
M Indicates Montgomery County had higher average temperatures

difference of greatest note was that Montgomery County receives more rainfall annually that Georgetown. With so little difference in average monthly temperatures, the researchers determined that the two locations could reasonably be compared.

Directly related to the limitation of a convenience sample was the limitation that data in each location were collected in different years. Georgetown's consumption was in 2014, while Montgomery County was from 2016. In considering the temperatures from each location, it was found that the differences in average monthly temperatures between these two years were greater than the initial average annual comparison. Generally, the high temperatures ranged from 0-4 degrees difference, but the delta between low temperatures was more substantial with multiple months in double digits. Table 2 displays the average temperatures for the years in which data was compared.

Table 2. Average Annual High and Low Temperatures from 2014 & 2016

Month	Georgetown 2014		Montgomery County 2016		Δ High	Δ Low
	Average High	Average Low	Average High	Average Low		
Jan	64°	26°	67°	41°	3° M	14° M
Feb	68°	26°	71°	42°	3° M	15° M
Mar	72°	30°	78°	47°	6° M	17° M
Apr	84°	50°	80°	55°	4° G	5° M
May	82°	60°	82°	65°	0°	5° M
Jun	88°	73°	85°	70°	3° G	3° G
Jul	86°	74°	88°	80°	2° M	6° M
Aug	89°	76°	90°	76°	1° M	0°
Sep	88°	64°	85°	66°	3° G	2° M
Oct	83°	63°	81°	58°	2° G	5° G
Nov	72°	34°	76°	47°	4° M	13° M
Dec	68°	37°	76°	34°	8° M	3° M
Averages	78.67°	51.08°	79.92°	56.75°	3.25° G	7.33° M

G Indicates Georgetown had a higher average temperature
M Indicates Montgomery County had a higher average temperature

From May to September, the delta between temperatures was fairly small. These months are important as they are the hottest of the year and thus tend to be times of highest electrical consumption (for air conditioning). Montgomery County had higher average high and low temperatures through the winter months (November to March).

The final limitation imposed on this study from the use of two separate data sets was home size. The sample of homes used in Georgetown ranged from 1,600 to 2,000 ft^2 while the homes in Montgomery County ranged from 2,000 to 2,600 ft^2. To address this limitation, comparisons between the two groups were made based on the kWh per square foot, based on the mean size of homes in each sample of: 2,300 ft^2 and 1,800 ft^2.

The limitations discussed threaten the generalizability of the findings of this study. However, as described, insofar as it was possible they were adjusted for to provide an analysis that is reliable. As a result of these limitations, this study is presented as a first attempt in quantifying the electrical consumption savings available through building codes.

ANALYSIS AND DISCUSSION

The sample of homes in Georgetown that were built with the 2000 IRC enforced consumed an average of 635.68 kWh in 2014. The average annual consumption of homes that were built without code enforcement, in Montgomery County in 2016 was 1,694.83 kWh. (These homes were built between 2003 and 2013). Some of the increase in consumption should be attributed to the size of the Montgomery County homes being larger than the Georgetown homes, so a closer look at the differences is necessary.

The consumption in Montgomery County is more than two and a half times that of Georgetown. When the numbers are adjusted to consider the size of the home (square feet), the difference is smaller, but still considerable. Homes in Georgetown consumed approximately 4.24 kWh/ft², while homes in Montgomery County consumed 8.84 kWh/ft², Just over double Georgetown's consumption per square foot.

To dig deeper into the data, a month to month comparison was conducted. In 11 of 12 months, the homes built with a code enforced had lower consumption and in 8 of 12 months the reduction in consumption was greater than 50%. Table 3 displays the results of that comparison. The differences are noteworthy; however, the authors

Table 3. 2014 Georgetown vs. 2016 Montgomery County Consumption

Month	**Montgomery County 2016**	**Georgetown 2014**	**Montgomery County kWh/ft² (2,300 ft²)**	**2000 IRC Georgetown kWh/ft² (1,800 ft²)**	**% Reduction of Georgetown**
Jan	1502	486	0.65	0.27	-58.5%
Feb	1637	629	0.71	0.35	-50.7%
Mar	1286	793	0.56	0.44	-21.4%
Apr	1197	1094	0.52	0.61	+14.8%
May	1342	982	0.58	0.55	-5.2%
Jun	1566	822	0.68	0.46	-3.24%
Jul	2159	602	0.94	0.33	-64.9%
Aug	2526	472	1.10	0.26	-76.4%
Sep	2333	416	1.01	0.23	-77.3%
Oct	2018	414	0.88	0.23	-73.9%
Nov	1564	462	0.68	0.26	-61.8%
Dec	1209	456	0.53	0.25	-52.8%
Total	20338	7628	8.84	4.24	-52%

draw particular attention to those found in months when space cooling is used.

This study was delimited to electrical energy consumption. As such, it did not include expenditures for space heating that occurs using natural gas. It was not known which homes included in the study had natural gas service. For those that did, electrical consumption is expected to decrease in months when space heating is required. The homes built in Montgomery County are rural, and thus less likely to have gas service and more likely to utilize electricity for space heating. The authors believe this may have driven up consumption in the winter months for Montgomery County. Because gas usage was not known, the differences in consumption from November to March may be due to variables that could not be controlled between the groups. As such, they should be interpreted with caution, and the authors chose not to draw any conclusions from the data in those months. The difference in consumption the rest of the year (April through October) are the focus of this discussion.

Code built homes (Montgomery Co.) saw an increased level of consumption compared to non-code enforced homes (Georgetown) in April. The researchers believe this is due to an unseasonably warm month of April in Georgetown that year (the average high temperature was 4 degrees higher than average, and higher than the average in May of the same year), which triggered air-conditioning use that Montgomery County would not have. The average high temperature for April in Montgomery County was 80 degrees, and thus still cool enough to limit air conditioning usage, Georgetown on the other hand had multiple days that reached 96 degrees. The difference between the two locations highlights the impact of air conditioner usage on electrical consumption.

From May to October, there was relatively little difference in temperatures between the two groups. However, there was considerable difference in the electrical consumption over that time period. Code built homes in Georgetown had a slightly reduced level of consumption per square foot, compared to non-code enforced homes in May and June. But, from July to October, the largest differences in consumption per square foot were seen with code built homes consuming between 64.9% and 73.9% less electricity than non-code enforced homes. Daily temperatures were not substantially different over these months, and in September and October the temperatures were actually higher for the code built homes. These results support the claim that code built homes can expect to have substantially lower electrical consumption than homes where a building code is not enforced.

The results further suggest conclusions about air conditioner SEER ratings as a major driver in reduced electrical consumption in code built homes. Homes in both locations are certainly using air conditioning from July to October. However, homes that are not mandated to use an air conditioner with a higher SEER rating (per the code) and thus a higher initial price are unlikely to do so.

Due to the significant difference between homes that did not have codes enforced, and homes built to the 2000 IRC, the researchers decided to conduct an additional comparison. Bigelow and Lopez (2015) reported on consumption data of code built homes dating back to 1985, a time when building codes dealt largely with life safety and had little if any focus on energy conservation components. The researchers sought to compare the electrical usage of homes built without code enforcement to homes built under the 1985 code. Comparison of these two groups would explore whether enforcement of a code, via inspections by a building official could be related to greater electrical energy efficiency and perhaps if materials improvements could be related to increased consumption. Table 4 displays the results of this comparison. Overall, the code built homes from the mid 1980's had an average reduction of 25% in electrical consumption compared to non-code enforced homes built in the early

Table 4. 2014 Georgetown vs. 2016 Montgomery County Consumption

Month	**Montgomery County 2016**	**Georgetown 2014**	**Montgomery County kWh/ft² (2,300 ft²)**	**1985 SSBC Georgetown kWh/ft² (1,800 ft²)**	**% Reduction of Georgetown**
Jan	1502	741	0.65	0.41	-36.9%
Feb	1637	744	0.71	0.41	-42.2%
Mar	1286	1057	0.56	0.59	+5.4%
Apr	1197	1538	0.52	0.85	+63.5%
May	1342	1477	0.58	0.82	+41.7%
Jun	1566	1391	0.68	0.77	+13.2%
Jul	2159	1094	0.94	0.61	-35.1%
Aug	2526	785	1.10	0.44	-60%
Sep	2333	645	1.01	0.36	-64.4%
Oct	2018	683	0.88	0.38	-56.8%
Nov	1564	807	0.68	0.45	-33.8%
Dec	1209	867	0.53	0.48	-9.4%
Total	20338	11829	8.84	6.57	-25.7%

2000's. Monthly consumption data comparing the two groups show four months in which the non-code enforced homes consumed less electricity (March to June). However, the rest of the year the code built homes consumed less electricity. As with the previous comparison, because it is unknown if natural gas is used for space heating or not, the differences from November to March are not considered. Over the remaining months (April to October), about a 25% reduction in consumption per square foot still occurs in the code built homes. These results suggest that some of the electrical consumption savings in homes built to code may be related to inspections occurring and not just what is stipulated in the building code, as energy efficiency measures had not been introduced to the building code in 1985.

These results also suggest that material changes from the mid 1980's to the early 2000's have had little or no impact on electrical energy consumption.

CONCLUSION

The differences in consumption noted support previous findings that building codes lead to reduced electrical consumption from one code iteration to the next. They also suggest that when compared to homes built without code enforcement, a code built home can expect to see a reduction in consumption of over 50% and that the process of code enforcement may be related to reduced consumption even when laying aside the energy efficiency requirements.

In the City of Georgetown, based on electricity rates, the differences would equate to an increase of more than $350 a year in utility expenses for the home owner. Perhaps more striking are the electricity rates in Montgomery County, where residents in homes around 2,300 sf are spending nearly $1,000 more each year on electricity than they would in a home that had been built with the 2000 IRC enforced.

Because it is not known how much the homes included in the sample cost to build, it is not possible to determine if building costs were consistent between the two groups or how long a pay-back period might be for specific upgrades. The authors recommend future research to investigate the relationship of cost to energy consumption as well as research to replicate this study with natural gas usage included.

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Wind Pressure Distribution on Single-Story and Two-Story Elevated Structures

Nourhan Abdelfatah[1], Amal Elawady[2], Peter Irwin[3], Arindam Gan Chowdhury[4]

[1]PhD Student, Department of Civil and Environmental Engineering, Florida International University, 10555 West Flagler, Miami, Florida, USA, 33174. 7865800075, nabde006@fiu.edu.
[2]Assistant Professor, Department of Civil and Environmental Engineering, Florida International University, 10555 West Flagler, Miami, Florida, USA, 33174. aelawady@fiu.edu.
[3]Professor, Department of Civil and Environmental Engineering, Florida International University, 10555 West Flagler, Miami, Florida, USA, 33174. peairwi@fiu.edu.
[4]Professor, Department of Civil and Environmental Engineering, Florida International University, 10555 West Flagler, Miami, Florida, USA, 33174. chowdhur@fiu.edu.

ABSTRACT

Along the shoreline, elevating low-rise coastal structures is recommended as a retrofitting measure to reduce flooding hazards. The Federal Emergency Management Agency (FEMA) provides guidance on the elevation needed for structures according to their location from the coastline. The elevation height of a typical building can reach as high as 4.6m above the ground level. The substantial benefits of elevating low-rise structures in coastal communities encourage builders and owners to elevate slab-on-grade and manufactured homes. However, aerodynamics of such structures are not well understood. Besides the increase of wind loads acting on the envelope of the house due to the increase in the wind speed with the increase in the structure's height, it is expected that aerodynamics of elevated structures will change and behave differently compared to the structure's slab-on-grade counterpart. As a result, structures elevated without careful consideration of the values and distribution of actual wind pressure are vulnerable to wind-induced damage. This agrees well with damage assessment observations made after recent hurricane events, such as Hurricane Irma and Hurricane Michael that impacted the state of Florida in the United States in 2017 and 2018, respectively. However, there are no available design guidelines or provisions pertaining to wind loading on the envelope or components of typical elevated buildings. In addition, very few studies in literature have investigated wind actions on elevated structures or mobile homes. Recently, two large-scale aerodynamic wind testing have been conducted on a single-story and a two-story elevated house models at the Wall of Wind (WOW) Experimental Facility at Florida International University. For each test case, the models were raised to four different elevations to investigate the effect of the gap height underneath the floor on the wind pressure distribution on the surfaces of the building. The models were instrumented using densely distributed pressure taps to measure wind pressure time histories. This paper discusses the distribution of the peak pressure coefficients on the building surfaces for each stilt height for the two test models. Comparisons showing the role of the roof mean height and the number of stories on the pressure distribution are presented.

INTRODUCTION

The primary role of elevating coastal houses is to mitigate flooding hazards. During past hurricane events, many coastal houses have been subjected to severe damages due to storm surge accompanied with wind gusts. In 2017, the United States was impacted by three powerful hurricanes: Hurricane Maria, Hurricane Irma, and Hurricane Harvey. The insured losses for the three hurricanes were estimated to reach up to $265 billion (Cangialosi et al., 2018; Blake and Zelinsky, 2018; and Pasch et al., 2019). In 2018, according to the National Oceanic and Atmospheric Administration (NOAA), Hurricane Michael affected 50,000 structures in Florida Panhandle, southwest Georgia, and southeast Alabama (NOAA, 2018). Numerous numbers of elevated structures in the impacted areas were elevated and yet experienced severe structural damage. This could be attributed to the aerodynamics uncertainty and the resulting wind actions on the building. Holmes (1994) conducted an experimental study to investigate the effect of elevating a gable-roof house by 2.1 m above the ground level (Holmes, 1994). The roof pitch angle was 10°, and it was tested considering a rural terrain exposure category with 0.035m roughness length and a length scale of 1:50. The study concluded that after elevating the model, the mean wind pressure increased by 40%-80%. In the current study, a large-scale experimental program has been conducted at the Wall of Wind facility to monitor the effect of elevation on the resulting peak wind pressure distribution over the model surfaces. The experimental study included two gable-roof residential houses using the same horizontal dimensions with different number of stories; i.e., single-story and two-story houses, and stilt height. The results presented at the end of this paper show the effect of increasing the stilt height on the distribution and magnitudes of the local pressure coefficients. In addition, the result section also shows a comparison between local peak pressure coefficient for the case of the single-story and two-story houses.

WALL OF WIND FACILTY

The Wall of Wind (WOW) is a large-scale testing facility located in Miami, Florida. It is capable of producing a category 5 hurricane according to Saffir-Simpson Scale (Chowdhury et al., 2017). The facility is powered by 12 large electric fan motors which are arranged in an arc shape. Figure 1 shows the flow management box that contains automated roughness elements and spires where the Atmospheric boundary layer (ABL) is formed. During the elevated house test, three triangular spires were adjusted at 45° and the automatic floor roughness elements were tilted at 25° angle. These settings were done to produce the ABL of an open terrain exposure category. The tested models were fixed to an automated turntable that can rotate 360 degree to account for different wind angles.

Figure 1. Flow management box and automated roughness elements of the WOW facility.

MODEL DISCRIBTION

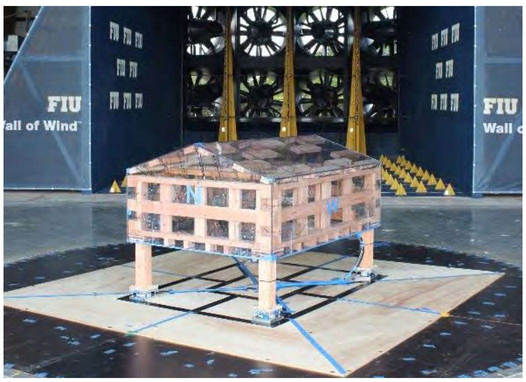
Two different 1:5 scaled models have been tested in the WOW to monitor the pressure variation on its surfaces for different stilt heights. In the first phase, a one-story house configuration was tested with four different elevation heights; zero stilt, 0.6 m stilt, 2.15 m stilt, and 3.65 m stilt. The models were installed on four columns located at the model corners as shown in figure 2-c. A number of 375 pressure taps were distributed along the model roof, walls, and floor. Those taps have been connected to a six Scanivalve ZOC33 pressure scanners to record the pressure time history in each location. As shown in figure 2-a & 2-c, the models were placed at the middle of a turntable and tested under wind directions ranging between 0° to 90° with increment of 3°. In the second phase, a two-story model was tested at four larger elevation heights; zero stilt, 2.15 m stilt, 3.65 m stilt, and 5.2 m stilt. Four edge columns and two middle columns were used to elevate the model with 2.5 cm clearance at the floor edges, and corners. A number of 307 pressure taps were distributed along only the quarter of the model roof, walls, and floor to densify pressure taps at the model edges, corners, and around the columns. As shown in figure 2-b & 2-d. The models were tested under wind directions ranging between 0° to 360° with increment of 3°. Table 1 shows the scaled model dimensions in the two phases.

Table 1 Stilt house configuration of the 1:5 scale models in the two tested phases

Building, Scale	Length (L)	Width (B)	Height (H)	Stilt Heights (SH)	Wind Direction
Phase one	175 cm	128 cm	76 cm	0.0, 4.8, 16.8, and 22.8in	0° to 90°
Phase two	175 cm	128 cm	131 cm	0.0, 16.8, 22.8, and 40.8in	0° to 360°

(a)

(b)



(c)

(d)

Figure 2. Model installed on the Wall of Wind turntable in the two phases of testing (a) Zero stilt phase one, (b) Zero stilt phase two, (c) 2.15m stilt phase one, and (d) 2.15m stilt phase two.

During the two tested phases, WOW fans were operating at 40% throttle corresponding to a mean wind speed of 28m/sec. Copra probes were used to measure the wind velocity for 3 minutes duration using 2,500 Hz sampling frequency. Figure 3 shows the average wind speed at each model roof mean height. The best fit power line shows that through the two tests, the ABL was produced successfully matching each other. The normalized wind speed turbulence power spectrum matches the open terrain exposure with roughness length 0.08m in the two phases.

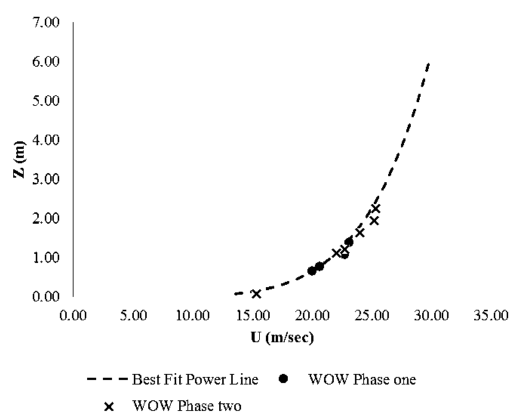


Figure 3. Mean wind speed profile in the two phases

DATA ANALYSIS

During the two tested phases, ZOC33 pressure scanners were connected to the pressure tap locations using long tubes. After testing, a transfer function was applied to eliminate the distortion effect of the tubing length as recommended by Irwin et al., (1979). The advantage of performing a large-scale test is to reduce the Reynolds Number effect. It is recommended to precisely simulate the flow separation and reattachment to increase the accuracy of the resulting peak pressure (Hoxey et al., 1997; Goliber, 2009). However, the size limitation of the test section affects the resulting power spectrum. Figure 4 shows the missing low frequency part of the response spectrum in the current 1:5 scale test. Therefore, the Partial Turbulence Simulation (PTS) method was used after testing to compensate for the missing frequency part assuming Gaussian probability distribution (Mooneghi et al., 2016, Moravej, 2018). For each tap location, the pressure coefficient was calculated using equation (1). Where the P_{Peak} is the peak pressure coefficient, ρ is the density of air, and V is the 3 sec gust wind speed at the roof mean height of each stilt case.

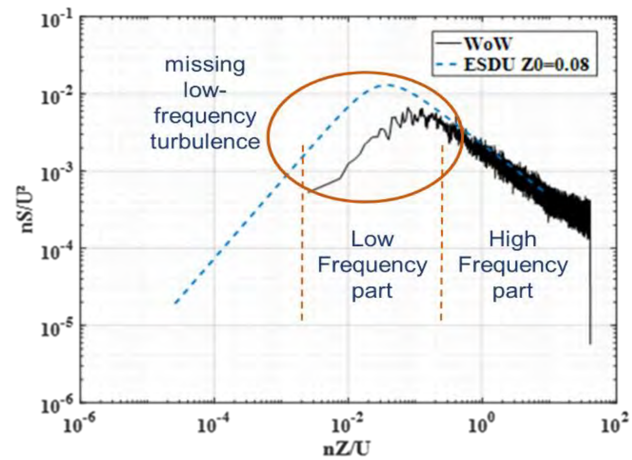
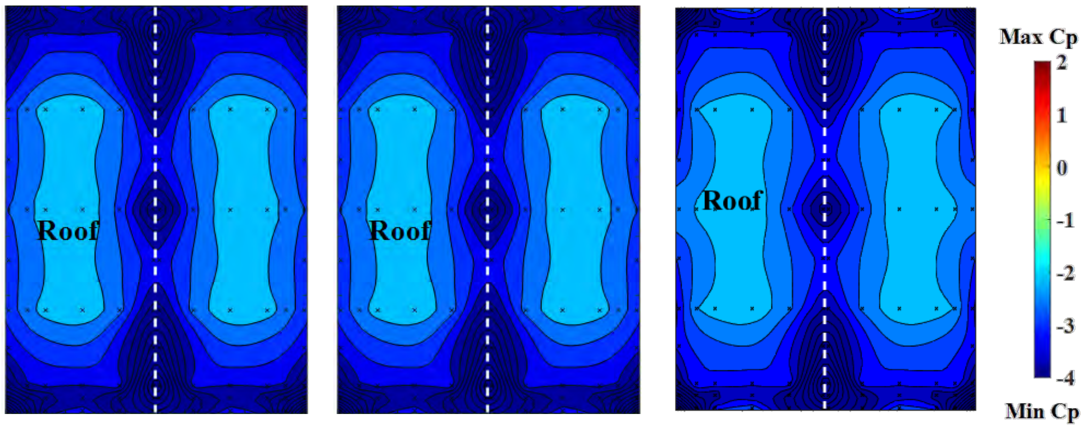


Figure 4. Power spectra of the tested model compared to the Von Karman full spectrum obtained from ESDU

$$C_{Ppeak} = \frac{P_{peak}}{\frac{1}{2}\rho V^2} \quad (1)$$

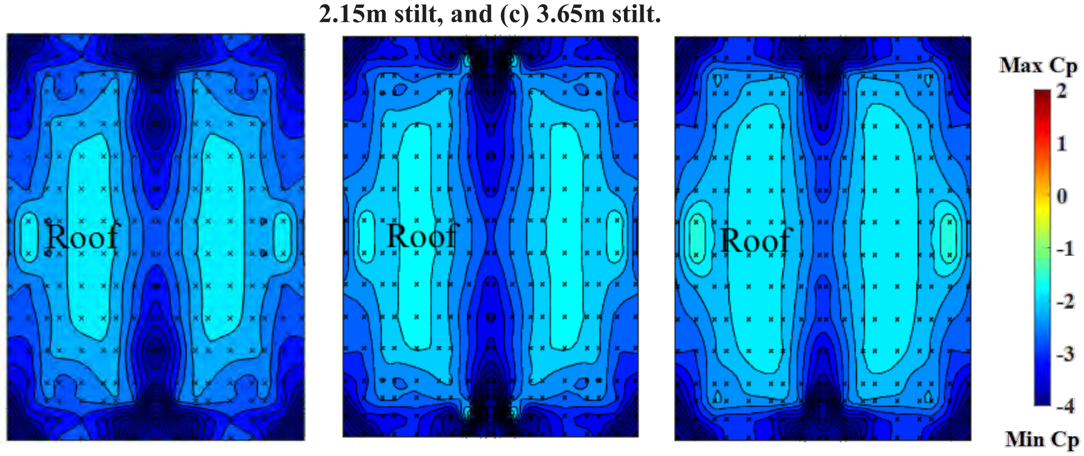
RESULTS

This section presents the resulting local peak pressure coefficient (C_{Ppeak}) for each test phase. Figure 5 (a-c) shows the C_{Ppeak} contour plots of the one-story model roof surface for the zero, 2.15 m, and 3.65 m stilt cases, respectively. Figure 6 (a-c) shows the C_{Ppeak} contour plots of the two-story model roof surface. In both cases, the results exhibit high suction located along the building ridge and at the roof edges. However, for the two-story building model the suction is less severe at the edges, there is no high suction at the middle part of the roof ridge like the one-story case. For the one-story case, as the stilt height increases, the pressure does not experience visible change. However, for the two-story case, the suction area at the edges decreases gradually as the stilt height decrease, especially at the roof ridge.



(a) (b) (c)

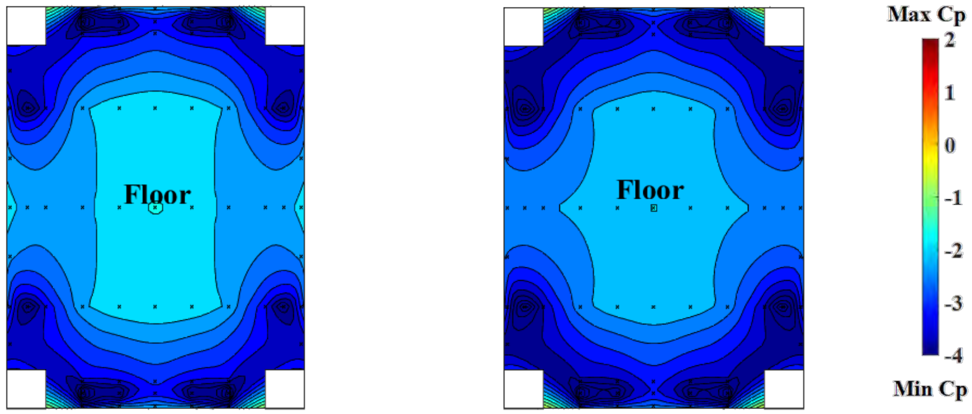
Figure 5. C_{Ppeak} distribution along the roof surface of one story model (a)zero stilt , (b) 2.15m stilt, and (c) 3.65m stilt.



(a) (b) (c)

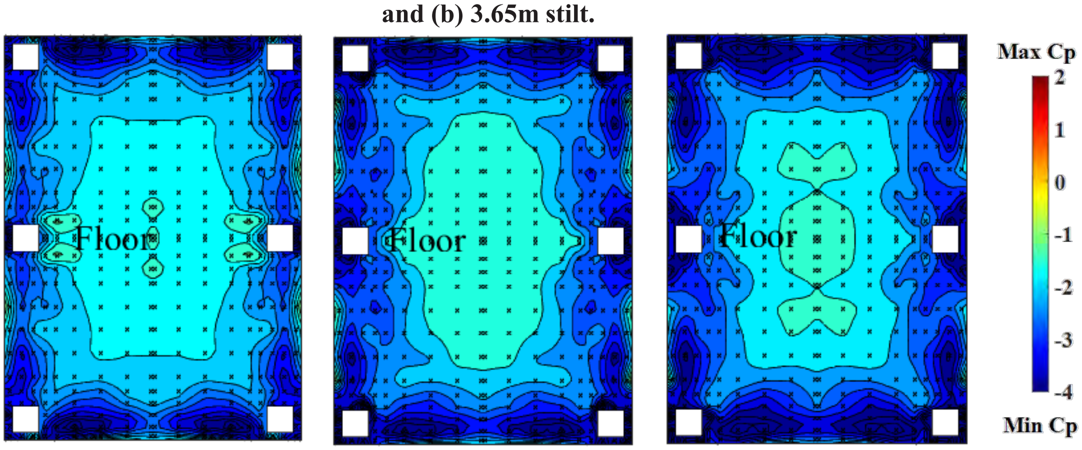
Figure 6. C_{Ppeak} distribution along the roof surface of two story model (a)zero stilt , (b) 2.15m stilt, and (c) 3.65m stilt.

For the floor surface, as shown in figures 7 and 8, the result showed high suction around the model columns. In phase one, the one-story model, the number of pressure taps were less and widely spaced and, therefore, did not precisely monitor the pressure change around the column. In addition, the column size was relatively large. However, the results as shown in figure 7 show an increase of the suction pressure around the columns as the stilt height increase. In the second phase, the two-story model, more dense pressure taps distribution was considered and a smaller column's cross section was used. The results of the second phase assured the findings of the first one; the flow turbulence that occurs, due to the presence of columns, leads to the presence of high suction around the columns. The two intermediate columns added to the model of the second phase led to a concentration of suction pressure developed also at the middle and was higher as the stilt height increase. This also agrees very well with the one-story case findings. By comparing the two phases, the suction located at the corner is more severe in the one-story model, however new area of suction is located due to the presence of the two intermediate columns in phase two.



(a) (b)

Figure 7. C_{Ppeak} distribution along the floor surface of one story model (a) 2.15m stilt, and (b) 3.65m stilt.



(a) (b) (c)

Figure 8. C_{Ppeak} distribution along the floor surface of one story model (a) 2.15m stilt, (b) 3.65m stilt, and (c)5.2m stilt.

CONCULSION

Two different coastal houses have been scaled down and tested in the WOW facility. The first one is one story and elevated at four different levels; zero, 0.6 m, 2.15 m, and 3.65 m. The second one is two story and elevated by; zero, 2.15 m, 3.65 m, and 5.2 m. This paper presents the resulting local peak pressure coefficient for each case and shows the effect of changing the number of stories, and the stilts' height on the resulting pressure on the model surfaces. C_{Ppeak} was calculated using the 3-sec gust wind velocity, at roof mean height of each stilt height, as a reference. The C_{Ppeak} distribution at the roof surface, in all cases, showed peak suction values at the edges and along the ridge. The two phases showed slight decrease of pressure coefficient as the stilt height increase. For the floor surface, high suction was noticed around the model columns in both cases. The area of this high suction increases as the model elevation increases. After comparing the two phases, the one-story model showed higher suction along the ridge, and around the model columns. It is recommended to develop a new criterion that helps in calculating the acting pressure on the floor surface for the design purpose.

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Performance of Residential Buildings in Hurricane Prone Coastal Regions and Lessons Learned for Damage Mitigation

Mehrshad Amini[1] and Ali M. Memari[2]

[1]Ph.D. Candidate, Department of Civil and Environmental Engineering, Penn State University, e-mail: mxa261@psu.edu

[2]Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering, Penn State University, e-mail: amm7@psu.edu

1. Abstract

Coastal residential buildings are vulnerable to significant damage due to different hurricane hazards. Recent damage to such residential buildings illustrates poor performance of coastal structures as it relates to hurricane hazards. This could mean that recent standards and building code provisions need to be improved in terms of loading and design requirements. Based on past hurricane experience, residential buildings have mainly suffered extensive damage to siding, roofing, foundation-to-superstructure connections, and wall-to-roof connections. Therefore, defining various damage types to residential buildings due to hurricane hazards is the first step to improve their performance in hurricane prone coastal regions, which will contribute to the overall resiliency of coastal residential communities.

This paper reviews the evidence from actual damage in past hurricanes with respect to direct and indirect damage to different types of residential buildings in coastal areas. The results show that building materials other than wood have better performance during strong hurricanes. Regardless of building materials, residential buildings have mainly suffered extensive wind-induced damage to envelope systems and roofs more than the structural systems. Therefore, selecting adequate connection systems, suitable wind resistant materials, and appropriate installation methods for wall/roof covering can significantly reduce the level of direct and indirect wind-induced damage. Furthermore, many non-elevated or low-elevation buildings sustain severe flood damage in coastal areas. Surge and subsequent wave heights are two important flood related hazards, which in most cases cause inevitable damage once flood reaches the first-floor level. It can be concluded that elevating the structure and its supporting base on deep embedded piles above the BFE is the most effective method to reduce flood damage to residential buildings in coastal areas. However, it might increase the wind damage due to the fact that the house is exposed to higher wind pressures so that further measures should be considered. Last but not least, selecting the appropriate foundation system, enhancing foundation connections, and using flood-resistant materials below the BFE can also reduce flood-induced damage to residential buildings in coastal regions.

Keywords: Hurricane Engineering, Residential Buildings, Wind/Flood-Induced Damage, Damage Mitigation Methods.

2. Introduction

Coastal residential buildings are vulnerable to significant damage due to hurricane related hazards such as high wind pressure/suction, air-borne debris impact, wind-driven rain, as well as potential flood due to surge and floating debris impact (NIST 2014). Almost all states in the United States are susceptible to damage caused by extreme windstorms such as tornadoes and hurricanes. Florida and Texas are the most vulnerable states, such that 85% of Category 4 and 5 hurricanes have directly hit either of these states (FEMA P-55a). From 1996 to 2012, hurricane related hazards have caused over 4,045 fatalities and resulted in property losses on the order of $250 billion (in 2012 dollars) in the U.S. (NIST 2014). Furthermore, the total damage cost of the four recent destructive hurricanes: Maria (2017), Irma (2017), Harvey (2017), and Sandy (2012) is estimated to be $330 billion (NCEI 2018). However, such damage extent illustrates the poor performance of coastal structures under the effects of hurricane related hazards. Over the past several decades, the population in coastal areas in the United States has increased significantly, which will result in larger economic losses during hurricanes in the future. Therefore, identification and quantification of these hurricane associated hazards is the first step in order to understand the behavior of residential buildings and identify common failure mechanisms and subsequent mitigation techniques.

Many studies have contributed to better understanding of the problem and attempts have been made to protect communities and homes against hurricane hazards (White, 1945; Xian et al., 2015; Park et al., 2017). Based on studies conducted on flood-prone areas, e.g., Flood Insurance Studies (FISs) program, FEMA has mapped flood hazards for nearly 20,000 communities in the United States called Digital Flood Insurance Rate Maps (DFIRMs) to show flood hazard areas and risk premium zones. Practically, the BFEs are shown on DFIRMs for riverine flood zones (Zone A, AE, AO, and AH) and coastal flood zones (Zone V and VE). In addition, FEMA developed guidelines and recommendations such as minimum lowest floor elevation, foundation type, suitable retrofit techniques, and other requirements for new and exciting buildings based on specific flood zones and structural characteristics. It should be noted that other factors such as proper planning, siting, design, and construction are subsequent steps in order to mitigate vulnerability of buildings to hurricane hazards in coastal areas (FEMA P-55b).

This paper presents a review of damage types to residential buildings under various hurricane hazards, including high wind, storm surge, and associated flood effects. The paper briefly reviews the evidence from actual damage in past hurricanes with respect to direct damage (structural system failure) and indirect damage (water intrusion) to residential buildings with different materials in coastal areas. In addition, common failure mechanisms and subsequent mitigation approaches are discussed based on available resources, which can help to provide a better understanding of the performance of residential buildings in coastal areas. Furthermore, the results can be used to determine the potential wind/flood damage sequences during hurricanes, which can be helpful to insurance companies and homeowners regarding settlement of insurance claims for hurricane related hazards.

3. Literature review on hurricane associated hazards

Hurricane is a tropical cyclone with a maximum wind speed of 74 mph or more, and is one of the most devastating multi-hazard natural catastrophic events. Hurricanes typically are categorized based on Saffir-Simpson Hurricane Wind Scale (SSHWS) updated in 2012 for more accurate outputs (NOAA 2012). The SSHWS consists of five separate categories based on peak wind speed. However, this scale does not consider other potential hurricane-related damages like storm surge, rainfall-induced floods, and tornadoes. This section briefly discusses various hurricane related hazards: high winds, storm surge, and associated flood effects, including hydrostatic forces, hydrodynamic forces, waves, erosion and scour, wind and flood-borne debris.

3.1. High winds

Strong winds are one of the most important hazards associated with hurricanes, which are able to cause serious direct and indirect damages to buildings. During a hurricane event, both positive and negative pressures simultaneously act on the building. ASCE 7-16 specifies 3-second gust speeds as the design wind speed (measured at 33 feet above the ground in Exposure Category C). The magnitude of design pressure is a function of several primary factors, including exposure, basic wind speed, topography, building height and shape, and internal pressure classification. Then, final forces are obtained by applying calculated design pressures to the appropriate tributary area for the main wind resisting system (MWRS) and different components and cladding (C&C). However, design against other damage modes such as water intrusion damage and integrity of the building envelope is still a challenge.

3.2. Storm surge/waves

Storm surge and subsequent waves cause the most destructive damage to residential buildings in coastal areas (Simpson and Riehl, 1981). Strom surge is a sea wave accompanied with combined lower barometric pressure and forward speed of hurricane rising above the normal sea level. Similarly, waves are generated in deep water by strong winds caused by hurricanes blowing across the surface, moving toward shallow water. Waves can damage coastal buildings by four main wave mechanisms, including breaking wave, wave runup, wave reflection/deflection, and wave uplift (FEMA P-55a). Among these mechanism, breaking waves are the most destructive factor for buildings in coastal. Storm surge and subsequent waves is a complex phenomenon, which can be affected by many factors such as hurricane wind speed, angle of approach to the coast, coastal bathymetry characteristics. Therefore, there is no simple method like SSHWS to predict the storm surge height and wave characteristics with respect to each hurricane category.

3.3. Flooding

Flood and subsequent hazards are the main reasons for fatalities during hurricane events, which also cause serious damage to buildings in coastal areas (FEMA P-499). Two types of flooding can occur during hurricanes, namely, rainfall-induced flooding and surge-induced flooding. The former happens due to rainfall in a very small region over a relatively small-time interval, while the latter occurs where the hurricane makes landfall. Moving floodwater generates hydrodynamic forces on submerged foundations and walls, which can cause failure of solid walls and building components due to inappropriate connections or load paths. However, once the water penetrates inside the building, hydrostatic pressures on both sides of walls and floors are equalized. Therefore, all building components are less likely to fail due to pressure equalization.

3.4. Erosion and scour

Erosion (general lowering of the ground surface over a large area) and scour (localized lowering of ground around foundation elements) are two secondary hurricane surge related hazards, which can cause serious problems independently or simultaneously such as partial or complete collapse of residential buildings in coastal areas. Unlike complex dynamic nature of erosion, which is hard to estimate, scour has mostly a predictable behavior and is generally limited to small, cone-shaped depressions less than 2 feet deep and several feet in diameter. Therefore, FEMA 55b recommends that scour depths around individual piles can be estimated as two times the pile diameter for circular piles and two times the diagonal dimension for square or rectangular piles.

3.5. Wind and flood-borne debris

Wind damage to building envelopes is not limited to direct wind pressure, but is also due to flying debris during the hurricane. Furthermore, building envelope defects and breaches caused by windborne debris result in undesirable problem like high internal pressure, rain penetration, and more debris. On the other hand, flood-borne debris typically consist of trees, breakaway wall panels, pieces of other damaged buildings, vehicles, etc., which are often capable of causing damage to unreinforced masonry walls, light wood-frame constructions, and small diameter posts and piles in two different ways, including impact and water damming (Robertson et al. 2007). There are several factors including characteristics of flood-borne objects, flood velocity, debris velocity, and duration of impact that should be considered in order to simulate the realistic loads (ASCE7-16).

4. Damage due to hurricane wind hazards

Wind-induced damage to coastal residential buildings can be categorized into three main groups, including structural damage, direct envelope damage, and indirect water intrusion damage. The most severe structural damage was recognized as the loss of roof structure and exterior wall collapses, which also resulted in subsequent extensive water intrusion. The structural framing damage is typically initiated by the onset of a breach on the windward side of the building, which results in an increase of internal pressure (pressurization). Figure 1a shows a masonry home with a wood roof structure, which suffered severe damage to roof structural components due to pressurization during Hurricane Charley (2004). It should be noted that installing shutters on windows and doors is known as an effective measure protect the envelope and prevent the subsequent increase in the internal pressure.

The lack of continuous load path from roof to the foundation is another important factor, which cause severe structural framing damage such as partial or even complete collapse of the building (FEMA P-55b). A building can have many continuous load paths, which can play an important role in resistance against various forces from hurricane hazards. It is important to mention that most load path failures occurred at connections such as roof sheathing to framing connection and roof framing to external walls other than failure of an individual structural members such as roof rafter or wall studs. Buildings can also suffer damage caused by pressurization and insufficient load path simultaneously, which is likely to result in a progressive sequence. Figure 1b shows a wood-frame house that experienced partial wall failures and severe damage to the roof and gable end wall due to lack of continuous load path. The partial wall failure can be considered as a trigger to initiate the internal pressurization, which caused additional damage to structural framing members leading to complete collapse of the building.

(a) (b)

Figure 1. Wind-induced damage to structural members (FEMA P-488): (a) severe structural damage due to pressurization during Hurricane Charley, 2004; (b) severe damage to roof, structure, and gable end wall during Hurricane Andrew, 1992.

Although the structural system suffered wind-induced damage, the building envelope system sustained more damage due to localized pressure along the edges and corners in hurricanes. Building components and cladding (C&C) consists of several elements, including roof and wall covering, sheathing, walls, windows, and doors. Additional observed damage was associated with wind-driven rain that entered and damaged building interiors through openings in the building envelope. As a result, significant increase in design loads for C&C has been considered in design standards and provisions over the past 20 years, such as the more recent editions of ASCE 7. Typical damage to residential houses during hurricanes occurred at or above the roof lines in terms of loss of asphalt shingles or tile roof coverings. However, houses with metal roof coverings had better performance during such hurricanes due to higher weight, longer and continuous length, and stronger connections. Figure 2 compares a typical asphalt shingle roof covering loss with an undamaged metal roof panel during Hurricane Charley (2004). The good performance of metal panels was also observed during Hurricanes Irma and Maria (2017). Furthermore, widespread loss of vinyl and aluminum soffit panels were observed, indicating that such panels were either pulled out by suction or pushed up by positive pressures. This type of damage can result in severe indirect damage due to wind driven rain to the interior components like drywall walls or ceilings.

(a) (b)

Figure 2. Typical roof covering loss during Hurricane Charley, 2004 (FEMA P-488): (a) asphalt shingle roof covering loss (Captiva Island); (b) undamaged metal panel roof (Pine Island).

Loss of roof sheathing is another common wind-induced failure in wood-frame houses during strong hurricanes due to lack of or inadequate connections between roof sheathing and roof structural frames. This type of damage has been observed in different building types with wooden roof structures. Figure 3 shows severe sheathing loss in the roof structure during Hurricane Charley (2004) and Katrina (2005). Moreover, extensive loss of roof sheathing resulted in lack of lateral bracing of the gable end wall from the top and subsequent partial or total collapse under high wind loadings. Lack of lateral support at the end gable wall can also be caused by the failure in unsupported rafter outriggers at overhangs, which lifts off by the wind and takes the roof sheathing with it. Therefore, the bottom or top chord can be pulled outward easily, twisting the truss and causing an inward collapse of the gable end wall. Last but not least, the gable end wall can also suffer serious damage when the wall sheathing fails as a result of poor connection to the wall framing system. It can be mentioned that failure of gable end walls during strong wind loads has been observed widely in residential buildings with wooden roof structural systems.

(a)

(b)

Figure 3. Sheathing loss and subsequent gable end wall and roof truss failure due to lack of lateral bracing during (FEMA P-488): (a) roof decking loss on one-story house, Hurricane Charley, 2004 (Punta Gorda); (b) wind damage to roof structure and gable end wall, Hurricane Katrina, 2005 (Pass Christian, MS).

Figure 4 shows elevated houses sustained severe wind-induced damage in terms of loss of roof coverings, roof sheathings, and roof structural members during Hurricane Ike (2008). As shown in Figure 4a, roof envelope damage occurred at the roof edge and roof corners, where the wind flow separation is quite significant. This flow separation can cause small vortices that can cause much higher pressures in small localized areas. Inadequate connection between roof cover and roof sheathing, and between sheathing and roof framing such as truss members or rafters caused extensive roof damage and subsequent indirect damage. It should be noted that nonstructural (e.g., shingles) and structural (e.g., wood studs) components, which fail under direct wind pressure can potentially act as windborne or flood-borne debris to cause severe damage to other surrounding buildings. As shown in Figure 4b, the whole roof structure was blown out due to insufficient connections to resist high uplift wind loads. In addition, severe loss of roof covering, and sheathing was also observed at roof edges and roof corners.


(a) (b)

Figure 4. Wind-induced damage to the roof structure of elevated houses during Hurricane Ike, 2008 (FEMA P-55a): (a) roof covering and sheathing damage at roof edge and roof corners (Galveston, TX); (b) total collapse of the roof structure (Galveston, TX).

Windborne debris is another important and widespread source that has caused serious damage to buildings during past hurricanes. The extent of damage is affected by several factors, including wind speed, debris source, debris elevation, and angle of impact. Windborne debris typically consists of several types, including roof coverings (tiles, shingles, metal panels, aggregate, etc.), damaged building components, trees, etc. It should be noted that windborne debris such as roof coverings that are detached from higher elevation can travel further with higher speed (one mile in some cases) than others from the ground, which can cause more severe damage to surrounding building envelopes (Figure 5a). As it was observed, use of appropriate laminated glass or shutter systems were the most effective ways to reduce such damage. However, protected building envelopes were still vulnerable to damage caused by windborne debris, which could initiate the pressurization and subsequent serious structural damage to the house (Figure 5b). Last but not least, buildings were observed to suffer severe damage by several types of falling objects such as trees, communications towers, rooftop equipment, etc. Therefore, corresponding measures, including bracing surrounding trees and anchoring outdoor equipment need to be considered in order to mitigate these types of damage to residual buildings.


(a) (b)

Figure 5. Damage due to windborne debris to building envelopes during Hurricane Charley, 2004 (FEMA P-488): (a) impact of structural wood members in the gable end, Pine Island; (b) a roof title punctured the shutter, Punta Gorda.

5. Damage due to hurricane flood hazards

Flood-induced damage to coastal residential buildings results from several hazards, including hydrostatic forces, hydrodynamic forces, waves, erosion, scour, and flood-borne debris. Hydrostatic pressures due to the weight of standing or slowly moving water, saturated soil, and water in the ground underneath a flooded building impose horizontal and vertical forces (buoyancy or floatation) on building components, which can also cause it to float off its foundation (Figure 6a). Moving floodwater generates hydrodynamic forces on submerged foundations, solid walls and building components, which can cause serious damage due to insufficient connections and lack of load path continuity (FEMA P-550). It should be noted that basement walls are more prone to failure due to the additional pressure from the saturated soil. Figure 6b shows typical damage to exterior walls due to hydrostatic and hydrodynamic forces during Hurricane Harvey (2017). It is important to mention that breaking waves are able to cause more severe damage to residential building in terms of damaging exterior walls or completely washing off houses elevated on piles or piers but with insufficient elevation, and also weak connections between the piers supporting floor beam and foundation.

(a) (b)

Figure 6. Typical damage to residential buildings due to hydrostatic and hydrodynamic forces: (a) building floating off its foundation during Hurricane Katrina, 2005 (FEMA P-550); (b) extensive damage to exterior walls due to 3 to 4 feet surge inundation during Hurricane Harvey, 2017 (FEMA P-2022).

Erosion and localized scour can threaten the overall performance of coastal residential buildings in many different ways. Erosion and scour effects are usually likely due to combination of waves and high velocity flow, which can easily undermine shallow foundations, and reducing penetration depth of pile foundations resulting in partial or total collapse of buildings. It has been observed that buildings with deep pile foundations performed better than buildings with shallow foundations. In addition, failures of erosion control structures can result in severe unpredictable damage to residential buildings particularly the ones with shallow foundation systems. Figure 7 compares the performance of two residential buildings against erosion and localized scour during Hurricane Irma (2017). Study of damaged homes in such events has also shown that houses sustaining severe damage due to erosion and scour in terms of loss of soil supports are more vulnerable to lateral wind and flood loads acting on the structures during the time of hurricane.

(a) (b)

Figure 7. Performance of residential houses against erosion and scour effects during Hurricane Irma, 2017 (FEMA P-2023): (a) total collapse of the house with shallow foundation due to erosion in Vilano Beach, FL; (b) elevated house with deep pile foundation survived erosion in Vilano Beach, FL.

Floodborne debris produced by costal flood events is often capable of destroying a wide variety of building types such as unreinforced masonry walls, light wood-frame construction, and small diameter posts and piles. In addition, debris trapped by structural components such as cross-bracing or closely spaced piles are capable of transferring flood and wave loads to the foundation of an elevated structure. Figure 8 shows damaged residential buildings in coastal areas due to flood-borne debris during different hurricanes. The impact loads resulting from floodborne debris can be estimated and applied based on the procedure in ASCE 7-16. There are some uncertainties which must be determined before estimating impact loadings, including physical characteristics of floating objects, flood velocity, most vulnerable portion of building, and duration of the impact. Therefore, the more reliable estimation will result in more accurate load calculation results.

(a) (b)

Figure 8. Damage to the coastal building due to floodborne derbies (FEMA P-55a; FEMA P-2023): (a) pile supported house washed into another house at Dauphin Island, AL. during Hurricane Georges, 1998; (b) boat and small debris washed into a house in Big Pine Key, FL, during Hurricane Irma, 2017.

Foundations in coastal areas must be able to perform several functions in order to ensure that buildings are able to resist various hurricane loads. The foundation system not only needs to provide a continuous path for vertical and lateral loads transferred from the building to the ground, it should also be able to directly resist different types of flood loads, including storm surge, wave, foodborne debris impact, erosion, and scour effects. For example, deeply embedded piles or other open foundation systems are required for V zones because of high waves and floodwaters. However, closed foundations are not recommended in coastal A zones and are not allowed in V zones due to the fact that these foundations provide a large surface area exposed to waves and flood forces. The performance of open/closed foundations rely on various factors, including sufficient load capacity of continuous foundation walls, piles, or piers against lateral loads (wind and flood), adequate connections between piles or piers with foundation and floor beams, and sufficient embedment length of piles. Figure 9 shows typical damage to different foundation systems of residential buildings in coastal areas in past hurricanes, including damage due to the erosion, scour, insufficient pile embedment, and lack of sufficient connections between piers and the foundation.

(a) (b)

(c) (d)

Figure 9. Typical damage to foundation systems of residential buildings in coastal areas (FEMA P-550): (a) slab-on-grade foundation failure due to erosion and scour from Hurricane Dennis, 2005 (Navarre Beach, FL); (b) partial collapse due to insufficient pile embedment during Hurricane Katrina, 2005 (Dauphin Island, AL); (c) column connection failure during Hurricane Katrina, 2005 (Jackson County, MS); (d) failure of pier on discrete footing due to overturning moment during Hurricane Katrina, 2005 (Pass Christian, MS).

6. Observation from buildings with material other than wood

Residential buildings in coastal areas can be mostly classified into four categories based on materials of the structural system, including wooden frame buildings, concrete masonry units (CMUs), reinforced concrete frames, and steel frames. Wooden frame buildings are widely adopted in residential building due to economic aspects, feasibility, and light weight. Reinforced concrete and concrete masonry units (CMUs) are also common building types in coastal areas, with wood/steel framings or trusses used as their primary roof structure. It has been observed that buildings with other than wooden frame systems have generally performed better against strong wind and flood loads. However, the nature and extent of flood damage to residential buildings regardless of material are more complicated and depends on several factors, including location, foundation type, and lowest floor elevation.

The CMU buildings compared to wooden frame buildings have a better performance during strong hurricanes against wind and flood loadings in terms of lateral and uplift resistance due to its larger self-weight and more effective continuous load path. However, widespread vulnerability in connections has been observed if CMU buildings have wooden roof trusses. For example, many CMU buildings with wood truss roofs that only had toe-nailed connections between rafters and beams and no additional strapping, plates, or bolts experienced severe failure during Hurricanes Irma and Maria (2017). Similarly, CMU buildings combined with steel joist roof system and metal deck suffered severe failure in welds at the plate connectors used to secure the steel joist to the wall system. Figure 10a shows the common wind-induced damage to typical CMU building with wooden roof structure in Hurricane Charley (2004).

Steel frame buildings are more vulnerable compared to reinforced concrete buildings and have experienced more damage to the structure and envelope system during strong hurricanes mainly due to poor and corroded connections. Several types of failure were observed, including loss of roof and wall panels, partial/complete collapse of structural frames, and damage to gable end walls due to inadequate lateral bracing. Steel frame buildings are more vulnerable to windborne debris so that subsequent pressurization due to possible breach to envelope system can also cause severe damage to the structure. Figure 10b shows partial and complete structural damage due to failures in connections between roof members and base plate for the gable end wall column.

(a)

(b)

Figure 10. Wind-induced damage to concrete and steel frame buildings during Hurricane Charley, 2004 (FEMA P-488): (a) damage to a multi-family building roof deck with inadequately supported and braced overhang; (b) roof framing failure and gable end wall collapse due to insufficient lateral supports.

Buildings with heavy concrete frames or prefabricated concrete wall and roof have shown to be less vulnerable to serious wind-induced structural and envelope damage during hurricanes. These types of buildings and their concrete roofs have performed well due to high load resistance of concrete and reinforcements. However, they are still vulnerable to flood-induced damage in terms of chloride penetration into the concrete, corrosion of reinforcements, and spalling of the concrete cover. In addition, metal R-panel roofs, corrugated metal roofs, and liquid-applied membrane roofs (applied over plywood roof covers) have generally performed well and for the most part did not sustain visible damage for example during Hurricane Irma and Maria (2017). However, it was observed that strict design details for the ridge are required in order to prevent water infiltration due to the wind-driven rain and subsequent damage to the interior (FEMA P-2021).

Regardless of the material used for the structural system, even fully engineered residential buildings but with elevated floors below the BFE with deep foundation systems (Zone V or A) have also sustained flood and erosion damage. Figure 11a shows a 5-story concrete building with shallow foundation system, which sustained severe damage due to surge, debris, and erosion effects during Hurricane Ivan (2004). In addition, exterior walls below the BFE regardless of material mostly suffered severe flood-induced damage particularly in V and A coastal zones. Figure 11b shows a concrete building elevated on deep piles, but with low elevation living unit that was destroyed due to surge, high waves, and subsequent flood debris. Based on observations during Hurricane Ivan (2004), regardless of material, almost 80 percent of lowest floor living units were destroyed by flood and erosion effects, despite the fact that most of buildings were constructed on pile foundation above the estimated BFEs selected from available DFIRMs.

(a)

(b)

Figure 11. Several flood-induced damage to concrete buildings during Hurricane Ivan, 2004 (FEMA P-550): (a) severe structural damage to the building with shallow foundation due to surge, wave, and floodborne debris; (b) partial/complete collapse of exterior walls below the BFE for a concrete building elevated on deep piles.

7. Lessons and mitigation methods

Actual observations show that building materials other than wood have better performance during strong hurricanes. However, they are still vulnerable to other types of damage, including widespread vulnerability in connections for CMU buildings and steel frame buildings, chloride penetration into the concrete, corrosion of reinforcements, and spalling of the concrete cover for buildings with heavy or prefabricated concrete frames. Regardless of building material, load path failures due to wind or flood mostly occur at connections either for structural members or envelope systems. Besides, residential buildings have suffered extensive wind-induced damage to envelope systems more than structural systems. It should be noted that selecting denser connection and bracing designs particularly at roof corners, edges, and wall corners, shallow roof slope, appropriate shutter systems or laminated glasses, absence of overhangs, suitable wind-load resisting material, and appropriate installation methods for wall/roof sheathing and covering can significantly reduce direct wind damage to envelop systems, which also results in the elimination of potential pressurization and subsequent progressive failures to structural members. Furthermore, using adequate connection system between structural members, sufficient lateral bracing for gable end walls, using wood structural panel as wall sheathing, and bracing surrounding tress and anchoring outdoor equipment can significantly reduce the level of direct and indirect wind-induced damage to the structural system for residential buildings. Similarly, past hurricanes show that many non-elevated or low-elevation buildings have sustained severe flood damage in coastal areas, where damage is almost inevitable once flood reaches first floor level. Failures typically occur in connections between piles/piers to the superstructure and foundation system due to high lateral flood loadings. The use of flood-resistant materials under the BFE can significantly reduce the potential flood-induce damage. Furthermore, use of open foundation systems reduce surge risk while slab-on-grade foundations suffer the most in flood, particularly against erosion and scour effects.

8. Conclusions

This paper briefly reviews the evidence from actual damage in past hurricanes with respect to direct damage and indirect damage to residential buildings with different materials in coastal areas. The results show that although building materials other than wood have better performance during strong hurricanes, they are still vulnerable to other types of damage such as connection failures. The concept of load path is an important factor, which affects the performance of residential buildings in coastal areas. The actual damage shows that residential buildings that are correctly designed in accordance to building code (e.g., IRC or IBC) requirements for wind and flood loads (e.g., 100-year flood level) have sustained less damage during strong hurricanes. However, additional guidance developed by FEMA needs to be considered by designers and homeowners. It should be noted that selecting adequate connection system, optimizing roof plan, suitable wind-load resisting material for the structural wall and roof systems, and appropriate installation methods can significantly reduce the level of direct and indirect wind-induced damage. It should be noted that elevating the foundation on deep embedded pile above the DFE (BFE+ freeboard) is the most effective method to reduce the flood damage to residential buildings in coastal areas. However, it might increase the wind damage due to the fact that the house is exposed to higher wind forces so that further measures should be considered. Furthermore, selecting the appropriate foundation system, enhancing foundation connections, and using flood-resistant materials below the BFE not only reduce direct flood-induced damage but also provide the overall strength and integrity for the building.

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An Overview of the Execution of 3D-Printed Subscale Habitat on Mars: A Case Study to Exemplify the Automated Construction Process

S. Nazarian*[1], J.P. Duarte[2], S.G. Bilén[3], A. Memari[4], N.K. Muthumanickam[5], N. Watson[6], A. Radlinska[7], N. Ashrafi[8], and M. Hojati[9].

1. Associate Professor, Department of Architecture, College of Arts and Architecture, Penn State University, 121 Stuckeman Family Building, University Park, PA, 16802. (814) 865-0875, sun14@psu.edu.
2. Professor, Stuckeman School of Architecture and Landscape Architecture, PSU, jxp4002psu.edu
3. Professor, SEDTAPP, College of Engineering, PSU, sbilen@psu.edu
4. Prof., Dept. of Architectural Engineering, College of Engineering, PSU, amm7@psu.edu
5. PhD Candidate, Department of Architecture, College of Arts and Architecture, PSU
6. MS Student, School of Engineering Design, Technology, and Professional Programs, PSU
7. Department of Civil and Environmental Engineering, Penn State University, azr172@psu.edu
8. PhD Candidate, Dept. of Architecture, College of Arts and Architecture/PSU, nza119@psu.edu
9. Assistant Professor, Department of Civil, Construction, and Environmental Engineering, The University of New Mexico, NM 87131, USA, hojati.maryam.gmail.com

*corresponding author: sun14@psu.edu

ABSTRACT

Since 3D printing of structures is expected to reduce construction time, material, cost, and energy, the building industry has come to realize the relevance and importance of digital design and additive construction, signaling a foothold in that regard and paving the way for much-needed advancement in the construction industry. Furthermore, the automation implied in 3D printing technology could introduce newfound applications; for example, it makes possible *in-situ* construction in harsh conditions on Earth and extraterrestrial environments such as Mars and the Moon prior to the arrival of human explorers.

This paper presents the dynamic and interrelated processes of design and development of materials, systems, and architectural constructs on a single BIM platform, on which the architectural design of a habitat, the tool-path design, and assembling and coordination of information regarding multiple interrelated variables such as materials properties, structural behavior, systems' transformation, costs, and logistics, can be systematically created, coordinated, managed, analyzed, and converged towards the common goal of automation in construction.

Through this case study we review the attempts made by the interdisciplinary team of Penn State faculty and students to print a sub-scale habitat for Phase III–Level 3 of NASA's 3D-Printed Habitat Challenge. NASA designed the multi-phase Challenge to catalyze research to advance the automated construction technology needed to create sustainable housing solutions for Earth and deep space habitats. As such, this paper presents a framework to quantitatively understand the benefits of and changes that AM will trigger in construction and logistics, rather than a focus on qualitative consequences in terms of the inevitable transformations it will trigger in architectural language and practice.

INTRODUCTION

Additive Construction (AC) will undoubtedly be adopted by the construction industry, not to replace conventional methods, but to satisfy several innovation drivers: more sustainable approaches due to freeform deposition (i.e., without formwork) of composite materials such as concrete and clay composites; achieving seamless transition between materials; precise deposition of Functionally Graded Materials (FGMs); and a response to the need for mass customization.

There are three dominant modes of printing at architectural scale: gantry systems, cable-driven systems, and robotic arm systems. (Watson et al., 2019) Of the three, gantry systems are most prevalent because they are less complex to design, construct, and control. (Labonnote et al., 2016) However, there is a need to levelize the site prior to setting up such a system. They comprise a large fixed frame, a nozzle travelling along the X, Y, and Z axes within the frame, and a concrete pump positioned on top of, or next to, the gantry frame that pushes the mortar through a hose to the nozzle. The system needs to be larger than the built form as the moving frame element needs to travel freely forth and back during printing. Due to the complexity of the set-up process, human oversight is required, which is difficult in remote or harsh environments. Rotating and angling nozzles and the ease of automated placement of reinforcement (Bos et al., 2018) are the system's best features.

Cable-based systems are more flexible, easier to scale up, more compact than the gantry system, easier to transport, and have a smaller footprint as they are strung between multiple fixed points. However, much like the gantry system, they cannot execute complex maneuvers. (Chesser et al., 2018) Maneuverability of the nozzle's position is made possible by pulling on the five cables.

The already-assembled, more compact six-axis (i.e., freedom of movement) robotic-arm printing systems are more agile, flexible, better equipped to achieve more complex geometries, (Den@Mars, 2019) and able to be folded to occupy less volume in transport. By changing the end-effector, its limited reach can be compensated to a certain degree to enable an altered range of motion to perform multiple tasks and post-processing details during construction. We selected the six-axis robotic extrusion of concrete because of its multiple advantages over the gantry and cable-based systems.

This paper presents an overview of a system for AC of concrete structures that we developed and modified repeatedly for NASA's 3D-Printed Habitat Challenge, addressing its benefits and shortcomings. It is important to note that the compatibility of the physical printing system with the material needs are of utmost importance and need be considered simultaneously and adjusted repeatedly. That is because all extrusion-based AC using concrete requires a mix that is workable, flowable in transition, and fast setting after deposition to avoid deformation. When automation is required, and in the absence of close oversight, these are essential problems to solve particularly if the environmental conditions of the construction site are not favorable and dictate nuances of their own in preparation of the mix design.

SYSTEMATIC RECIPROCITY BETWEEN SYSTEMS, MATERIALS, AND DESIGN

In preparation for the future colonization of Mars, NASA prepared a well-developed brief for an international, multiphase, multilevel competition—"3D-Printed Habitat Challenge"—inviting the public to contribute to the refinement of AC technology and to accelerate the adoption of automated AC in the construction industry. The competition required the use of indigenous regolith and mission-recycled materials; the design and development of an automated printing system; and the necessary logistics to deploy the system. Penn State participated in Phase II and III of the competition. This paper focuses on the team's attempts in Level 3 of Phase II, and Construction Levels 2 and 3 of Phase III.

To achieve precise but simple geometries of structural members with little tolerances in Phase 2 (Fig. 1), we developed various 3D-printable mixtures of cementitious and non-cementitious mortars and systematically documented rheological properties and characterized the deformation of the materials after extrusion. For the competition, we developed a concrete formulation that we call MarsCrete™, using basalt rock, kaolinite, sodium, and silicon, all of which can be harvested on Mars to create a concrete mixture using local materials.

We collected detailed data regarding the behavior of the overall system in response to multiples of variables including nozzle cross-sections and diameters, water flow rate, dry material feed rate, mortar properties, shape accuracy, tool-path design, speed of extrusion, material setting rate (just enough to hold their shape), types of pump rotors, pump rotation speeds, environmental conditions (such as temperature and moisture), among many others.

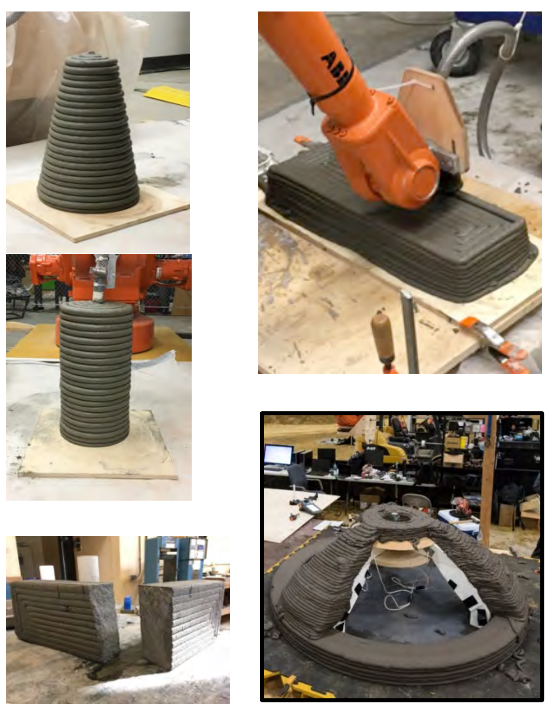
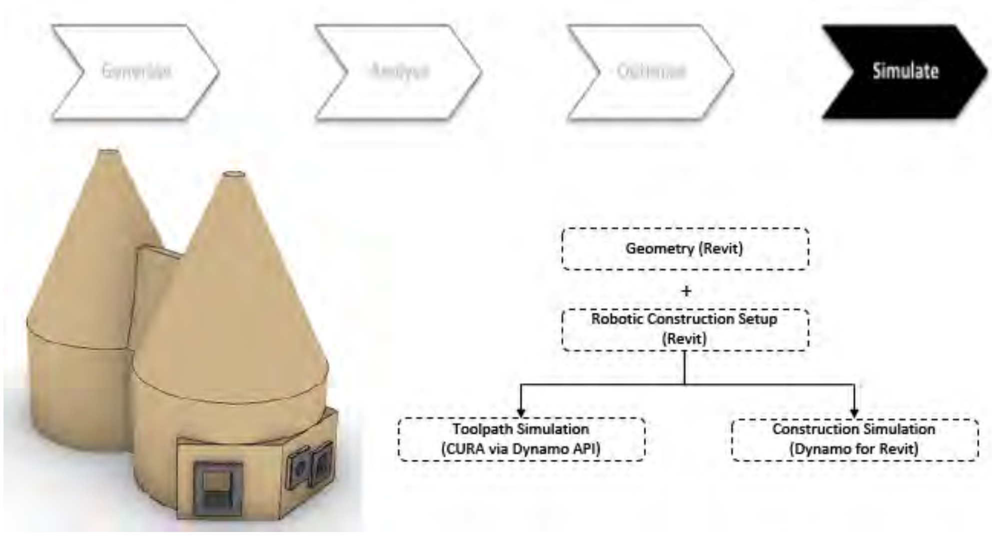


Fig. 1. 3D-printing of cylinder, beam, and dome for Phase II of NASA 3D-Printed Habitat Challenge

In parallel, we were rethinking and transforming the familiar robotic-arm system to the desired macro-scale, involving better understanding of possible end-effectors, pushing the boundaries of the system's physical reach, and logistics involved in on-demand mobility protocols.

The physical printing system is comprised of two components. The first is a concrete mixer–pump (m-tec Duo mix 2000), which is used to pump concrete through a hose to the nozzle. Dry concrete powder is added into the mixer–pump, in which water and powder are mixed in a chamber and subsequently fed into a pump component. Concrete is then pumped through the hydraulic hose, which feeds the concrete into a nozzle held by the second part of the system, which is a six-axis ABB IRB 6640 robotic arm with a 2.8-m reach. The nozzle we use has an internal diameter of 25.4 mm, which results in an extruded filament/bead approximately 25 mm wide and 15 mm high.

A major goal has been to explore meaningful ways in which digital design and AC technologies can augment the contemporary construction industry. The use of BIM was required by the competition for 3D design representation, and 3D and 4D simulations were required to capture construction sequencing in time. We engaged in an innovative approach to using BIM as a framework for design, analysis, and simulation (3D and 4D) to aid in the actual design-and-construction process. This approach comprised: a) parametric generation of the design with building design variables; b) analysis of the variables, simulating structural and environmental performances, and exploring the reach of the robotic arm through simulation techniques; c) optimization of multiple variables; and d) 4D simulation of the toolpath and of the construction processes and stages in time. (Muthumanickam, 2019) (Fig. 2). This unique approach enabled us to design and simulate a structure that was, in fact, fully realizable through this technology without the need to rely on any temporary support structures,formwork, or prefabricated components.



(Fig. 2). Simulation of 3D-habitat for designing the 3D-printing toolpath.

DISCUSSIONS

To date, rapidly emerging additive manufacturing methods have been deployed to produce precision parts in industry (e.g., critical replacement parts for engines, other specialty components), medicine (e.g., medical prostheses, dentistry), business (e.g., prototyping), and hobbyists (to produce everyday objects for personal use). 3D printing, particularly at larger scales, has been used to produce structures that we have already been able to produce through other means of production, with the most obvious added advantages, for example, gained from the speed of production and cost savings.

With a vision to advance construction technology on Earth and beyond, we began exploring the boundaries of this technology and its unique potential in the construction industry. Our goal is to produce fully 3D-printed and habitable structures without the use of any conventional means, i.e., molds, support structures, prefabricated parts, or skylights to enclose the roof. This is a bigger challenge than the deliverables during Phase III of the NASA competition. We participated in the competition to accelerate our efforts to reach this goal.

Our strategy is based on exploring three independent and interrelated rudiments including materials, system, and design in its broadest definition. “Disruptive technologies are unique in that they span other new technologies and applications as they grow”, say Fiske, et al. in a paper delivered in the AIAA Space Forum. (Fiske et al., 2007)

Our intension was not only to configure 3D-printing technology to print concrete at large scale, but also to fully automate the process. To achieve our goals, we have had to design and develop our own 3D-printable concrete mixes; design and assemble our own printing systems; transform the design processes to accommodate the new technologies and take advantage of their unique affordances; to understand multiples of interrelated variables; configure the logistics to unite and implement the various tasks in many ways; and coordinate complex and interrelated variables using Building Information Modeling (BIM). Automated Additive Manufacturing, particularly at large scale, is undoubtedly a disruptive technology, which has already set in motion many new opportunities and paths of discovery.

IMPACTS AND GAME-CHANGING BENEFITS

Using the competition to accelerate our research, we have been able to help advance and accelerate the development of AC technologies and systems. Since the completion of the competition, we have continued to develop several other humanitarian and cost-effective materials and techniques using local resources and *in-situ* materials such as clay-based mixtures and the possibility of harvesting such materials. These discoveries inform and advance construction technology for implementation on Earth and beyond, shifting the paradigms of design and design-thinking, architectural design, industrial design, construction, mass customization, logistics, and sustainable materials and practices. They signal significant changes in the building industry and the costs associated with them.

Keywords: Additive/Robotic Construction, 3D printing in construction, 3D Printed Concrete, 3D Printing at Architectural Scale, Design and Automated Construction, NASA 3D-Printed Habitat Challenge.

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Structural Analysis of Full-Scale and Sub-Scale Structure for Digitally Designed Martian Habitat

Keunhyoung Park[1], Ali Memari[2], Shadi Nazarian[3], José Pinto Duarte[4], Maryam Hojati[5]

[1]Graduate Student, The Department of Architectural Engineering, The Pennsylvania State University, 310 Sackett Building, University Park, PA 16802, (814) 308-3014, khpark@psu.edu
[2]Professor, The Department of Architectural Engineering/Civil and Environmental Engineering, The Pennsylvania State University, 222 Sackett Building, University Park, PA 16802, (814) 863-9788, amm7@psu.edu
[3]Associate Professor, The Stuckeman School of Architecture and Landscape Architecture, Pennsylvania State University, 222 Stuckeman Family Building, University Park, PA 16802, (814) 865-0875, sun14@psu.edu
[4]Professor, The Stuckeman School of Architecture and Landscape Architecture, Pennsylvania State University, 222 Stuckeman Family Building, University Park, PA 16802, (814) 863-4584, jxp400@psu.edu
[5]Assistant Professor, The Department of Civil, Construction and Environmental Engineering, The University of New Mexico, 3052 Centennial Engineering Center, Albuquerque, NM 87131, (505) 277-1488, mhojati@unm.edu

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Over the past few years, digital design and additive construction have been gaining recognition and acceptance for terrestrial construction, and their enormous potential coupled with automation is accordingly justified for space colonization programs. Building a habitat in deep space, in places such as Mars or Moon, would face challenges different from those encountered on Earth in terms of design, construction, and structural performance. 3D printing or additive manufacturing using robots enables us to build shelters autonomously using indigenous materials. For making a livable environment for humans on Mars, the habitat needs to be pressurized and provide enough protection against harsh solar radiation. As such, the walls of the habitat would need to be much thicker than structures on Earth.

In this study, a numerical finite element model (FEM) was constructed to conduct the analysis/design process of a Martian habitat using Revit by AutoCAD to coordinate the habitat design with the structural analysis and later the printing process. The information for the configuration of the habitat design was transferred from the design authoring program Revit by Autodesk to Autodesk Nastran through the Standard ACIS Text (SAT) and the stereolithography (STL) file format using Autodesk Fusion. The file format is also used to deliver data from the design authoring program to the printing system preparation process.

Finite element (FE) modeling and analysis were used to study the structural performance of different schemes for the habitat design under relevant gravity loads and internal pressures. The geometric data of different design schemes were indirectly transported from the BIM model to the FE model, the optimized model was proposed for the printing process, and a subscale habitat was modeled and evaluated for actual construction. Portland cement mortar-based printing material was used as the construction material.

1 Introduction

Additive Manufacturing of Concrete (AMoC), also known as 3D printing of concrete (3DPC), has taken a considerable role in automation of building construction, thanks to the potential for flexible shape design and economic benefits resulting from eliminating molding process. Moreover, the relatively simple manufacturing mechanism of 3DPC reduces the complicated construction process, which leads to the possibility of building a structure with low manpower and a short time (Cor, 2019).

The National Aeronautics and Space Administration (NASA) has been interested in the potential of 3DPC to support its space exploration mission (NASA, 2019). Because of the limitation of cargo weight onboard spaceships intended for space exploration missions, minimum construction material may be transported for the purpose of habitat construction. The solution that NASA is trying to achieve is to use the material found on the planet and at a given site to build habitats.

On the other hand, there is a handful of the challenges in using 3DPC to accomplish the quality of traditionally constructed concrete buildings while the construction process for cast concrete structures has matured over decades. Especially, the vast range of possible shapes resulting from using 3DPC raises a new challenge in performing structural analysis. Growing nontypical building designs intended to use 3DPC increases the difficulty in both generating computational modeling and assessing the structural result from the analysis. This study considered a configurative information exchange process for generating computational modeling in finite element analysis (FEA) to unleash the inherent capability of 3DPC, allowing various shapes for the Mars habitat design. At the same time, Matlab was used to generate a figure illustrating principal stresses as part of FEA's post-processing.

The 3D printed Mars habitat competition organized by NASA aimed to encourage the development of feasible habitat design. In this study, 3DPC was considered, including the spatial design, environmental control and life support system (ECLSS), and construction procedure analysis.

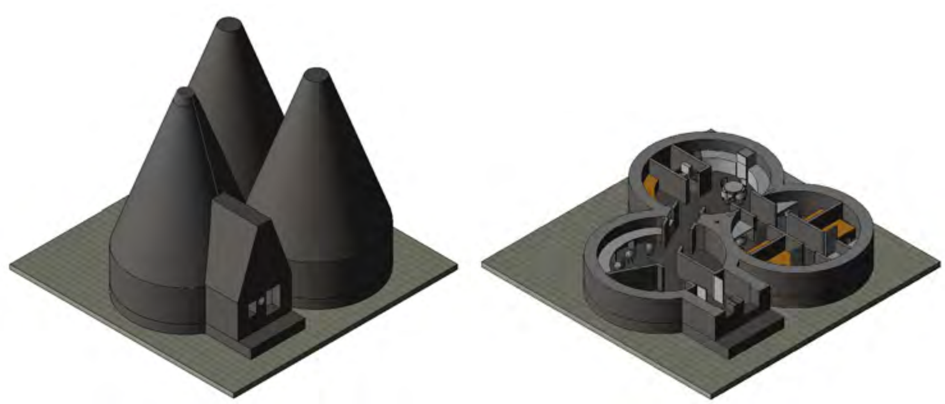
2 Design of a space exploration habitat on the Mars surface

2.1 Design requirements

Minimum configuration requirements for the habitat are determined based on the Martian surface environment and architectural design. Structural consideration is based on the derived habitat design following the configuration requirements for NASA's space exploration mission. Accordingly, the habitat should have a minimum area of 93 m^2 for the astronauts' living and working space. To be specific, the entrance design for easy access from outside the habitat, sustainable energy circulation for livable condition maintenance, and proper spatial program design for various activities were the main requirements for the habitat design. Furthermore, to maximize the space exploration mission's feasibility, the printed habitat is supposed to be autonomously built on the Mars surface without human intervention as part of preparation before the arrival of astronauts. The habitat design needs to meet the construction process limitation for autonomous construction.

Prior to the habitat configuration design, the Penn State research team started the design of the wall thickness to provide protection from space radiation on the Mars surface. Considering the maximum amount of allowable radiation exposure used in the safety regulations for the nuclear power generation facility, the team determined that the habitat should have a minimum 600 mm thickness for the full-scale habitat in its outer wall. However, for the sub-scale habitat, 200 mm was chosen.

For the final habitat design, the loading conditions for the structural design were determined. With lack of sufficient information and understanding of the environmental conditions on the Mars surface, a somewhat conservative approach had to be taken when applying loads on the structure. The design developed in this study and shown in Figure 1 aimed to achieve the optimal design while meeting the design requirements.



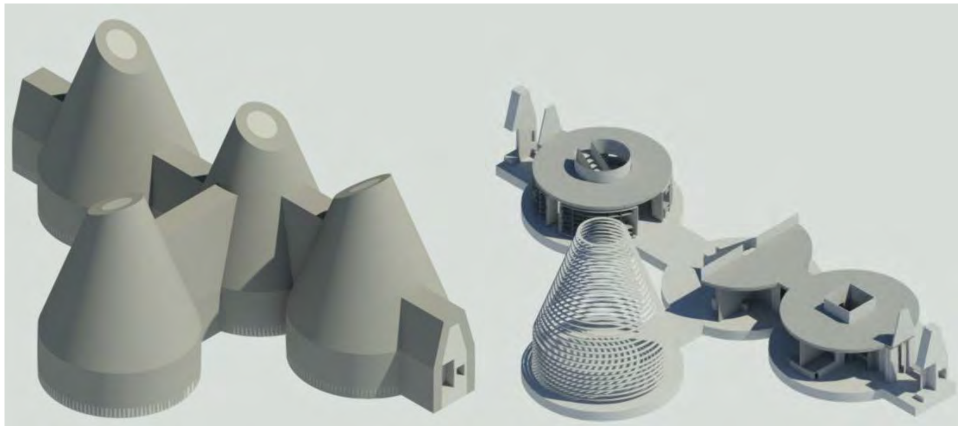


Figure 1. Shape configuration and spatial program design in Revit modeling of the 3D printed Mars habitat design

Major loading conditions that significantly affect the habitat's structural system consist of gravity load, internal air pressure, and temperature variation, as listed in Table 1. Gravity load and internal air pressure are fixed for all loading scenarios. The temperature loading has three cases of the highest, lowest, and the average temperature outside the habitat due to the sunlight variation (NASA, 2020; Williams, 2018). It is reasonable that the habitat location would be around the equator or the mid-latitude area of Mars if it considers the benefits of landing the spaceship in the area. For this NASA completion, our site for the habitat was decided to be on the Equator and at Endurance Crater. While in the paper presented here temperature loading is not considered, such analysis is considered for a different publication. Accordingly, the moderate temperature conditions will follow the consideration of the extreme temperature conditions at the selected site.

Table 1. Environmental conditions at the Mars surface and the inside of the habitat

Loading Case	Mars Surface	Inside of the habitat
Gravity Acceleration	3.721 m/s^2 (146.496 in/s^2)	
Air Pressure	0.6 kPa (6.0 mbar; 0.087 psi)	101.3 kPa (1013 mbar; 14.692 psi)

The habitat is supposed to maintain a proper livable environmental condition so that astronauts can carry on their space exploration mission without wearing an additional life-maintenance-equipment inside the habitat. Among the expected loading conditions, the gravity load on the Mars surface is considered minor because the gravity acceleration on the Mars surface is much lower than on the Earth's surface (38% of Earth's gravity). On the other hand, the very low air pressure on the Mars surface (0.6% of Earth's atmospheric pressure) becomes a critical element to be considered once the habitat's interior is pressurized to the Earth's atmospheric level to maintain a livable environment for astronauts inside the habitat. At the same time, the varying Mars surface temperature is also expected to cause a significant stress concentration due to thermal expansion, which will be considered in a separate publication.

2.2 Finite element analysis (FEA)

Finite element analysis was performed to estimate the response of 3D printed habitat under the gravity and internal pressure loading conditions. Autodesk Nastran embedded in Inventor by Autodesk was used for the finite element analysis. Autodesk Nastran can interpret a Standard ACIS Text (SAT) file format from Revit by Autodesk, which was used as the design authoring program in this project. SAT file format is a geometric modelling kernel developed by Spatial Corporation (Spatial-Co, 2020) and vastly used by various computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) (Dassault-Systems, 2020; Wikipedia, 2020a). The stereolithography or Standard Triangle Language (STL) is a file format developed by Chuck Hull of 3D Systems (3D-Systems, 2020) to deliver surface geometry information of a three-dimensional object (ASTM, 2012; Wikipedia, 2020b). The data files used to generate the printing toolpath were converted to SAT files by using the Autodesk Fusion program. Importing the shape information from a design authoring program to a finite element analysis program through SAT file format allows a more efficient working process compared to the case of generating a mass shape by using a built-in shape CAD platform in an FEA program. This mode of data transforming process allows extensive parametric design studies through Dynamo, which is the programming language embedded in the Revit program.

The FEA was repeated for the gravity load and internal air pressure load cases. The analysis with a single load case aims to see the effect of the individual loadings separately. The material properties used in structural analysis for the sub-scale and full-scale habitat design are listed in Table 2 derived from the material testing done by Penn State 3D concrete printing research team.

Table 2. Mechanical properties of materials used in the analytical solution of a 3D printed beam with steel rebar

Property	Concrete Ultimate Strength, f'_c, ksi (MPa)*	Concrete Elastic Modulus, E_c ksi (MPa)	Concrete Yield Strength, ksi (MPa)**	Concrete Tangential Elastic Modulus, E_{ct} ksi (MPa) ***
Value	3.6 (24.7)	1,341 (9,246)	2.2 (15.5)	250 (1,724)

* for GCT concrete, ** 40% of Ultimate Strength, *** Assumed as 20% of the elastic modulus

This study assumed that the FE modeling is suitable to predict the structural behavior of the sub-scale habitat configuration by comparison to the actual crushing test results to validate the FEA result. Based on this assumption, this study tried to correlate the FEA results of the sub-scale and full-scale habitat cases so that the FEA of full-scale habitat can be carried out with more confidence.

3 Analysis results

For each loading case, the resulting deformations and normal stresses are considered for comparison with the material properties in Table 2 determined through laboratory testing of prisms/beams.

3.1 Sub-scale habitat analysis

Sub-scale habitat design was intended for preliminary examination and actual printing as well as for the better understanding of the feasibility of printing the full-scale habitat and its behavior upon design and printing. FEA of unusual shapes may not follow the stress distribution tendency of the traditional rectangular-shaped building structural elements.

The sub-scale habitat has the exact shape of the full-scale habitat design, except it is at 1/3 scale. The FEA of the discretized modular configuration allows a better understanding of the expected unique structural behavior of the structure under the assumed loading conditions.

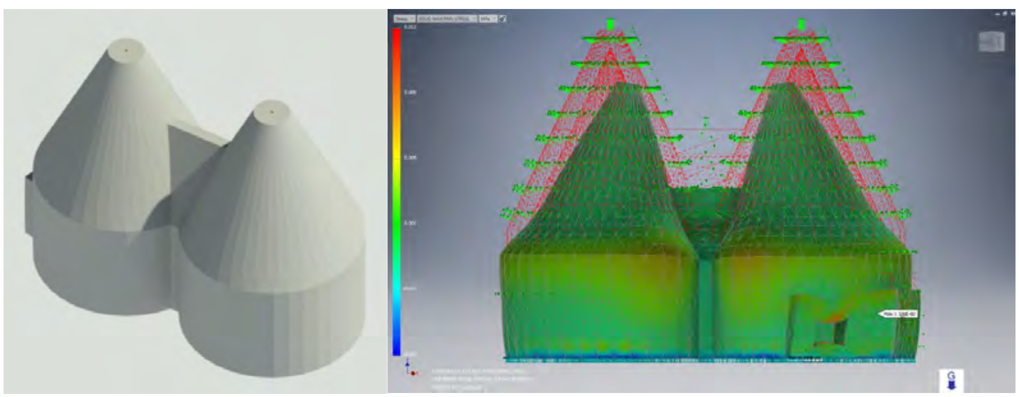
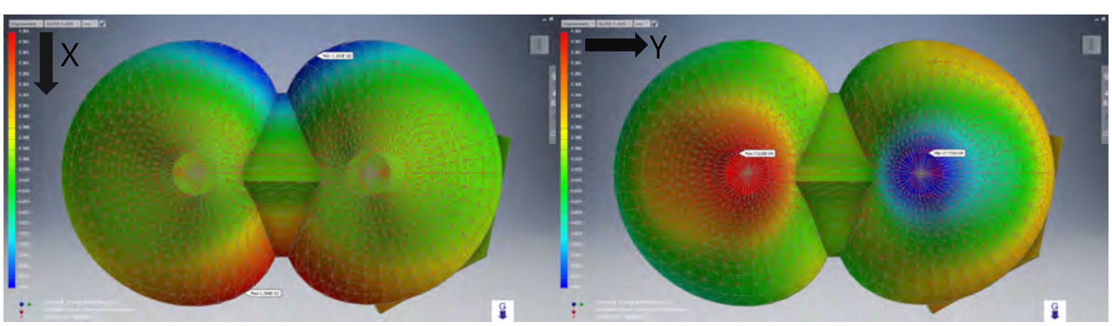


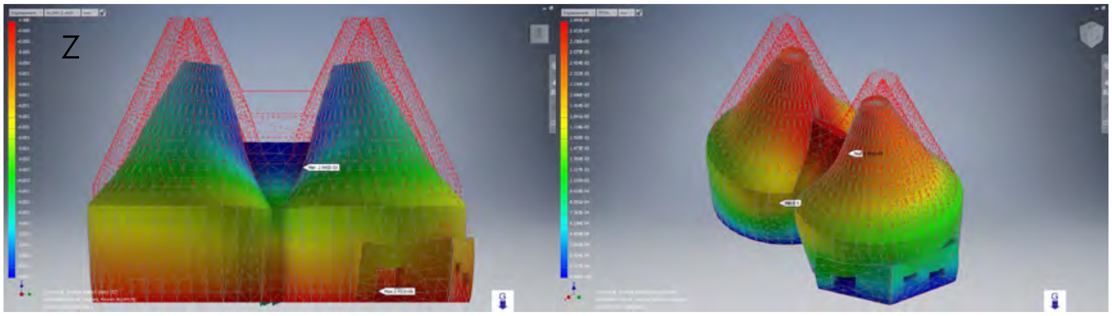
Figure 2. Digital modeling of the sub-scale habitat and the FEA results by using Autodesk Nastran

Sub-scale Habitat under the Gravity Load

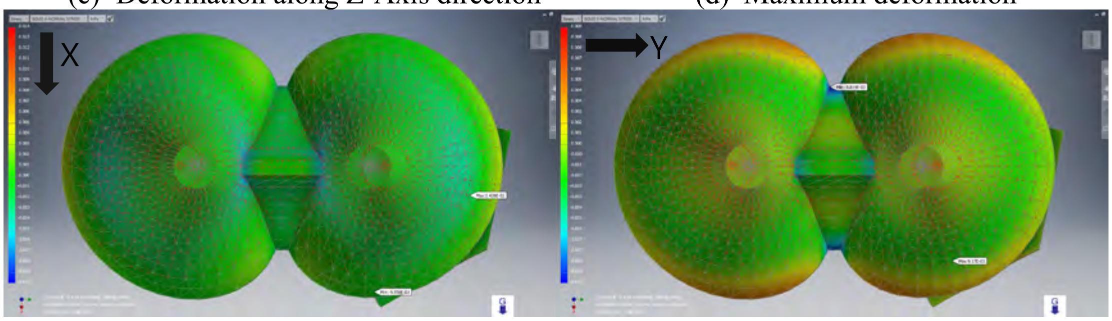
The Martian low gravity acceleration that is one-sixth that of the Earth, does not cause severe stresses on the habitat when it is compared to the structure's strength. Deformation and stress distributions along the X, Y, and Z directions in the sub-scale habitat due to the gravity (self) load are shown in Figure 3.



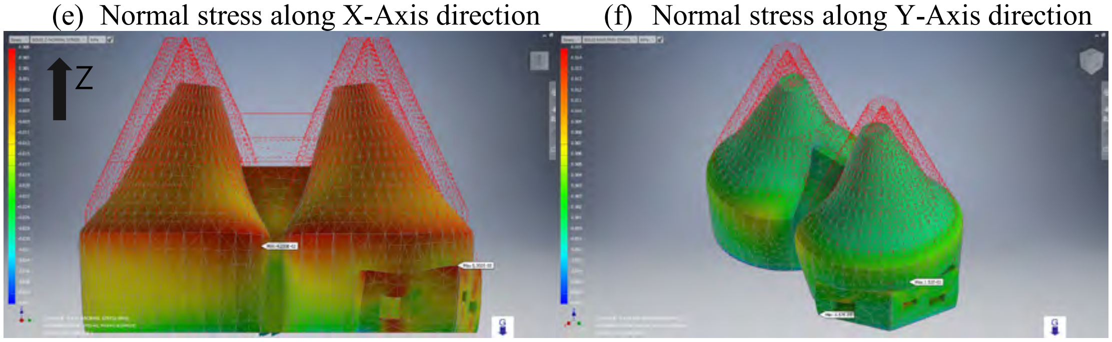
(a) Deformation along X-Axis direction (b) Deformation along Y-Axis direction



(c) Deformation along Z-Axis direction (d) Maximum deformation



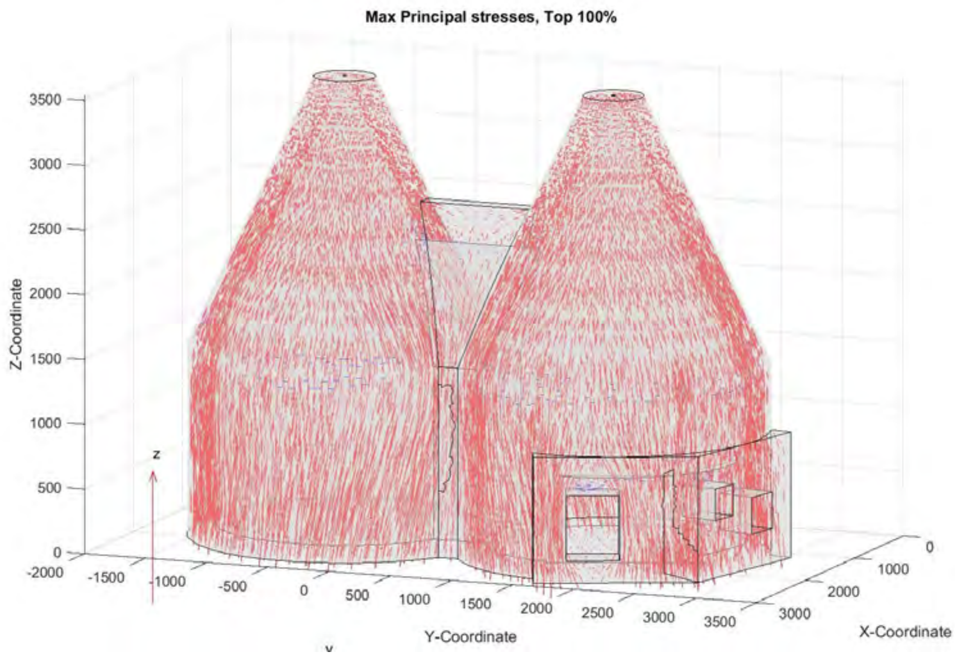
(e) Normal stress along X-Axis direction (f) Normal stress along Y-Axis direction



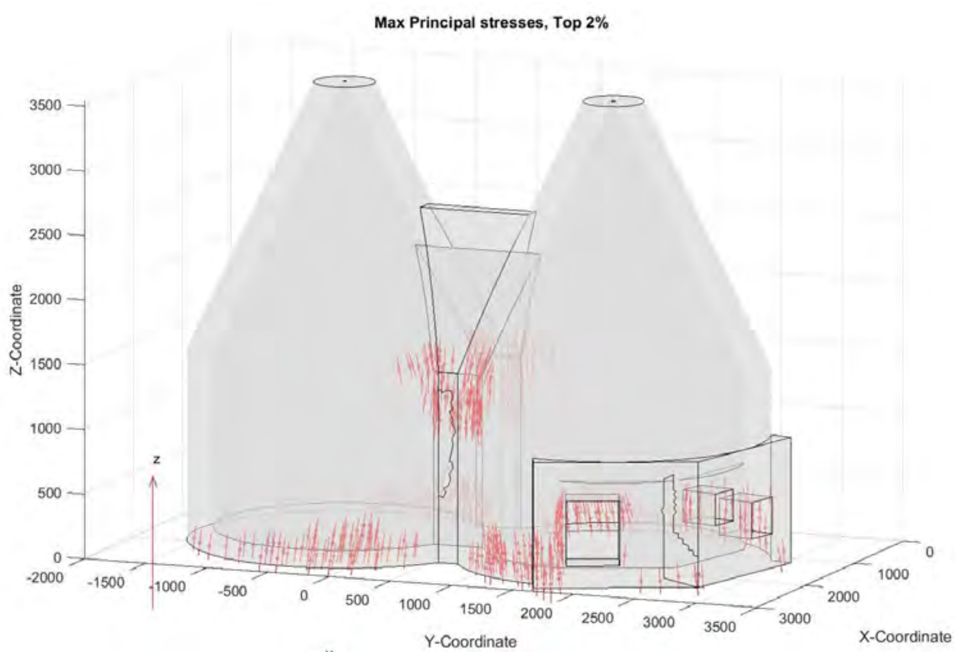
(g) Normal stress along Z-Axis direction (h) Maximum principal stress

Figure 3. Deformation and normal stress distribution of the sub-scale habitat under the gravity load

It is observed in this case that the weight of the roof is transferred to the top of the cylindrical wall segments, as shown (g) and (h) in Figure 3. In addition to the contours of stress and deformation distributions, Figure 4 shows the direction of principal stresses as the vector's flux, which allows a better understanding of how stresses flow inside the habitat. While (a) in Figure 4 shows vectors of all finite elements of the model, (b) in Figure 4 shows only the locations of elements with the highest top 2 percent of critical stress magnitudes. The maximum principal stress case is the enveloped values by selecting the case having maximum absolute value among principal stresses A, B, and C which represents the maximum, median, and minimum (or negative with maximum magnitude) normal stress, respectively, experienced by an element with no shear stresses as seen in the Mohr's circle (Autodesk, 2020).



(a) Maximum principal stress vectors at the center of all finite elements



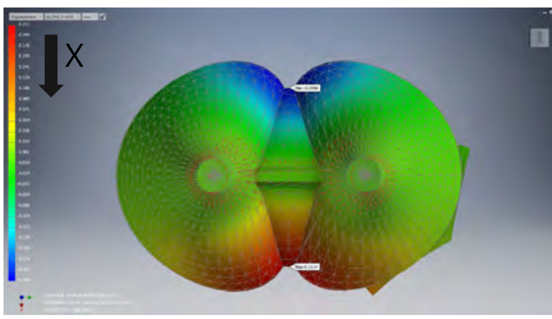
(b) Maximum principal stress vectors at the center of the finite elements of the top 2 percent of the magnitude

Figure 4. Vectors indicating the direction of maximum principal stress due to the gravity load on the Mars surface

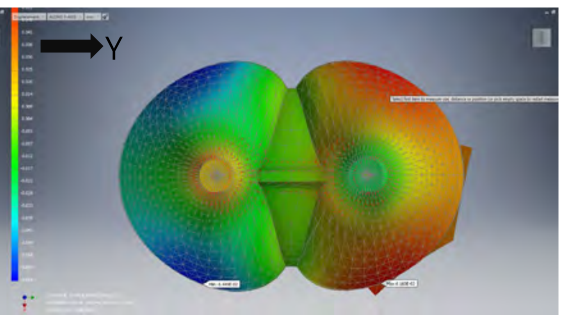
The pattern of maximum principal stresses shown in Figure 4-(a) indicates a certain tendency in the direction of stresses. The largest principal stresses are in the Z coordinate direction, which is the direction of the gravity load applied to the habitat. The top 2 percent of the largest magnitude principal stresses observed in Figure 4-(b) illustrate the critical location due to the load. The foundation supports the major part of the accumulated weight from the rooftop while the connection wall carries partial load near the wall. The upper part of the main entrance has considerable tension due to the bending moment illustrated by the blue color in Figure 4-(a), while the other part only has compression stresses. The distribution of maximum principal stresses in Figure 4-(b) reasonably agrees with the critical locations of maximum vertical deformation shown in Figure 3-(c).

Sub-scale Habitat under the Air Pressure Load

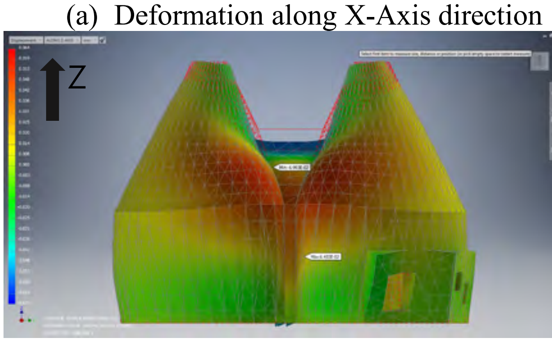
The internal air pressure (due to assumed applied Earth's atmospheric pressure) caused much higher stresses and deformations compared to that due to the gravity load. Because the pressure is applied in the perpendicular direction to the habitat's surfaces, the habitat wall is subjected to dilatational deformation. The cylindrical shape of the wall and cone-shaped roof provide a beneficial feature to distribute the stresses between cylindrical and conical parts smoothly; however, the complex shape component that connects the cylindrical units showed experiencing the stress concentration illustrated in Figure 5.



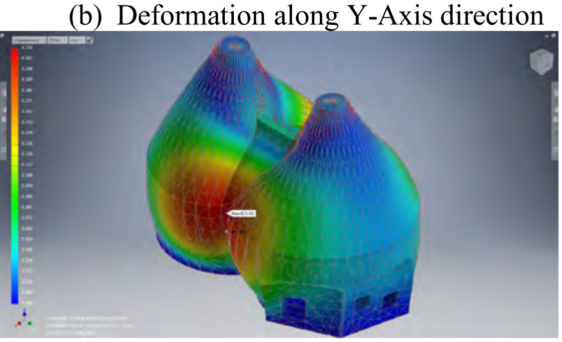
(a) Deformation along X-Axis direction

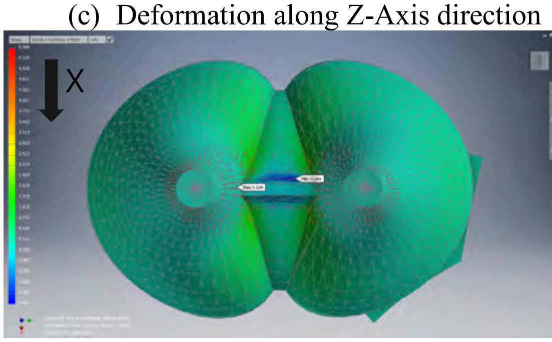


(b) Deformation along Y-Axis direction

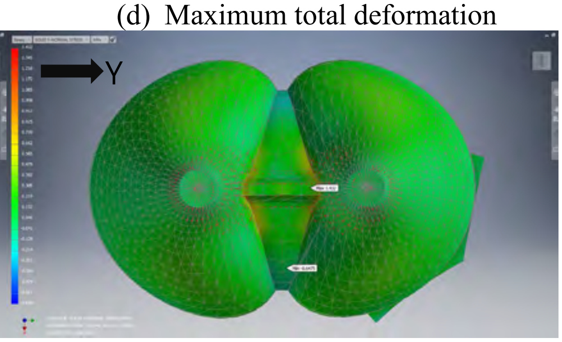


(c) Deformation along Z-Axis direction

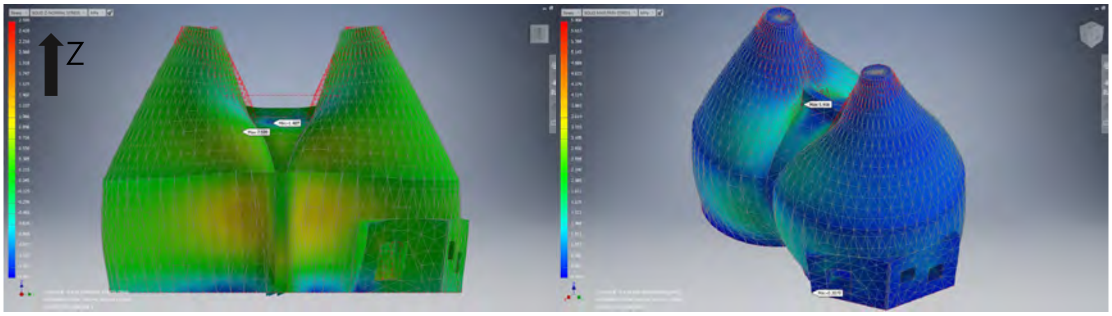

(d) Maximum total deformation



(e) Normal stress along X-Axis direction



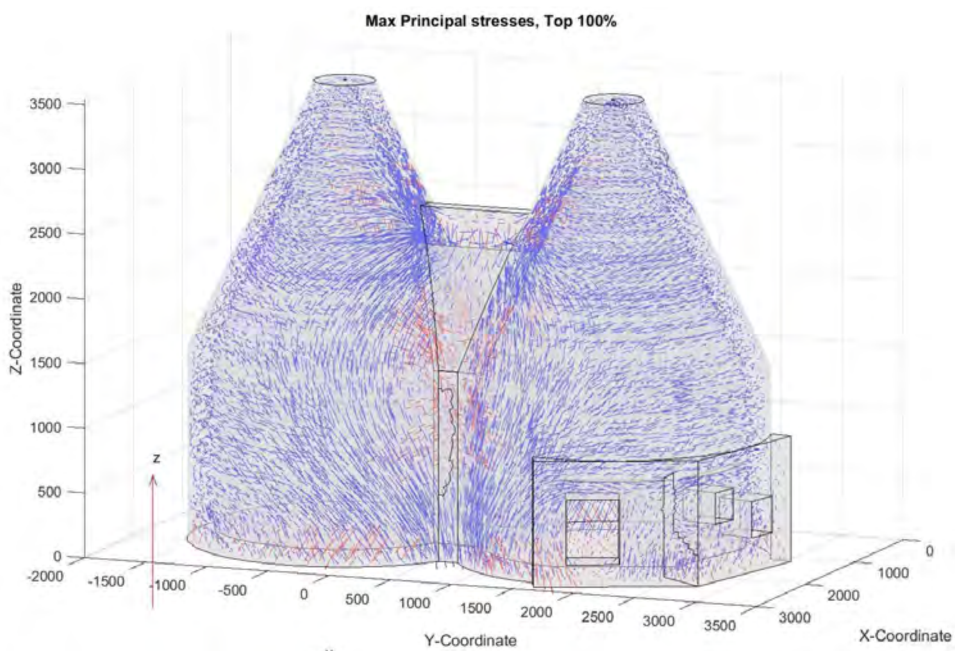
(f) Normal stress along Y-Axis direction



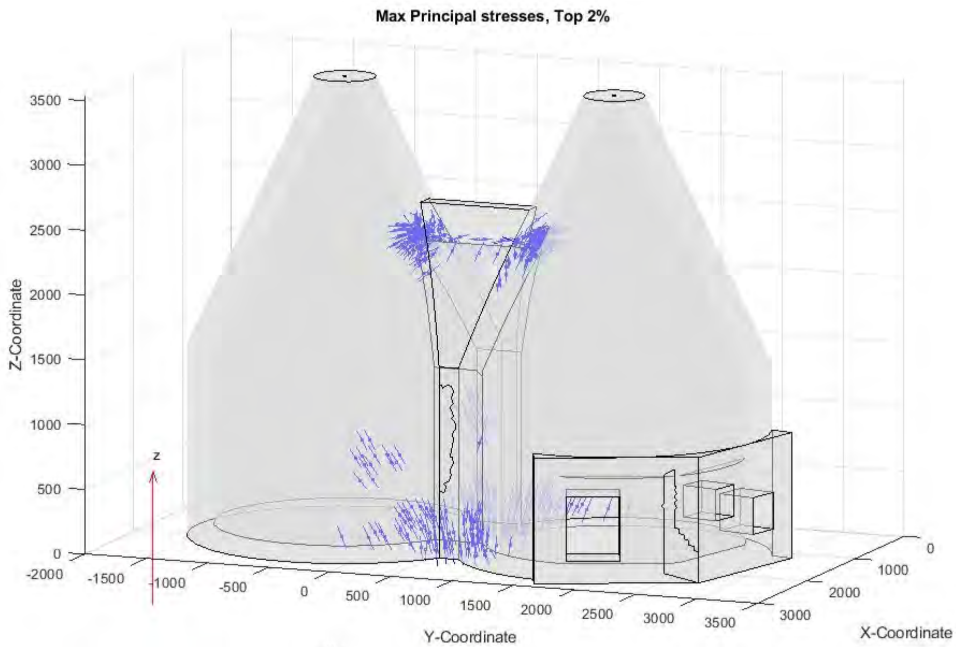
(g) Normal stress along Z-Axis direction (h) Maximum principal stress

Figure 5. Deformation and normal stress distributions of the sub-scale habitat under the pressure load

Figure 6 shows the vectors of the maximum principal stresses due to the internal air pressure load. Compared to the gravity load case, it shows distinctly different distribution patterns.



(a) Principal stresses vectors at the center of all finite elements



(b) Principal stress vectors at the center of the finite elements of the top 2 percent of the magnitude

Figure 6. Vectors indicating the direction of principal stresses due to the air pressure

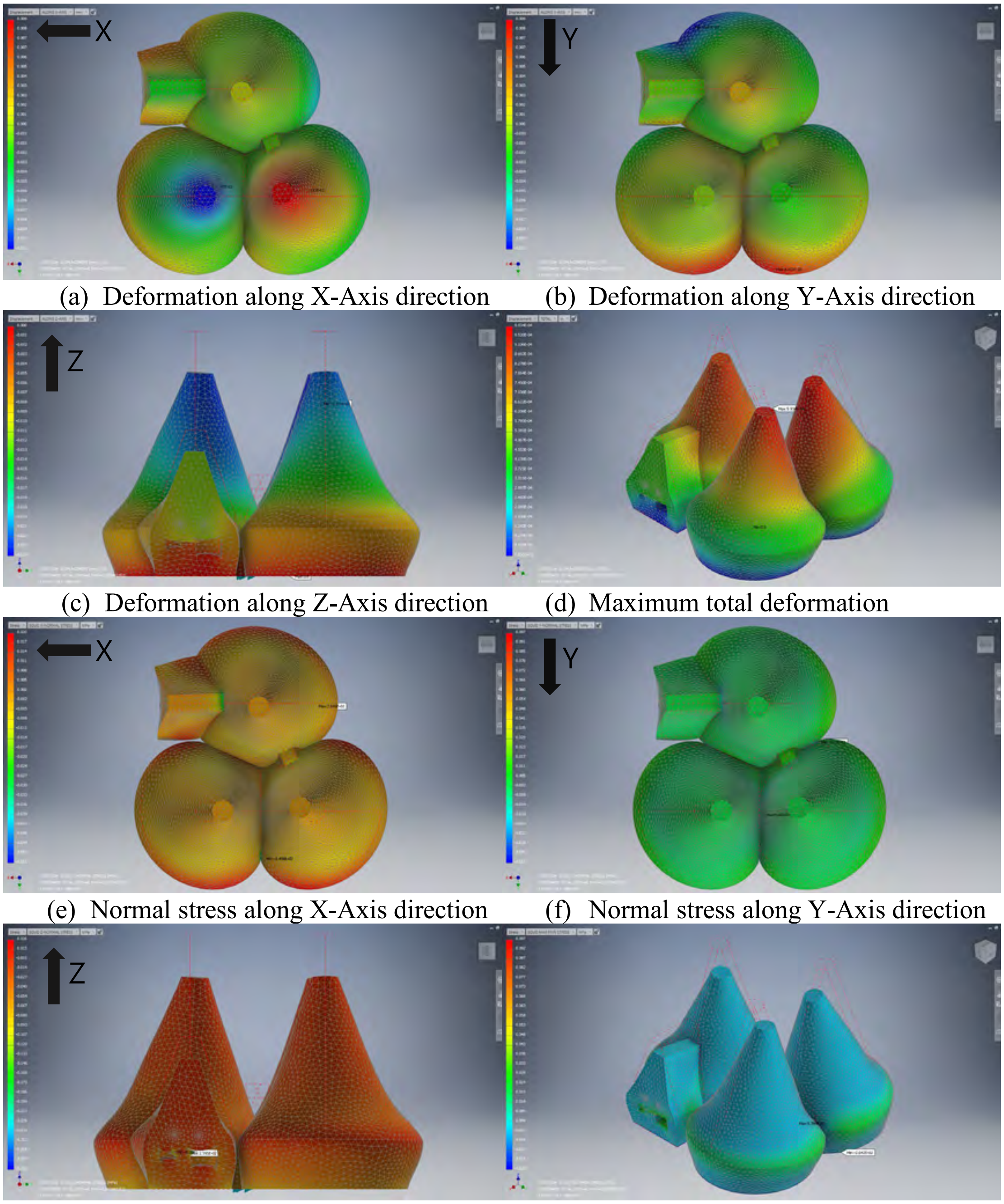
The internal air pressures tend to expand the habitat's wall outwardly. The blue color vectors in Figure 6-(a) show the outer surface of the habitat wall being under the tension because of the dilatational deformation. At locations away from the constraining positions, such as the middle of the wall, the results show that wall surfaces have compression and tension in perpendicular direction. On the other hand, the bottom end of the wall near the foundation shows compression and tension stresses aligned parallel to wall surfaces. Figure 6-(b) identifies the critical locations for the largest stress to be the corner edge between the connection segment and habitat units.

3.2 Full-scale habitat analysis

Structural analysis of the full-scale habitat design aims to consider actual structural response as the finalized habitat configuration design will have distinct behavior. The results of the sub-scale habitat analysis can be used to determine the feasibility of full-scale habitat design options. One of the finalized full-scale habitat designs shown in Figure 1 is analyzed through FEA.

Full-scale Habitat under the Gravity Load

The FEA results shown in Figure 7 confirm the expectation that there should be no critical stress in the full-scale habitat due to the gravity loads.



(a) Deformation along X-Axis direction (b) Deformation along Y-Axis direction

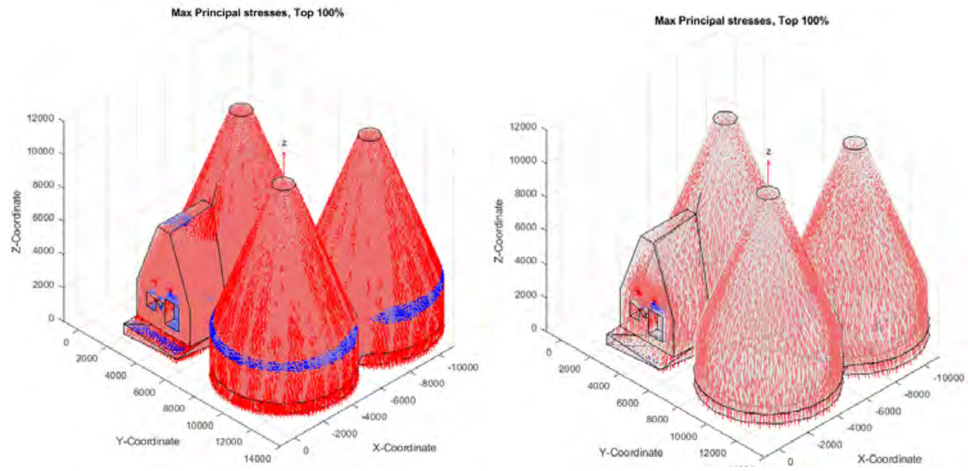
(c) Deformation along Z-Axis direction (d) Maximum total deformation

(e) Normal stress along X-Axis direction (f) Normal stress along Y-Axis direction

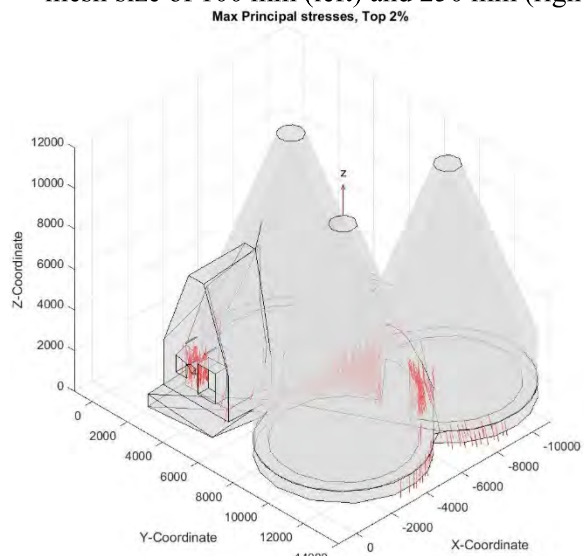
(g) Normal stress along Z-Axis direction (h) Maximum principal stress

Figure 7. Deformation and Normal stress distribution of the full-scale habitat under the gravity load

The cylindrical-shaped wall held the transferred weight of the roof with durable deformation of less than 0.01 mm along with both the horizontal and vertical directions, as seen in Figure 8-(a).



(a) Principal stresses vector at the center of all finite elements, the case of the average mesh size of 100 mm (left) and 250 mm (right)



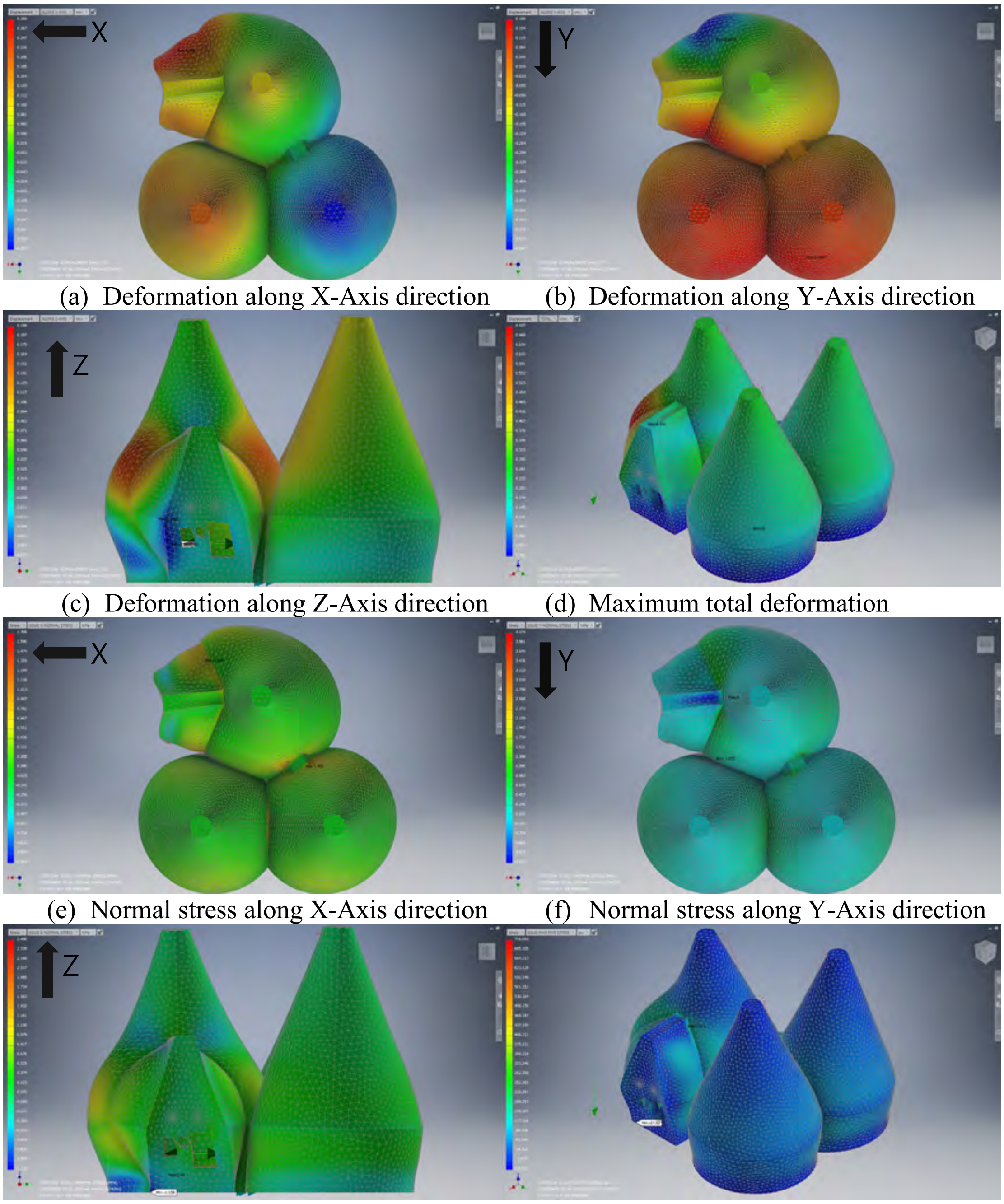
(b) Principal stresses vector at the center of the finite elements of the top 2 percent of the magnitude

Figure 8. Vectors indicating the direction of principal stress of the full-scale habitat due to the gravity load on the Mars surface

The maximum principal stresses due to the gravity load on the full-scale habitat are located along the edge of walls joining with the roof and foundations as Figure 8-(b). Those locations are expected to have simultaneous axial and bending stresses because of the roof's shape. The combined compressive stresses due to the bending moment and axial force resulted in stress concentrations shown in Figure 8. The blue color vectors indicating the tensile principal stresses in Figure 8-(a) are due to the bending moment at the wall to the roof joint.

Full-scale Habitat under the Air Pressure Load

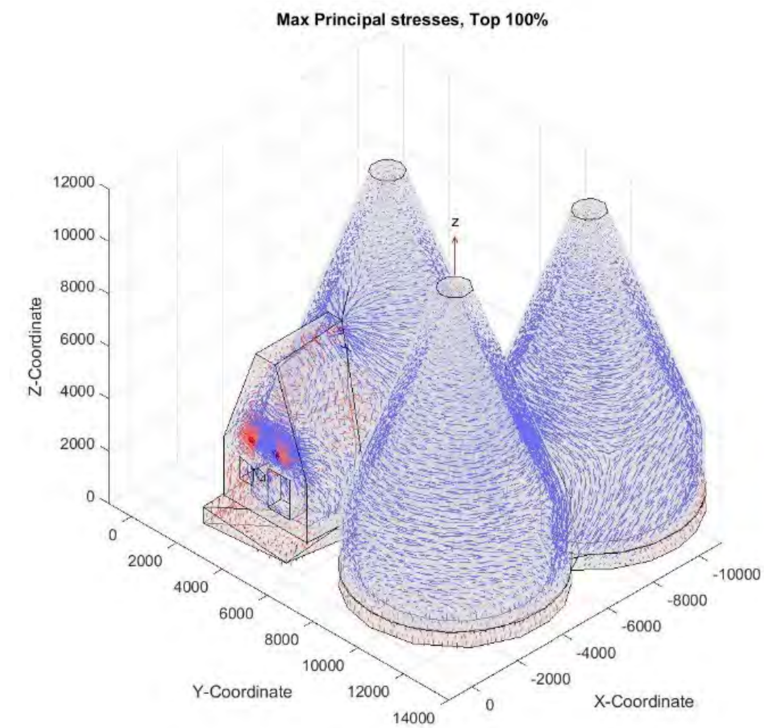
The closely grouped units constituting the full-scale habitat helps restrain the deformation by supporting to each other. The circular perimeter shape of the habitat unit is effective in retaining the outward force of the internal air pressure within the habitat.



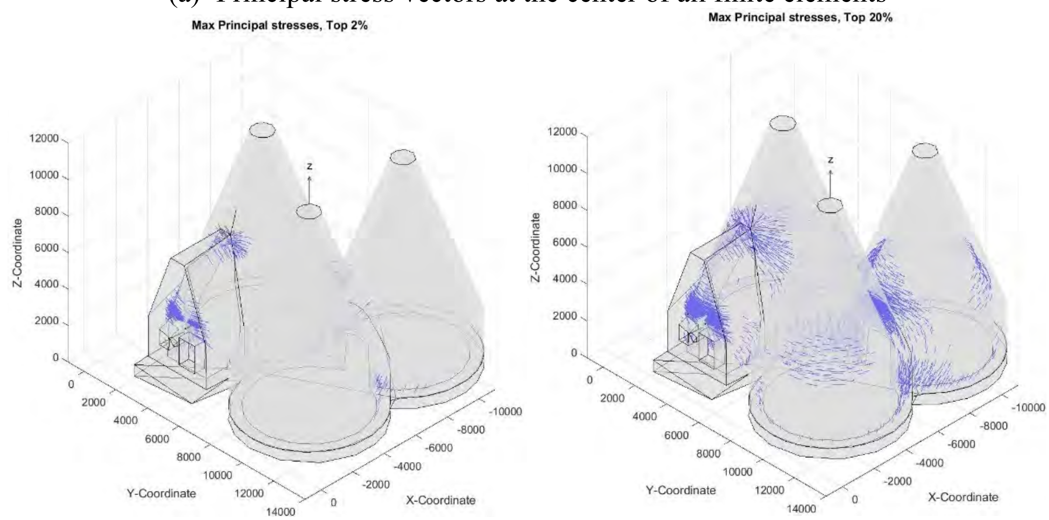
(a) Deformation along X-Axis direction
(b) Deformation along Y-Axis direction
(c) Deformation along Z-Axis direction
(d) Maximum total deformation
(e) Normal stress along X-Axis direction
(f) Normal stress along Y-Axis direction
(g) Normal stress along Z-Axis direction
(h) Maximum principal stress

Figure 9. Deformation and Normal stress distribution of the full-scale habitat under the pressure load

The maximum principal stresses of the full-scale habitat due to the internal air pressure show the positive principal stresses resulting from the dilatational behavior of the roof and wall. The connection between adjacent habitat units has a distinct stress flux because of its saddle shape, as shown in Figure 10-(a).



(a) Principal stress vectors at the center of all finite elements



(b) Principal stress vectors at the center of the finite elements with the top 2 and 20 percent largest magnitude

Figure 10. Vectors indicating the direction of principal stresses for the full-scale habitat due to the interior air pressure load

Based on principal stresses shown in Figure 10-(b), the critical locations for the principal stresses are near the connections between the units and the entrance segment. It is clearly observed that the edges of two intersecting planes have higher principal stresses than smooth surfaces.

3.3 Result summarization

The maximum deformation and stress values resulting from the structural analysis under the two loading conditions for both sub-scale and full-scale habitat design are listed in Table 3. Gravity load and internal air pressure resulted in significantly different stress magnitudes and patterns, with the latter having a more dominant condition for both the sub-scale and full-scale habitat designs. The maximum principal stresses due to the air pressure load in the full-scale habitat are about 53 times in tension and 5 times in compression larger than the stresses due to gravity load. For the sub-scale habitat design, the ratios are much higher, 389, and 32, respectively, for tension and compression. It should be noted that in this study, the same material properties were used for both the sub-scale and full-scale habitats. For more accurate analysis, the potential difference in material properties for construction on Earth vs. Mars may need to be taken into account.

The full-scale habitat under the gravity load does not show any critical stress, as the maximum compressive normal stresses along with X, Y, and Z directions have a magnitude less than 0.3 MPa, and the maximum principal stress is less than 0.1 MPa. On the other hand, under the interior air pressure conditions, the maximum positive principal stress (4.70 MPa, indicating tensile stresses), which is the bent edge at the top of the main entrance transitioning to the cone roof, exceeds 10% of the ultimate strength (2.47 MPa).

Table 3. Maximum values of the Structural analysis result under the varying load scenarios

		Deformation (μm)				Stress (kPa)			
		X-Dir.	Y-Dir.	Z-Dir.	Total	X-Dir.	Y-Dir.	Z-Dir.	Max Principal
Sub-scale Habitat	Gravity	-1.3	-0.8	-2.9	0	-9.6	-9.8	-42.3	-6.5
		1.4	0.8	2.4e-3	2.9	14.2	9.2	5.3	15.2
	Pressure	-208.6	-64.5	-69.9	0	-1,681	-647.5	-1,487	-207.9
		211.4	61.8	64.3	215.5	5,509	1,432	2,599	5,908
Full-scale Habitat	Gravity	-9.6	-9.2	-23.4	0	-39.4	-42.7	-217.7	-32.5
		8.4	8.6	0.3	24.7	20.5	88.2	35.5	88.6
	Pressure	-201.8	-607.3	-72.8	0	-1,032	-929	-1,348	-149.8
		262.1	182.3	183.6	652.1	1,320	3,088	4,355	4,697

3.4 Future Works

The considerable variation of air temperature on the Mars surface, as listed in Table 4, is one of the critical load cases, which should be considered in addition to the gravity and interior air pressure for the habitat design on Mars. The thickness of the habitat's wall for securing enough protection against the space radiation can be a cause of significant stresses from thermal expansion. In the follow-up study, the sub-scale and full-scale habitat designs will also be subjected to temperature load on Mars at the site where the habitat is considered for construction. After all three load cases are considered, the habitat design may need to be revised/updated to reflect the critical locations in each load case.

Table 4. Temperature variation in differences between the Mars surface and the inside of the habitat

Loading Case	Mars Surface	Inside of the habitat	Temperature Difference from the Room Temperature (Δ)
High Temperature (Viking 1 lander site)	-31°C (242K; -24°F)	25°C (298K; 77°F)	56°C (56K; 101°F)
Low Temperature (Viking 1 lander site)	-89°C (184K; -128°F)		114°C (114K; 205°F)
Highest Temperature (Equator)	20°C (293K; 68°F)		5°C (5K; 9°F)
Lowest Temperature (South pole)	-153°C (120K; -243°F)		178°C (178K; 320°F)
Average Temperature	-63°C (210K; -82°F)		88°C (88K; 158°F)

4 Conclusion

This study dealt with the challenge of generating the modeling for the 3D printed habitat for the intensive parametric design study by using the SAT data transferring platform by Autodesk, which is connected to STL file format through the Autodesk Fusion and 3Ds Max.

As expected, the FEA of sub-scale habitat and full-scale habitat showed close similarity in the overall tendency in stress distribution for both cases. This means that the findings from studying sub-scale habitat design can be used in developing the full-scale habitat design. The following conclusions may be drawn from the study presented, in particular, structural analysis results:

- Exchanging the configurative information of a printing object needs the manipulation of the file format for securing the mesh integrity of FE analysis; for example, if a design authoring program gives a geometry consisting of 3D mass and plates, FE modeling would face challenges such as defining the analysis dimensions, applying load to an object, or constraining a body.
- For printing on the Mars surface, just as on Earth, continuity of the load path in a habitat's geometry is essential.
- The internal air pressure applies dilatational stress distribution with a concentration near the connection of the habitat unit. Hence, an additional consideration such as reinforcing bar, mesh, or cord to restrain the tensile stresses at the critical weak areas would be needed.
- It is observed that the wall and roof's circular geometry in the habitat design effectively helps to prevent critical stress due to the internal air pressure. The habitat's wall and roof have mild stress distribution within

allowable stress magnitude relative to the assumed rupture stress (10% of the ultimate stress).

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Experimental Testing and Finite Element Modeling of 3D-Printed Reinforced Concrete Beams

Keunhyoung Park[1], Ali Memari[2], Maryam Hojati[3], Mehrzad Zahabi[4], Shadi Nazarian[5], José Pinto Duarte[6]

[1]Graduate Student, The Department of Architectural Engineering, The Pennsylvania State University, 310 Sackett Building, University Park, PA 16802, (814) 308-3014, khpark@psu.edu
[2]Professor, The Department of Architectural Engineering/Civil and Environmental Engineering, The Pennsylvania State University, 222 Sackett Building, University Park, PA 16802, (814) 863-9788, amm7@psu.edu
[3]Assistant Professor, The Department of Civil, Construction and Environmental Engineering, The University of New Mexico, 3052 Centennial Engineering Center, Albuquerque, NM 87131, (505) 277-1488, mhojati@unm.edu
[4]Graduate Student, The Department of Architectural Engineering, Pennsylvania State University, 310 Sackett Building, University Park, PA 16802, mzz29@psu.edu
[5]Associate Professor, The Stuckeman School of Architecture and Landscape Architecture, Pennsylvania State University, 222 Stuckeman Family Building, University Park, PA 16802, (814) 865-0875, sun14@psu.edu
[6] Professor, The Stuckeman School of Architecture and Landscape Architecture, Pennsylvania State University, 222 Stuckeman Family Building, University Park, PA 16802, (814) 863-4584, jxp400@psu.edu

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Additive construction through digital design and 3D printing of concrete elements is expected to transform the construction industry in the near future and is rapidly gaining acceptance. The advantages include the fact that it eliminates the cost of formwork and associated labor and enhances the ability to create more complex shapes, surface conditions, new details, and making new spatial and architectural expressions possible. The structural behavior of these 3D printed concrete components is different from conventional cast elements due to the nature of 3D printing by laying filaments side by side to make a layer and layer over layer to make a 3D shape. This may result in concrete with lower strength compared to cast concrete due to potentially less than perfect bond between filament (potential for cold joint) and tiny gaps between filaments due to the round shape of the filaments. There is limited research with many unknowns regarding the mechanical properties of printed hardened concrete components, which has hindered their practical application. One area of significance is how to reinforce these elements and how to model them numerically -- as printed concrete exhibits low tensile strength. Embedding reinforcing rebars in a printed beam would be an option; however, the response of the printed component would be essentially different from reinforced cast beams. Using a pump to extrude filaments and the occasional presence of voids between these filaments make the printed material anisotropic with directionally dependent properties and with different mechanical behavior compared to conventional concrete. In this study, two different rebar types, FRP and Steel, were used to reinforce 100×150×1200 mm beams, and their strengths were measured by conducting three-point bending flexural tests. Structural analysis was then performed on finite element models of the beams to determine the response of printed beams. In this modeling, the printed concrete was assumed to be isotropic just as cast concrete, thus not accounting for the potentially weaker bond between filaments. The experimental results indicated low bond strength between the printed material and embedded rebars, causing the beams to fail under relatively low bending stress due to the separation of the reinforcement from the printed material (filaments) when concrete cracked. This means that the reinforcement did not reach the state of yielding as it is expected in reinforced concrete design. Autodesk Nastran that is embedded in Inventor 2019 by Autocad was used to carry out Finite Element Analysis using the tetrahedron element for volumetric mesh generation. The finite element modeling validation was done by comparing the numerical results to the analytical solution of simple reinforced concrete beams. The mechanical properties of the 3D printed concrete are estimated through a comparison of the analytical and numerical responses of the beam to the actual testing results.

1 Introduction

Concrete for additive manufacturing (AM) systems has a unique behavior distinct from the typical cast Portland cement concrete and must be able to realize proper buildability, extrudability, and pumpability at the same time (Asprone et al. 2018; Bentz et al. 2018; Bos et al. 2016; Gibson et al. 2015; Gosselin et al. 2016; Wu, Wang, and Wang 2016). This paper provides information related to compressive testing of rectangular prism samples and bending tests of simple pin-supported beams to help understand the basic mechanical behavior of printed beams with the AM concrete mix designed by Penn State 3D concrete printing research team and GCT ('Gulf Concrete Technology'). Due to the limitation in large volume production of the Penn State's concrete, the readily off the shelf available GCT concrete was used to study the behavior of reinforced 3D printed concrete. The ultimate compressive strength and modulus of elasticity based on the compressive tests are used to predict the bending test results through computational modeling.

Several beams with varying reinforcement configurations were printed and tested under flexural loading conditions. In this study, the direction of reinforcement for flexural strength was parallel to the direction of filaments. Such tests of printed beams help to determine whether printed concrete members will have sufficient structural capacity. Besides conventional steel rebars, FRP rebars were also used as reinforcement for comparison purposes. In addition to the beams, this paper reports on testing printed and cast prisms to determine the compressive strength and stress-strain relations. Such tests were also aimed at studying the effect of direction of loading with respect to printed filaments. One aspect of 3D printing of beams and other reinforced components is the concern for anisotropic behavior of printed concrete.

2 Estimation of the 3D printed beam's flexural bending behavior

2.1 Determination of material properties for computational analysis modeling

Samples for compressive loading were cut from a 3D printed beam into a prism shape specimen with dimensions of 120mm x 120mm x 240mm. Additionally, cubic prisms were also cast to the size of 100x100x200 mm to compare their strength with printed concrete. Compressive axial loading test on the prisms was performed by using a Boart Longyear Loading Frame (BLLF) (Figure 1) after specimens were tested on the universal testing machine (UTM) (2) with a capacity lower than ultimate compression strength for determining the ultimate compressive strength as shown in Table 1.

Figure 1. The material testing machine used to determine the ultimate strength of the samples: Boart Longyear loading frame Model CM-625 with a CSI Model CS-100-2A Retrofit with a Capacity of 400Kips

As mentioned above, prior to testing the prisms for ultimate compressive strength, compressive axial loading tests were carried out on the printed prisms by using a UTM (2) up to about 40% of estimated compressive strength. The measured ultimate compressive strength of the prism then allowed accurate determination of the 40% of the ultimate compressive stress, which is assumed to be the elastic range of normal concrete materials according to the ASTM C469.

Table 1. Measured ultimate compressive strength and calculated elastic range compression for each specimen cases

Case	Ultimate Compressive Strength		40% of Ultimate Compressive Strength	
	Axial Load	Axial Stress	Axial Load	Axial Stress

	lbs	kN	psi	MPa	lbs	kN	psi	kN
V11[1)]-PSU[4)]	130,350	579.83	5,614	38.71	52,140	231.93	2,246	15.48
V21-GCT[5)]	79,485	221.45	3,586	24.72	28,294	125.86	1,434	9.89
H11[2)]-PSU	89,130	383.13	3,807	26.25	35,652	158.59	1,523	10.50
H22-GCT	66,130	294.16	2,872	19.80	26,452	117.66	1,149	7.92
C2[3)]-PSU	108,200	481.30	8,283	57.11	43,280	192.52	3,313	22.84

1) V means the beads pattern in the specimen is aligned parallel to the loading direction, 2) H means the beads pattern in the specimen is aligned perpendicular to the loading direction, 3) C means there is no bead's pattern in the specimen because it is cast, 4) PSU means the material is designed by Penn State, 5) GCT means the material is designed by Golf Concrete Technology.

Compression loads were applied to the prism samples, which had electric strain gauges attached to the center of all four side surfaces as shown in Figure 2. Using the UTM, the compression loading reached a maximum of 55 kips without failure of the prism with two repetitions for the same specimen. The applied axial force and displacement of the testing machine's bed were recorded with the same timestamp of the strain gauges on the sample. The normal stress value of the horizontal cross-section of the sample due to the compression loading is calculated by dividing the applied force by the cross-section area. It is assumed that the stresses on the cross-section are uniformly distributed.

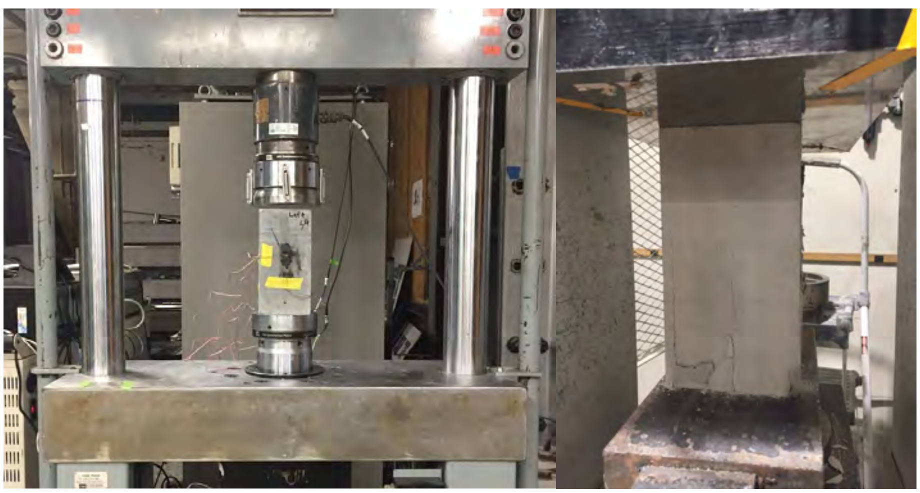


Figure 2. Universal testing machines used for applying axial compression loading to the samples

The stress-strain relation was derived based on the testing results using UTM. The measured stress-strain values over the time-varying period are plotted as points and then regressed with a curve of power series form with the nonlinear least-squares method shown as the continuous line in Figure 3. Secant modulus of elasticity for each test sample was calculated based on the function of the regressed Stress-Strain curve at the point whose stress value is 40% of its ultimate compressive strength, which was determined by using the BLLF machine.

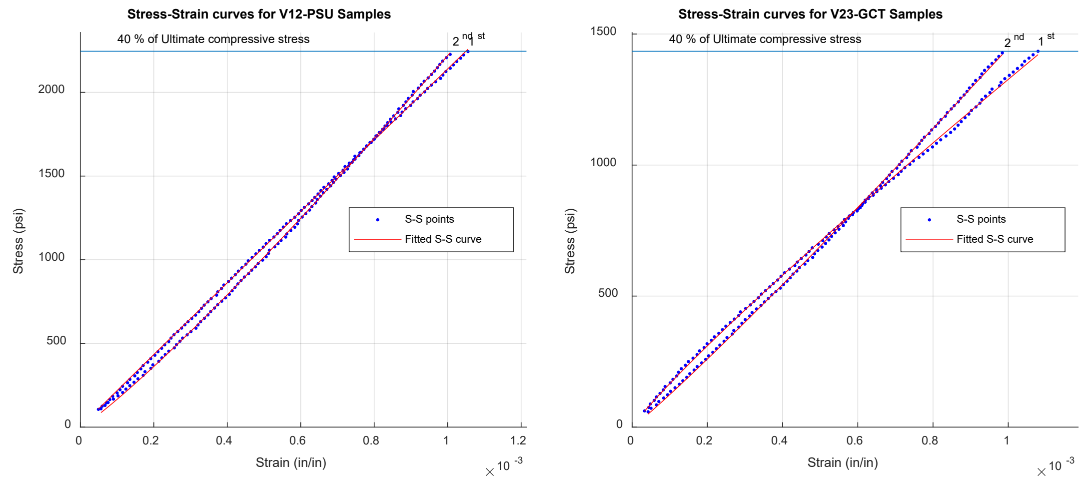


Figure 3. Strain-Stress curves of the 3D printed prisms made of material designed by Penn State 3D printing research team (sample V12, left graph) and GCT (sample V23, right graph).

For all sample cases, the values of secant modulus of elasticity at the point of 40% of the tested ultimate compressive strength are listed in Table 2.

Table 2. Secant modulus of elasticity and the ultimate compressive strength based on the testing result for all sample cases

Case		Secant Modulus of Elasticity at 40% at the Ultimate Strength, ksi (MPa)	Measured Ultimate Compressive Strength, psi (MPa)
V12-	First	2,139 (14,748)	5,614 (38.71)
PSU	Second	2,223 (15,327)	
V23-	First	1,317 (9,080)	3,586 (24.72)
GCT	Second	1,445 (9,963)	
H12-	First	2,893 (19,947)	3,807 (26.25)
PSU	Second	3,190 (21,994)	
H23-	First	2,438 (16,809)	2,872 (19.80)
GCT	Second	2,037 (14,045)	
C1-	First	2,151 (14,831)	8,283 (57.11)
PSU	Second	2,164 (14,920)	

2.2 Analytical estimation of the flexural bending of a 3D printed beam

This three-point load beam bending test is intended to gauge the accuracy of structural computational modeling of a 3D printed beam to predict the response of the beam under a simple pin loading condition. The secant elastic modulus and ultimate compressive strength from the compressive load testing listed in Table 2 were used in the modeling. Such data allows the modeling of printed beams and cast beams; however, in this study, only printed beams were made. The measured deflection at the center of the test beam where a point load is applied is compared to the computational modeling when the beam failed. The result helps to see the feasibility of the analytical modeling to estimate the flexural behavior of a 3D printed concrete beam.

Beam without reinforcing bars

Initially, a beam without reinforcing bars was considered for such a comparison in order to establish the model accuracy for an unreinforced and pure concrete beam.

The 3D printed beam without reinforcement had printed beads parallel to the longitudinal direction of the beam. The loading consisted of a point load applied at the mid-span of the simply supported beam where two simple pins support spaced at 1000 mm provided the reaction points as shown in Figure 4.

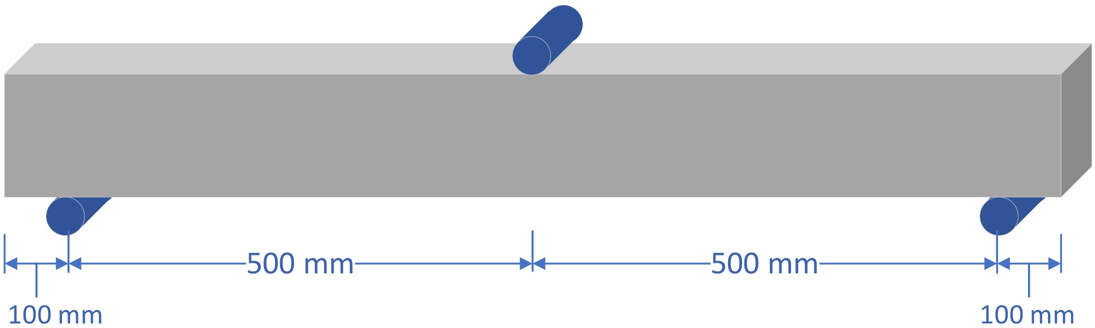
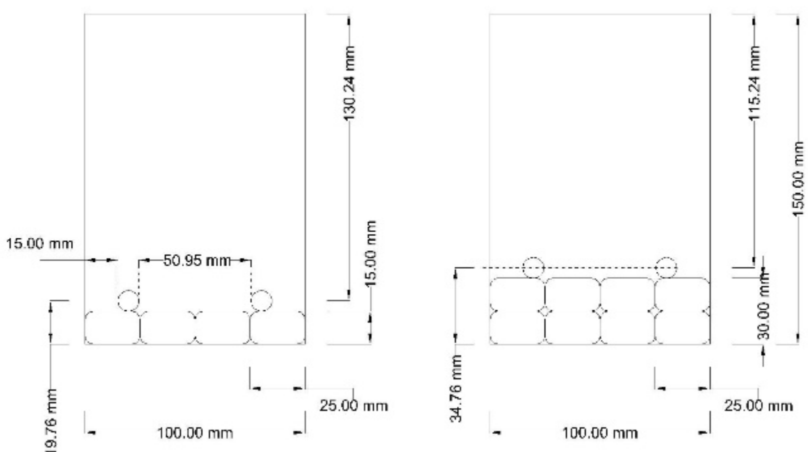


Figure 4. Flexural bending testing of a simple pin-supported beam sample

Assuming linear elastic behavior for the beam, we can determine the flexural resistance based on the assumption that a plane section before bending remains plane after bending, which leads to linear normal strain distribution over the cross-section.

Beam with reinforcing bars

Considering that concrete is brittle, adding reinforcing in a concrete beam will reduce crack widths due to tensile stresses and is an effective way to increase the beam's flexural strength. In order to evaluate the effective placement of rebars, several configurations for the number and location of the reinforcement with respect to printed filaments were considered as shown in Figure 5.



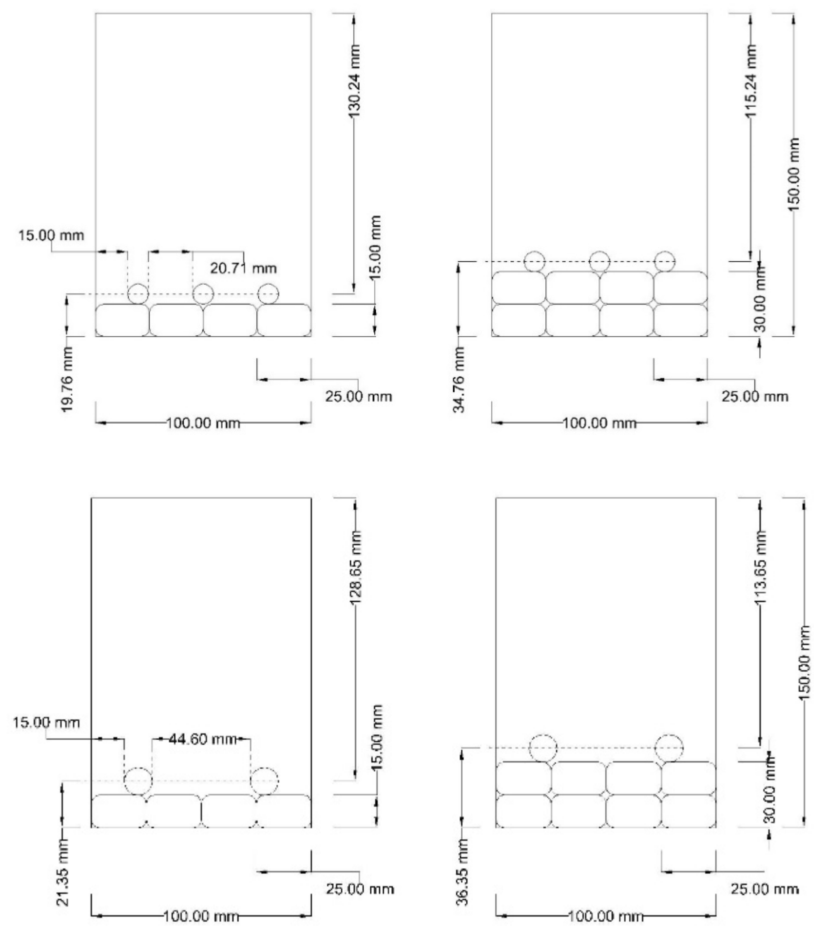


Figure 5. Reinforcement configurations considered for the printed beams limited in using #3 (9.5 mm dia.) (Top and Middle) and #4 (12.7 mm dia.) size rebar (Bottom); The left side beams in the figure have 15 mm clear cover at the bottom, while the ones on the right side have 30 mm clear cover at the bottom; the clear cover on the sides for all beams 15 mm.

The reinforcing bar area was chosen not to exceed 2% of the effective area for all considered rebar configurations. The calculated maximum compressive and tensile stresses (at the top and bottom fibers of the beam section) based on cast reinforced concrete structural analysis are compared to the stresses obtained from the FEM results, which are based on using the prism test results (compressive strength).

Based on the properties of typical steel rebar and the GCT concrete shown in Table 3, Table 4 shows the tabulated calculation for the printed beams reinforced with steel rebars.

Table 3. Mechanical properties of materials used in the analytical solution of a 3D printed beam with steel rebar

Property	Steel Yield Strength, f_y ksi (MPa)*	Steel Elastic Modulus, E_y, ksi (MPa)	Concrete Ultimate Strength, f'_c, ksi (MPa)**	Concrete Elastic Modulus, E_c ksi (MPa)	Concrete Yield Strength, ksi (MPa)***	Concrete Tangential Elastic Modulus, E_{ct} ksi (MPa) ****
Value	58.0 (400.0)	29,006 (200,000)	3.6 (24.7)	1,341 (9,246)	2.2 (15.5)	250 (1,724)

* Typical steel rebar basis, ** for GCT concrete, *** 40% of Ultimate Strength, **** Assumed as 20% of the elastic modulus

The moment capacity of the printed beam with steel rebar has an excellent agreement (with less than 0.1% error) between the conventional analytical solution and the strain compatibility method, except a beam has double tensile rebar layers with three rebars per each layer that has compression-controlled failure mode. Table 4 shows the result from the strain compatibility method because it is expected to consider the more accurate status of the beam's failure mode than the conventional analytical solution reflecting conservatively.

Table 4. Calculated moment capacity for beams with steel rebars and the critical stress values

Cases			Effective Depth, d_e, in (mm)	Rebar Area in^2 (mm^2)	Rebar Area Ratio (%)	Max. Tensile Stress σ_t at the rebar, ksi (MPa)	Max. Tensile Strain of Rebar (in/in)	Nominal Moment Capacity*, k-ft (kN-m)	Failure Mode	Pin Load Capacity for Beam kips (kN) **
#3 Rebar	15 mm cover	1-Layer with 2 Rebar/layer	5.1 (130)	0.22 (142)	1.1	58.0 (400)	0.00929	6.0 (4.4)	Tension-controlled	5.4 (23.9)
		1-Layer with 3 Rebar/layer	5.1 (130)	0.33 (213)	1.6	58.0 (400)	0.00519	6.2 (8.4)	Tension-controlled	7.6 (33.7)
		2-Layer with 2 Rebar/layer	4.6 (118)	0.44 (284)	2.2	58.0 (400)	0.00314	5.7 (7.7)	Transitioning	6.9 (30.8)
		2-Layer with 3 Rebar/layer	4.6 (118)	0.66 (426)	3.3	58.0 (400)	0.00209	5.6 (7.6)	Transitioning	6.9 (30.8)
	30 mm cover	1-Layer with 2 Rebar/layer	4.5 (115)	0.22 (142)	1.2	58.0 (400)	0.00787	3.8 (5.2)	Tension-controlled	4.7 (20.8)
		1-Layer with 3 Rebar/layer	4.5 (115)	0.33 (213)	1.9	58.0 (400)	0.00425	5.0 (6.8)	Transitioning	6.1 (27.1)
		2-Layer with 2 Rebar/layer	4.1 (103)	0.44 (284)	2.5	58.0 (400)	0.00244	4.1 (5.7)	Transitioning	4.9 (22.0)
		2-Layer with 3 Rebar/layer	4.1 (103)	0.66 (426)	3.7	57.6 (396.9)	0.00198	4.4 (5.9)	Compression -controlled	5.3 (23.7)
#4 Rebar	15 mm cover	1-Layer with 2 Rebar/layer***	5.1 (129)	0.4 (258)	2.0	58.0 (400)	0.00368	6.3 (8.5)	Transition section	7.6 (34.0)
		1-Layer with 3 Rebar/layer	5.1 (129)	0.6 (387)	3.0	53.4 (368.1)	0.00184	6.5 (8.8)	Compression -controlled	7.9 (35.1)
		2-Layer with 2 Rebar/layer	4.5 (115)	0.8 (516)	4.0	54.9 (378.5)	0.00189	5.9 (7.9)	Compression -controlled	6.7 (29.8)
		2-Layer with 3 Rebar/layer	4.5 (115)	1.2 (774)	6.0	42.8 (295.4)	0.00148	5.8 (7.8)	Compression -controlled	7.0 (31.3)
	30 mm cover	1-Layer with 2 Rebar/layer	4.5 (114)	0.4 (258)	2.3	58.0 (400)	0.00290	4.9 (6.7)	Transitioning	6.0 (26.7)
		1-Layer with 3 Rebar/layer	4.5 (114)	0.6 (387)	3.4	48.8 (336.2)	0.00168	5.2 (7.0)	Compression -controlled	6.3 (28.0)
		2-Layer with 2 Rebar/layer	3.9 (100)	0.9 (516)	4.5	52.6 (362.6)	0.00181	4.6 (6.3)	Compression -controlled	5.2 (22.9)
		2-Layer with 3 Rebar/layer	3.9 (100)	1.2 (774)	6.8	41.4 (285.6)	0.00143	4.4 (6.0)	Compression -controlled	5.4 (24.0)

* Nominal moment capacity adopts the strength reduction factor value 0.65 for compression-controlled beam, 0.9 for the tension-controlled beam with the max tensile strain in the rebar greater than 0.005, and interpolated between 0.65 and 0.9 based on the rebar's strain for the beam with the max tensile strain in the rebar between 0.002 and 0.005 (ACI 318-14, Section 21.2)
** The simple pin support beam has 1m length
*** Selected case for the actual pin-loading test as shown in the left part of Figure 6

The results in Table 4 show that the moment capacity for one layer vs two layers is usually not significantly different (max. 3% difference), except when the case of 2-rebar per layer with #3 rebar (max. 28% difference), but the capacity of rebars on one layer vs two layers of filament is considerable (about 17% on average of all cases). Changing the number of rebars per layer from two to three results in the noticeable increase in moment capacity (about 20% average of all cases) while making double the rebar layer does have relatively less moment capacity increasing (about 7.4% average of all cases). The beam with two #4 steel rebar with 15 mm cover thickness is chosen as the testing specimen scheme because it accomplishes the best moment capacity among the cases where the rebar area ratio does not exceed 2% of the beam's effective cross-section area.

On the other hand, Fiber-reinforced polymer (FRP) provides an alternative option for steel rebar reinforcement. FRP rebars offer beneficial characteristics such as lightweight, high strength, and corrosion resistance. The FRP rebar herein is GFRP (Jabbar and Farid 2018; Tu et al. 2019), which has higher tensile strength but lower elastic modulus compared to the steel rebar's yield strength and elastic modulus, respectively, as shown in Table 5. The tensile strength of FRP rebar is regarded as the brittle failure limit because FRP rebar has no ductility compared to the steel rebar (Jabbar and Farid 2018).

Table 5. Mechanical properties of materials used in the analytical solution of a 3D printed beam with FRP rebar

Property	FRP Tensile Strength, f_y ksi (MPa)	FRP Elastic Modulus E_y, Ksi (MPa)	FRP Yield Strain, ε_y, in/in	Concrete Yield Strength, f'_c, ksi (MPa)**	Concrete Elastic Modulus, E_c ksi (MPa)	Concrete Extreme Strain, ε_c', in/in
Value	85.6 (590)	7,252 (50,000)	0.2	3.6 (24.7)	1,341 (9,246)	0.003

* Typical steel rebar basis, ** GCT concrete mentioned in Section 2.1.

A beam with FRP rebar shows some difference between the strain compatibility method and conventional analytical solution at a maximum of 13%. The moment capacity reduction factor for this beam is fixed as the minimum value 0.65 for compression-controlled failure mode because of the lack of ductility in FRP rebar after its yields.

Table 6. Calculated moment capacity for beams with FRP rebars and the critical stress values

		Cases	Effective Depth, d_e, mm (in)	Rebar Area mm^2 (in^2)	Rebar Area Ratio (%)	Max. Tensile Stress σ_t at the rebar, ksi (MPa)	Max. Tensile Strain of Rebar (in/in)	Nominal Moment Capacity* ,k-ft (kN-m)	Failure Mode	Pin Load Capacity for Beam Ksi (kN) **
#3 Rebar	15 mm cover	1-Layer with 2 Rebar/layer***	5.1 (130)	0.22 (142)	1.1	72.6 (500)	0.01001	3.9 (5.2)	Compression -controlled	4.7 (20.9)
		1-Layer with 3 Rebar/layer	5.1 (130)	0.33 (213)	1.6	58.2 (401)	0.00802	4.5 (6.1)	Compression -controlled	5.5 (24.4)
		2-Layer with 2 Rebar/layer	4.6 (118)	0.44 (284)	2.2	49.6 (342)	0.00685	4.0 (5.4)	Compression -controlled	4.9 (21.7)
		2-Layer with 3 Rebar/layer	4.6 (118)	0.66 (426)	3.3	39.6 (273)	0.00547	4.6 (6.2)	Compression -controlled	5.6 (24.8)
	30 mm cover	1-Layer with 2 Rebar/layer	4.5 (115)	0.22 (142)	1.2	69.5 (479)	0.00959	3.2 (4.4)	Compression -controlled	3.9 (17.6)
		1-Layer with 3 Rebar/layer	4.5 (115)	0.33 (213)	1.9	55.8 (385)	0.00770	3.8 (5.1)	Compression -controlled	4.6 (20.5)

		2-Layer with 2 Rebar/layer	4.1 (103)	0.44 (284)	2.5	47.7 (329)	0.00658	3.3 (4.4)	Compression -controlled	4.0 (17.7)
		2-Layer with 3 Rebar/layer	4.1 (103)	0.66 (426)	3.7	38.2 (263)	0.00527	3.7 (5.0)	Compression -controlled	4.5 (20.1)
#4 Rebar	15 mm cover	1-Layer with 2 Rebar/layer	5.1 (129)	0.4 (258)	2.0	53.5 (369)	0.00738	4.9 (6.6)	Compression -controlled	5.9 (26.3)
		1-Layer with 3 Rebar/layer	5.1 (129)	0.6 (387)	3.0	42.9 (296)	0.00592	5.6 (7.6)	Compression -controlled	6.8 (30.4)
		2-Layer with 2 Rebar/layer	4.5 (115)	0.8 (516)	4.0	36.6 (253)	0.00505	4.7 (6.4)	Compression -controlled	5.8 (25.7)
		2-Layer with 3 Rebar/layer	4.5 (115)	1.2 (774)	6.0	29.3 (202)	0.00405	5.3 (7.2)	Compression -controlled	6.5 (28.9)
	30 mm cover	1-Layer with 2 Rebar/layer	4.5 (114)	0.4 (258)	2.3	51.7 (356)	0.00713	4.1 (5.5)	Compression -controlled	5.0 (22.2)
		1-Layer with 3 Rebar/layer	4.5 (114)	0.6 (387)	3.4	41.6 (287)	0.00573	4.7 (6.4)	Compression -controlled	5.8 (25.6)
		2-Layer with 2 Rebar/layer	3.9 (100)	0.9 (516)	4.5	35.6 (246)	0.00491	3.8 (5.2)	Compression -controlled	4.7 (20.9)
		2-Layer with 3 Rebar/layer	3.9 (100)	1.2 (774)	6.8	28.7 (198)	0.00396	4.3 (5.9)	Compression -controlled	5.4 (23.5)

* Nominal moment capacity adopts the strength reduction factor value 0.65 for all cases because FRP rebar has no ductility after it yields (ACI 318-14, Section 21.2)
** The simple pin support beam has 1m length
*** Selected case for the actual pin-loading test as shown in the right part of Figure 6

Considering the limited width of the beam, maximum rebar area ratio (2%), failure mode, convenience of rebar placing, and the larger capacity for the position of rebars above a layer of filament, the following reinforcement configuration as shown in Figure 6 was adopted for comparison of the computation modeling to actual load test.

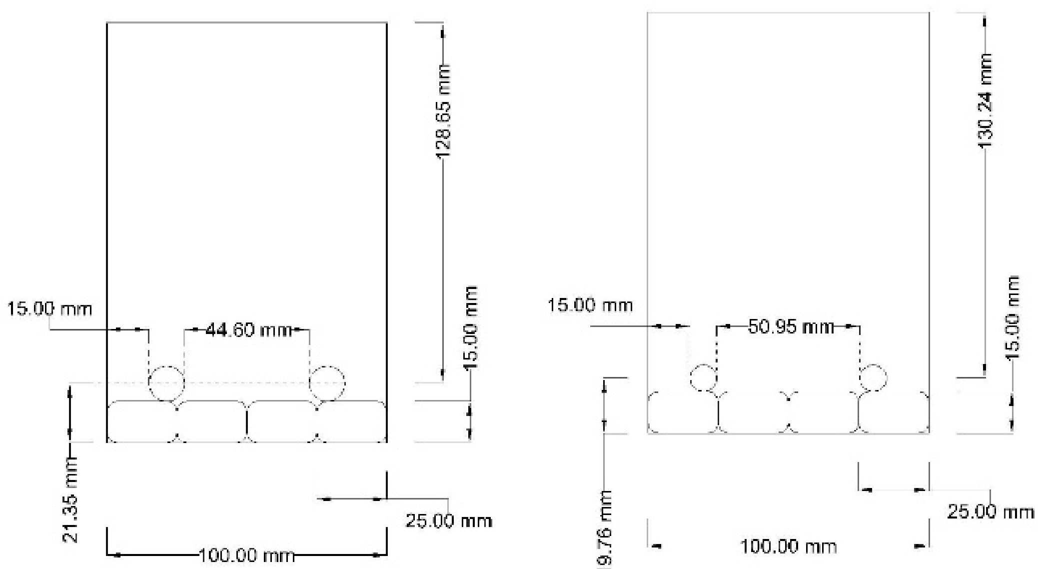


Figure 6. Reference reinforcing configuration for the printed beams with two #4 steel rebars (left) and two #3 FRP rebars (right)

3 Measurement of bending behavior of a printed 3D concrete beam

3.1 Flexural bending test of a printed beam

The 3D printed beams were tested to determine the bending moment by applying a point load at the mid-span of the beam as both ends are supported as shown in Figure 4 and Figure 7. This testing aimed to validate a structural analysis with the material properties from material testing by comparing it to a printed beam testing result.

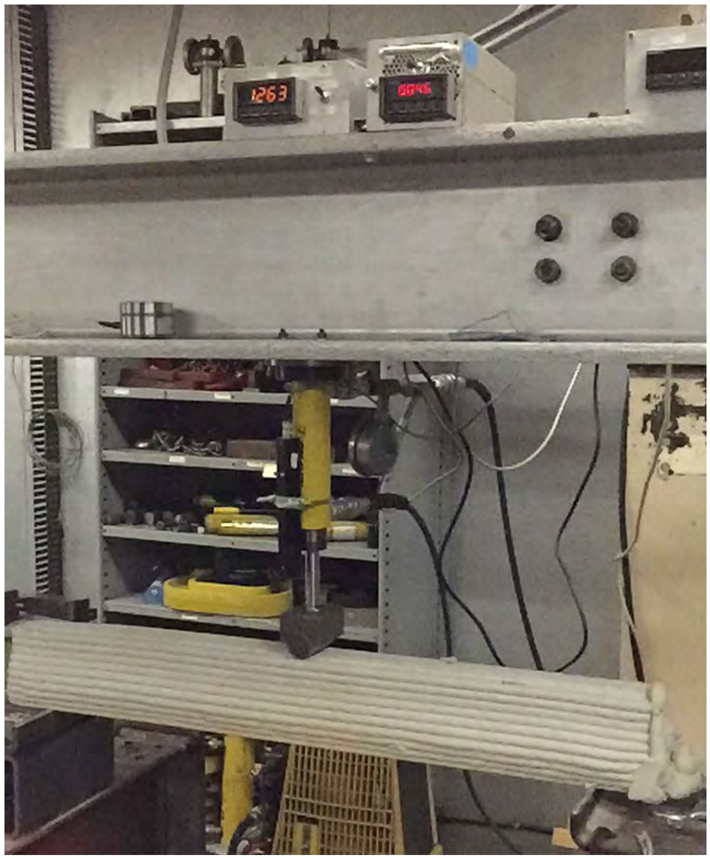


Figure 7. Flexural bending test of a printed beam as the simple pin supported beam

The deflection and the applied load at the beam's mid-span point were measured from the LVDT embedded in the actuator and the load cell supporting the actuator for the printed beam with FRP reinforcement case.

3.2 Comparison of actual testing result and analytical solution to FEA result

From Tables 4 and 6, one can compare the printed beam's load capacity vs. the nominal capacity. Table 7 shows the percentage of differences between the analytical solution and the test results. It should be mentioned that the analytical solution includes the capacity reduction factor (0.79) and 0.65 for the beam with steel rebar and FRP rebar, respectively.

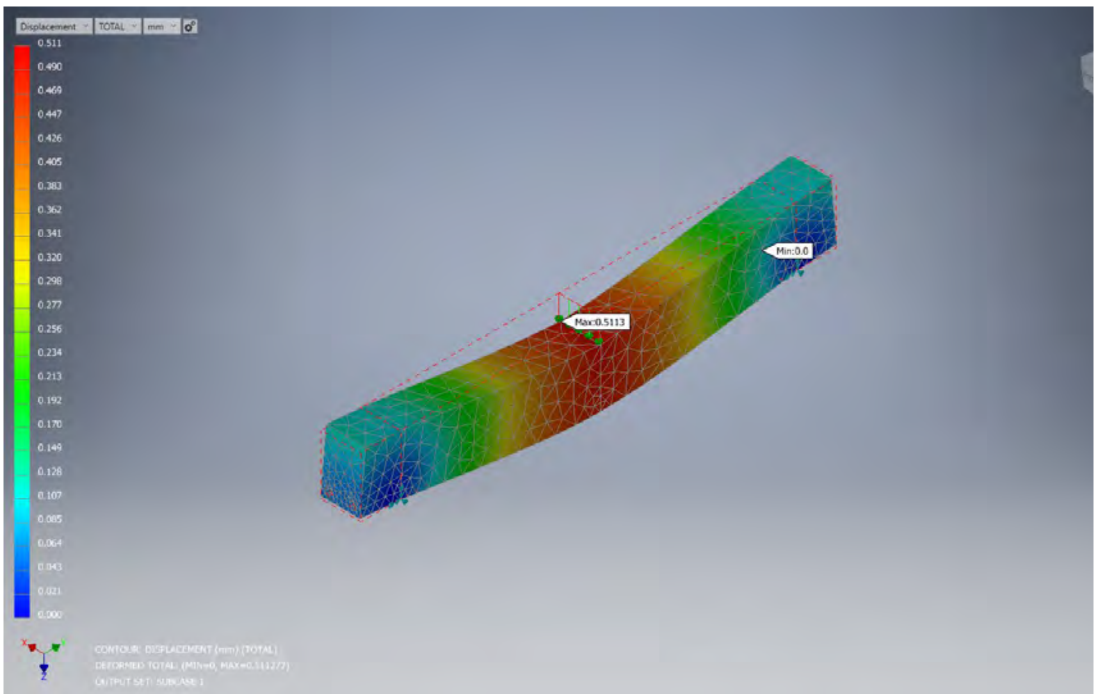
Table 7. Comparison of the load capacity from analytical solution expectation to the testing result

Reinforcement Cases	Maximum Load Capacity	Error (%)

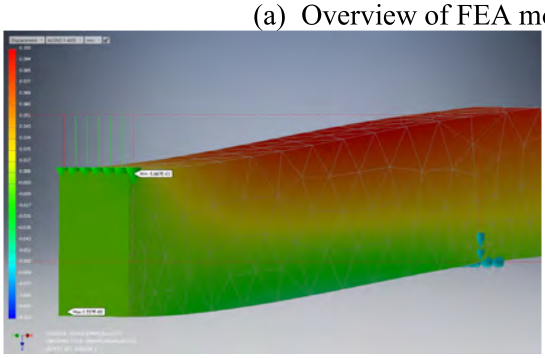
	Testing Result, lbf (kN)	Analytical Solution, lbf (kN)	
Steel Rebar 1 *	5,980 (26.6)		11.4
Steel Rebar 2	5,665 (25.2)	5,366 (23.9)	5.6
Steel Rebar 3	4,024 (17.9)		-25.0
FRP Rebar **	2,338 (10.4)	4,699 (20.9)	-50.2

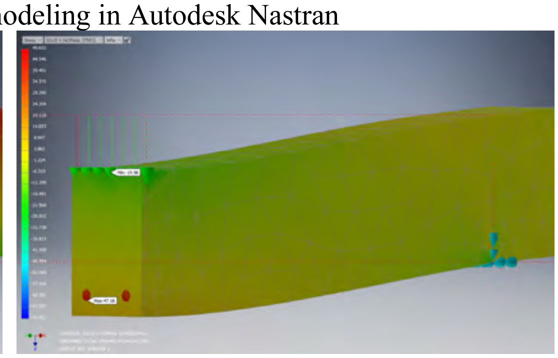
* The number after “Steel Rebar” (1, 2, or 3) shows the test number of the three test repetitions of a pin-loading test of the beam having rebar scheme of Figure 6 (left), whose analytical solution corresponds to the case marked with *** in Table 4
** FRP Rebar means the pin-loading test of the beam having rebar scheme of Figure 6 (right), whose analytical solution corresponds to the case marked with *** in Table 6

Autodesk Nastran embedded in Inventor 2019 by Autodesk was used to perform a series of finite element analyses, as shown in Figure 8 as an additional examination. The material’s mechanical properties have the same values as in the analytical solution, as listed in Tables 3 and 5. The nonlinearity of properties is considered by using bi-linear (Elasto-plastic).



(a) Overview of FEA modeling in Autodesk Nastran





(b) Displacement of beam (c) Stresses contour of beam

Figure 8. Computational simulation of beams with and without the reinforcement by using Autodesk Nastran

The critical stresses of a printed beam's failure mode are considered through FEA simulation at the extreme concrete fiber and steel rebar position under the simple beam testing load, as listed in Table 7. The stresses resulting from FEA match those of the beam failure stresses, as shown in Table 8.

Table 8. Comparison of the stresses from the testing and computational simulation for a printed beam with reinforcement

Beam Case	Pin Load kips (kN)	Compressive Stress f_c', ksi (MPa)		Error (%)	Tensile Stress f_y, ksi (MPa)		Error (%)
		Testing	FEA		Testing	FEA	
Steel Rebar 1	6.0 (26.6)	3.6 (24.7)	3.4 (23.44)	-5.6	58.0 (400)	19.0 (131.0)	-67.2
Steel Rebar 2	5.7 (25.2)	3.6 (24.7)	3.3 (22.84)	-8.3	58.0 (400)	17.9 (123.5)	-69.1
Steel Rebar 3	4.0 (17.9)	3.6 (24.7)	2.6 (17.7)	-28.8	58.0 (400)	12.5 (86.2)	-78.4
FRP Rebar	2.3 (10.4)	3.6 (24.7)	2.7 (18.6)	-26.3	85.6 (590)	4.7 (32.4)	-94.5

The compressive stresses resulting from the FEA for the steel-reinforced beams generally show good agreement in compressive stress (28% maximum difference), while there is a significant difference in the tensile stress values (about 80% maximum). This result suggests that the rebars did not reach yield strength as the beams failed. One explanation is that as shown in Figure 9, the voids between the printed filaments affected the development of compressive stresses. As a result, the concrete failed before the rebar could develop enough tensile stress to realize the full bending strength. Actual testing of the beam with FRP rebar showed similar failure mode with the steel-reinforced beams but with more brittle failure behavior. The FEA result of the beam with FRP rebar also showed that the tensile stresses reached only 5% of its strength (85.6 ksi (590 MPa)), while the compressive stress in the concrete reached 73% of the compressive strength from prism test (3.6 ksi (24.7 MPa)). One explanation for such a failure is the loss of bond between the FRP rebar and the surrounding concrete, as Figure 9 clearly shows the separation of the rebar from the concrete body.

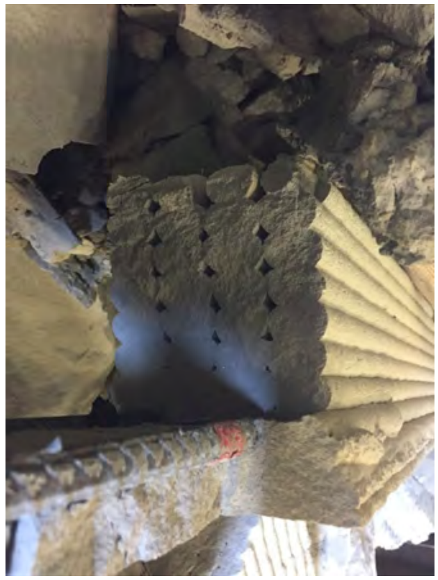


Figure 9. Voids in a 3D printed beam due to the material deposition process

4 Conclusion

A series of printed beams with reinforcement in the traditional configuration were tested as simply supported beams to characterize the mechanical behavior under the bending moment loading condition. The compressive loading test of the prism shape specimen helped to understand that the printed material has anisometric characteristics due to the structural pattern resulting from the material deposition process. Even though the anisometric material properties should be considered in the computational modeling to precisely predict the response of the tested beams, in this study, only isometric properties were used in conventional analytical solution and FEA computational simulation. Accordingly, it is assumed that the difference between the estimation of the beam's response through FEA and the actual testing result is partially due to the effect of a material's anisometric characteristics, which shows considerable variation even in test results from one specimen to another. In future research, performing structural analysis by using anisometric material properties including void structure in cross-section would help to more accurately evaluate the effect of toolpath and inter-layer bond on the strength of printed concrete components. This will also require a more extensive testing program.

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Role of Infrastructure in Success of Urban Housing Developments

Shay Chakraborty[1], M.G Matt Syal[2], and Sinem Mollaoglu[3]

[1] M.S Graduate, Construction Management, Michigan State University, East Lansing, MI, shayonee1987@gmail.com, (682)247-1927
[2] Professor, Construction Management, Michigan State University, East Lansing, MI, syalm@msu.edu, (517) 432-2951
[3]Associate Professor, Construction Management, Michigan State University, East Lansing, MI, sinemm@msu.edu, (517) 353-3252

ABSTRACT

The infrastructure is an important part of the success of any residential development, but it takes on a critical role in the case of urban housing developments, both new and redevelopment projects. This research reviewed literature and several case studies nationwide to define supporting infrastructure for residential redevelopments. The review led to defining thirteen categories of infrastructure systems and each system was then divided into subsystems leading to a total of forty infrastructure subsystems. The infrastructure systems and subsystems required for the success of an urban residential redevelopment were separately prioritized with the help of structured interviews with six developers and four municipal/state government officials in Michigan. The data from each group was collected in the context of their perspective on development success criteria such as Company/Municipal Success, Profitability, Primary and Secondary Project Success Aspects and Branding. ELECTRE III, a multi-criteria decision-making model that effectively helps in prioritization or optimized ranking of alternatives, was used for data analysis. The results reflect that the top five priorities for developers are Digital Infrastructure, Utilities, Education, Transport and Green Infrastructures whereas the Municipal Officials' preference list includes Digital, Employment, Utility, Transport, Retail in order of priority. Infrastructures like Renewable Energy and Green Space are yet to gain widespread popularity in the real estate industry. The authors believe that this analysis will be valuable in guiding the developers and municipal officials in prioritizing the infrastructure options for a given budget to get the most impact on the success of a residential redevelopment project.

INTRODUCTION

According to the recent trends, both developed and developing countries witness an unprecedented growth and movement of population in urban regions (Farid, 2011). This situation is accompanied with the emergence of a new pattern of developing centralities towards the periphery of the cities, coined as the 'Urban Sprawl'. To facilitate the demand of habitat, triggered by the urban sprawl, new housing developments appear in the scenario. Consistent with the massive surge of population, communities witness rise in the land acquisition cost and time. Hence, to deliver maximum values to the customers, the developers need a solution besides the new development projects. 'Urban Redevelopment' with its salient features provide such an alternative.

Complete Community Toolbox (2018) adapted from International City/county Management Association (ICMA) to describe redevelopment as modification of a pre-existing structure or previously developed property for a new purpose, often different from its original one. The idea ranged from refurbishing an existing building/housing to reusing a contaminated brownfield to develop new housing. The redevelopment projects effectively build on the remnant framework of basic infrastructures of the earlier development with necessary additions and refurbishment to suit the customers' requirement. Hence, such projects provide livability of a quality equivalent to new developments. Thus, by opting for feasible urban redevelopment projects alongside the new developments, developers can streamline their product offerings and meet the diverse demand surge emanating from the burgeoning urban population.

This paper begins with a brief overview of the literature studied and several case studies investigated, outlining the categories and sub-categories of infrastructure required in a residential redevelopment. It emphasizes the importance of infrastructure, points out the benefits and discusses the factors of success in a residential redevelopment.

LITERATURE AND CASE STUDY REVIEW

1. Infrastructure

After establishing the requirement of redevelopment as a way out to develop housing projects, the next step is to understand the role of infrastructure in its success. U.S.-EPA (2019) summarized in three points, the necessity of redevelopment projects and effect of existing infrastructure on its development and success.

- Redevelopment changes discarded sites into community features such as parks and plazas, mixed-use developments, and homes.
- Policies play an important role in shaping ease and cost of redevelopment.
- "Sites are often in infill locations with existing transportation and utility infrastructure. Redevelopment in infill locations can use vacant buildings, parking lots, or other underused sites for new amenities, homes near existing neighborhoods. When infill development occurs near transit or employment centers, it can reduce the distance people need to drive and give them other transportation options."

A review of single-family, multi-family and mixed-use type of residential redevelopments across the United States assisted this study in defining key infrastructure for successful residential developments. The determination of the success of these case studies is based on the analysis conducted by Urban Land Institute (2004), various government commissions and Municipal Development Authorities of several states.

Based on the case studies and the literature review, the infrastructure required to support a residential development can be split into thirteen broad categories and then can be further divided into forty sub-categories, as shown in Table 1 (Bracknell Forest Council, 2012).

2. Stakeholders and Associated Parameters of Success

It is very crucial to understand the success of the redevelopment project to be able to relate it with availability or absence of infrastructure. Since a project has various stakeholders associated, each will have its own definition of measuring success. The same project is mapped differently by the developers and the government officials who are the two primary stake holders of the project from its conception stage. The private developers who actually invest in the project generally show profit seeking and risk-taking characteristics to achieve cost effective outcomes. However, the same project can be used by the government and municipality to promote community development, remove blights and contamination and bring taxpayers into the city. Because of these different perspectives, the requirements of the different stakeholders from a project often varies distinctively. After an extensive literature review for definition of success, the following measures of success for different stakeholder's perspective was found in a research conducted by Wai et. Al (2012). According to the research, success can be classified into five categories, as shown in Table 2.

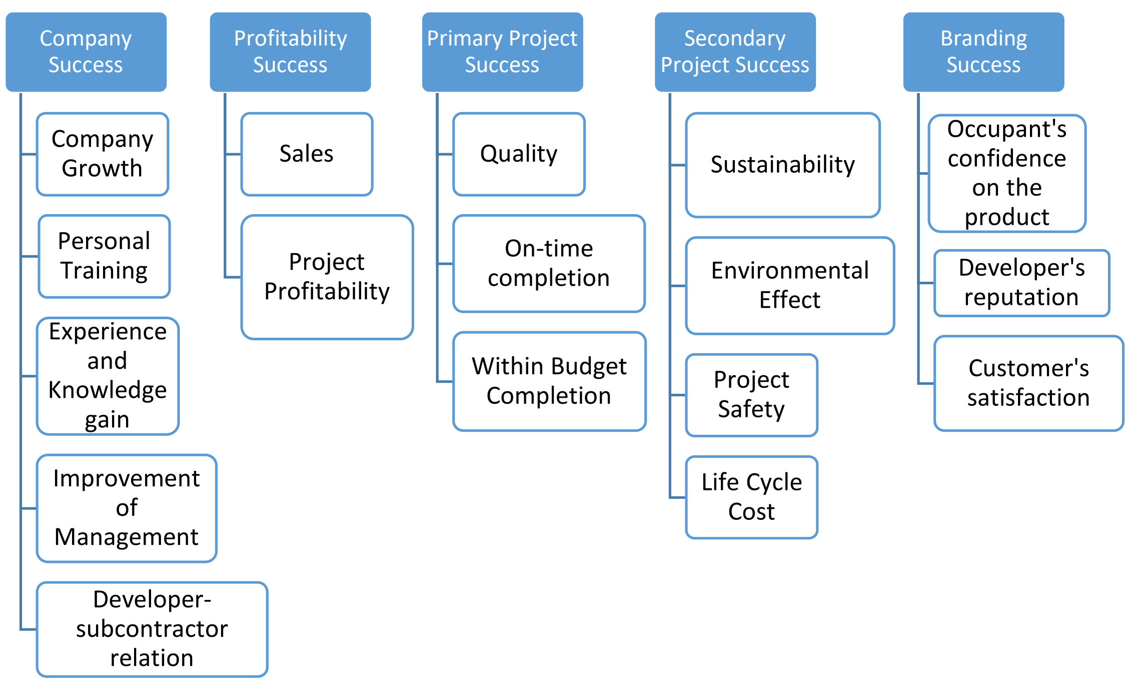

Table 2: Criteria of measuring success

A1	**Transport Infrastructure**	Local Road Network
		Footpaths & Cycle ways
		Public Transport
		Parking
A2	**Waste Management**	Waste Collection
		Recycling
A3	**Utilities**	Water Supply
		Wastewater Management
		Electricity Network
		Gas Network
		Telecommunications
A4	**Renewable Energy**	Solar Energy
		Wind Energy
A5	**Education**	Early Years
		Primary Education
		Secondary Education
		Further education (Colleges)
A6	**Community Infrastructure**	Community Centers
		Libraries
		Built Sports
		Pools
A7	**Social Infrastructure**	Children's Day Care
		Religious spaces
A8	**Emergency Services/ Safety**	Police Service
		Ambulance Service
		Fire & Rescue Service
		Street lighting
A9	**Health**	Primary Health Care
		Hospitals
		Senior Citizens' Care
A10	**Green Infrastructure**	Open Space
		Arboretum/Biodiversity
A11	**Digital Infrastructure**	Internet Access
		Cable Access
A12	**Retail**	Restaurants
		Banks
		Grocery stores
A13	**Employment Infrastructure**	Employment Potential
		Office Spaces

Table 1: Infrastructure Needed to Support a Residential Development

DATA COLLECTION

The primary stakeholders for the project in terms of the investment and project quality are private developers and government officials respectively. Government officials can include city councils, county commissioners, planning and zoning board members and other elected officials (Novak,1996). As the purpose of this research is to develop a ranked list of infrastructures, which may contribute to the success of a residential redevelopment, the authors found it necessary to utilize the perspectives both developers and officials in determining the list. Hence data is collected from both the groups.

In person interviews were conducted for data collection and discussions. Ten local developers and nine city officials from Michigan were contacted to collect data. Out of the ten developers and nine city officials contacted, the author could successfully communicate with six developers and four city officials. All the interviews took place in Michigan. The Government officials are members of Department of Environmental Quality (DEQ), Michigan Economic Development Corporation (MEDC), Lansing Economic Area Partnership (LEAP) and Brownfield Redevelopment Authority (BRA), Lansing, all of which are under state authorities of Michigan. The interviews lasted between 30-45 minutes. All developers interviewed have extensive experience in Single-family, Multi-family and Mixed-use residential developments in Michigan. One of the developers has done multiple projects in North Carolina, South Carolina, Texas, Ohio and Florida. The data collected was analyzed to obtain ranking of different categories of infrastructure.

A structured interview was employed at this phase of the study to find the overall and relative importance of infrastructure categories in the success of a residential redevelopment for key stakeholders. The project scope focused on the developers and the municipal officials while both groups were asked to also keep in mind the future residents' perspective when answering the interview questions.

The questionnaire developed for interviewing the developers and the municipal officials, was divided into three sections:

Section1: Background of the Developer/ Municipal Official

Section 2: a. Prioritization of sub-categories

b. Prioritization of broad categories

Section 3: Incentives and Barriers to Redevelopment

The open-ended questions in the final sections of the questionnaire was to account for the difference in perspectives of developers and municipal officials. A reference scale of 0-10 was used, with 0 being extremely unimportant, 5 being neutral and 10 being extremely important.

DATA ANALYSIS

Considering the limitation of inadequate sample size, the authors ruled out quantitative data analysis and investigated qualitative methods. The lookout was for a method which reflects the preferential analysis ability of a human mind and after a thorough research of different methods, results were narrowed down to two methods, Analytical Hierarchy Process (AHP) and ELECTRE III.AHP, developed by Saaty (1980), helps in analysis of decision-making problems. It builds in the preference modelling by comparing two categories at a time; however, the condition of analyzing the impact of all five success criterions together made the process extremely cumbersome. Alternatively, ELECTRE III (Velasquez & Hester, 2013) proved to fit the bill with its simple procedures.

ELECTRE III is a multi-criteria decision-making model that effectively helps in prioritization or optimized ranking of alternatives. The underlying principle for outranking in ELECTRE III is the preference of a decision-maker for a given set of alternatives. An alternative a is said to outrank an alternative b, if the decision-maker's preference supports the conclusion that a is at least as good as b. The authors created a decision matrix to determine the ranks of various categories in ELECTRE III. The matrix is meant to establish a relation between the alternatives (i.e., 13 categories in Table 1) and the criteria (i.e., five categories of success in Table 2). Once a matrix is developed with these variables, participants' evaluations were inserted in the model. The final ranks calculated for each participant is tabulated and the mean is calculated as the final rank.

RESULTS

Two different sets of results are obtained for the ranking of the broad categories, the sub-categories. Results are compiled separately from the perspective of the developers, the municipal officials, followed by combined results. These results are presented in the sections below.

a.1 Ranking of Broad Categories

The ranking of the broad categories of infrastructure obtained through data analysis in ELECTRE III considering the opinions of the developers and the government officials respectively are shown in Tables 3a and 3b. Table 3c shows the combined rankings.

a.2 Observations

Since these results are based on expert opinions who know their market well, these ranks can be considered a reflection of the infrastructure needs currently prominent in a residential redevelopment.

The ranks provided for developers and municipals show that both stakeholders agree with the importance of most of the categories except a few. Both Developers' and Government officials have ranked Digital Infrastructure as of topmost importance. Since the people today heavily rely on internet access and cable access for working and staying connected, Digital Infrastructure has become as basic a requirement as

Utility Infrastructure, i.e., gas and electric lines, which is ranked 2nd by the developers and 3rd by the government officials. Transport Infrastructure and Emergency services also gains equal importance to both the stakeholders and ranked 4th and 7th among the thirteen. Among the differences, education is considered very important (ranked 3) by developers whereas government officials ranked it 10. According to developers well rated schools in neighborhood attract families more for purchasing the redeveloped residentials. Hence it is very profitable as they really do not have to invest anything to build or maintain a school in the neighborhood. Similarly, Employment is ranked

FINAL RANK	INFRASTRUCTURES
1	Digital Infrastructure
2	Utilities
3	Education
4	Transport Infrastructure
5	Green Infrastructure
6	Retail
7	Emergency Services/ Safety
8	Waste Management
9	Health
10	Social Infrastructure
11	Employment
12	Community Infrastructure
13	Renewable Energy

Table 3a: Ranking of Broad Categories of Infrastructure from a developer's perspective

FINAL RANK	INFRASTRUCTURES
1	Digital Infrastructure
2	Employment
3	Utilities
4	Transport Infrastructure
5	Retail
6	Renewable Energy
7	Emergency Services/ Safety
8	Green Infrastructure
9	Community Infrastructure
10	Education
11	Waste Management
12	Health
13	Social Infrastructure

Table 3b: Ranking of Broad Categories of Infrastructure from a Government Official's perspective

FINAL RANK	INFRASTRUCTURES
1	Digital Infrastructure
2	Utilities
3	Transport Infrastructure
4	Education
5	Employment
6	Retail
7	Green Infrastructure
8	Emergency Services/ Safety
9	Waste Management
10	Community Infrastructure
10	Renewable Energy
12	Health
13	Social Infrastructure

Table 3c: Combined Ranking of Broad Categories of Infrastructure

by the municipal people and 11 by the developers. Municipal people want to bring more population to the neighborhood and increase the count of taxpayers. Hence having employment sources near the residentials is beneficial as it restricts the population from spreading out to the suburbs. It's interesting to see that both the stakeholders are trying to attract customers/population but using two different means. It seems there is a requirement to strike a balance between these two infrastructure provisions to reduce the gap between the requirements of both stakeholders. It's a good thing that developers are paying more importance to the environmental aspects like green infrastructure, green spaces, etc. for their projects, whereas the renewable energy provisions hold more importance with the government officials as they are trying to promote bio energy consumption in the industry. It may take some time before it becomes widely popular with the private developers and residents also.
Social Infrastructure and Community Infrastructure holds lower ranks meaning that this type of infrastructure comparatively holds less importance in a development. It can be inferred that the availability of banks, restaurants, grocery stores and social/religious spaces is not of prime importance but can be an added advantage to a development.

b.1 Ranking of Sub-categories

The ranking of the sub-categories shows a similar trend as observed from the ranking of broad categories. Tables 4a and 4b show the top ten ranks from a developer's and Government official's perspective, respectively. Finally, Table 4c shows the combined ranking of sub-categories.

b.2 Observations

The final rankings of the sub-categories are shown in Table 4c. The sub-categories at the top 10 ranks all belong to the broad categories of Utilities, Education Infrastructure and Digital Infrastructure and employment. Internet Access that is a part of Digital Infrastructure obtained Rank 7, which suggests that Internet Access is given more value than cable access in recent times. The most critical amenities are water supply, electricity and gas network, wastewater management, education infrastructure except colleges, and telecommunications. Local Road Network at Rank 8 indicates that the availability of well-connected roads is valued in a development. The ranks at the bottom are achieved by religious spaces, libraries and pools. These infrastructure can be given less importance if the development project has time or budget constraints.

A prominent difference in the views of the developers and the government officials shows the inclination of the Developers towards Education infrastructure. Primary and secondary education holds rank 6 and 9, respectively for Developers' ranking in table 4a however, it is not listed in top ten ranks by the government officials.

RANK	SUBCATEGORY
1	Internet Access
2	Water Supply
2	Electricity Network
4	Wastewater Management
5	Gas Network
6	Primary Education
7	Telecommunications
8	Local Road Network
9	Secondary Education
10	Early Years

Table 4a: Ranking of Sub-categories from a developer's perspective

RANK	SUBCATEGORY
1	Water Supply
1	Electricity Network
1	Gas Network
4	Telecommunications
5	Wastewater Management
6	Employment potential
7	Internet Access
8	Local Road Network
9	Open Space
10	Footpaths & Cycle ways

Table 4b: Ranking of Sub-categories from a government official's perspective

RANK	SUBCATEGORY
1	Water Supply
1	Electricity Network
3	Gas Network
4	Wastewater Management
5	Internet Access
6	Telecommunications
7	Local Road Network
8	Fire & Rescue Service
8	Police Service
10	Primary Education

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Table 4c: Combined Ranking of Sub-categories of Infrastructure

DISCUSSION

There are multiple purposes for developing this paper. It defines the requirement and benefits for housing redevelopment and provides a prioritized list of infrastructures to make the project successful. But who are the probable audience for this pitch? This section will discuss the potential audience who in view of the authors may be benefitted directly and indirectly from the results.

i) Housing developers - Though redevelopment is a practical option beside new development, an analysis is required to gauge feasibility and ensure success of the proposed work. The preferred infrastructure distance from the project location forms an important guideline to Site selection for a revitalization project. The site with access to the major surrounding infrastructures will have an advantage in this case.

Additionally, the priority list of infrastructures will also help developer to select infrastructures of absolute necessity in case of a limited budget project.

ii) Financing Organizations - Developers team up with financing organizations for financing development works. These results may serve as a guide to financial organizations to decide on the viability of funding a project.

iii) Civic Authorities - The civic authorities may play a crucial role in developing awareness about the necessity of redevelopment. The existing difference in opinion on the ranks of infrastructure between developers and officials need to be eliminated through early collaboration and mitigations. Also, the results of the government officials can be used to promote redevelopment initiatives. The distance of infrastructures can be used in potential neighborhood revitalization planning by the municipality.

iv) Customers/Buyers - The customers/buyers will benefit from the overall impact of the redevelopment work. If properly planned and executed, redeveloped project will bring in functioning infrastructures and updated facilities into a community.

v) Environmentalists - Without the option of redevelopment, the existing site would have been a source of unhealthy contaminations, blights, source of pollutions and environmental degradation. Ensuring redevelopment works hence definitely adds value from an environmentalists' perspective. Moreover, one redeveloped site may be equivalent to one less new development.

vi) Auxiliary and Ancillary trades - A redevelopment project opens the route for several auxiliary and ancillary works to support the redevelopment. Hence it generates more employment, revenue and helps developing the economy of a region.

LIMITATIONS & FUTURE RESEARCH

The research is not without any limitations. The decision-making model ran in ELECTRE III has some limitations which may tamper the results to some extent. There are 13 alternatives in the matrix and the score assigned is in a range of 0-10. This range is restricting the differentiation in scores to some extent and hence generating clubbed ranking.

The developers participating in the survey have experience all over the country, and they have brought the geographical diversity in their results, however the municipal and state officials are restricted to certain counties of Michigan only. The survey results for government officials will vary depending on locations and changes in geographic conditions.

The results reflect only the mindset of developers and government officials only. The customer's views on the workability and appropriateness of the infrastructure provided to them is not considered in the scope of research.

These results are strictly limited to redevelopment projects for single family, multifamily and mixed-use housing in urban areas. The results will definitely vary for specialty housings, economic housings or projects in rural or suburban areas.

This research can be expanded more by incorporating the opinions of the customers and comparing the results. The residents are the end users and one of the important attributes of the projects. The final success of the project finally depends on the customer satisfaction to a great extent. Provision of infrastructures is discussed in this research but the scope and importance of maintaining the infrastructures is excluded from scope. During the project life, how the performance of the infrastructures is defining the success of the project, can form a good research question in future.

CONCLUSIONS

This research deals with two crucial aspects of the urban development, redevelopment and infrastructure. While each holds its own importance, an ideal relation between the two can also bring improvements to the well-being of a society. For years, experienced developers and real estate builders have provided successful residential projects to the society. This is an attempt to recognize the priority of the different infrastructures and their contribution towards success of a redevelopment project in a residential area. The results also try to bridge the gap between the requirements of a developer and a municipal authority and come up with a solution which includes expertise from both the stakeholders. The authors are positive that the results will provide useful information to developers and government officials to collaborate for urban redevelopment projects that are needed in many urban centers in the USA.

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Improving the User Experience (UX) of Green Building Certification Resources for Multifamily Housing Units

Dwayne Jefferson[1] and Frederick Paige[2]

[1]M.S. Student, The Charles Edward Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 200 Patton Hall, 750 Drillfield Drive, Blacksburg, VA 24061; email: dejeffer@vt.edu

[2]Associate Professor, Society Technology Infrastructure & Learning Environments Research Team, The Charles Edward Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, 114 Patton Hall, 750 Drillfield Drive, Blacksburg VA 24061; PH (540) 231-5009; email: freddyp@vt.edu

ABSTRACT

Designing complex sustainable infrastructure systems, such as energy-efficient affordable housing units, requires an abundance of expert knowledge. To improve the construction industry's capacity to deliver sustainable infrastructure, guidance on optimizing green building systems needs to be more accessible. Green infrastructure certifications are an emerging open access method for providing sustainable engineering guidance to designers. EarthCraft Multifamily (ECMF), an evolving green building certification, has been utilized to deliver more than 45,000 energy-efficient housing units. This study identifies the impact ECMF tools and resources, such as the program manual, worksheet, and technical guidelines, have on enhancing project delivery for builder-developers. EarthCraft has been successful in increasing the delivery of energy-efficient affordable housing, and this study leverages user experience (UX) methodologies to understand how to further improve ECMF and replicate its success. The strengths and weaknesses of ECMF are identified through data collected from stakeholder interviews, user interviews, and usability analysis. Preliminary findings show potential for ECMF resources to evolve in their design, content, and delivery methods. Resources need appropriate visual representation such as readability and hierarchy to improve their usability. The usability analysis has revealed that the selection of sustainable design practices in new construction and renovation projects have been influenced by ECMF tools. ECMF resources have the ability to lower the level of expertise required for sustainable infrastructure delivery which can allow for the inclusion of a broader set of stakeholders. With accessible guidance, the agency of non-expert stakeholders is increased allowing them to better manage their role in delivering sustainable infrastructure. This study provides transferrable findings with implications for the improvement of existing practices, and the creation of new innovations for green infrastructure project delivery. Green infrastructure certification programs, requiring similar resources to ECMF, can be improved leveraging the methods and findings from this study.

INTRODUCTION

Over recent years, green building certifications have emerged to provide guidance to engineers and designers for promoting sustainability (Retzlaff, 2008). An explanation for the emergence of green building certifications is the increase in demand for green products over the last decade. Builder-developers in the process of delivering sustainable infrastructure to consumers are guided by green certifications. By promoting sustainable design methodologies, green building certifications minimize environmental impacts and promote energy efficiency in infrastructure. Housing infrastructure has been significantly affected by green building certifications as centralized commercial scale products and procedures are being adapted to the residential sector. While the commercial sector still leads residential in regard to depth and diversity of green building certifications, multiple green building certifications exist to improve residential buildings (Miller, 2010).

Within residential construction, green building certifications are typically stratified by building type. EarthCraft Multifamily (ECMF) provides guidance on standards to address sustainability issues in low-rise and mid-rise multifamily projects through a certification process (EarthCraft Multifamily, 2018). Over the years, project teams have utilized EarthCraft resources to assist in delivering 45,000 buildings that are more sustainable than traditional housing units (EarthCraft Multifamily, 2018). Environmental performance, affordability, building quality, and satisfaction are sustainable considerations that ECMF resources are structured to help projects attain a point-based certification level (Southface, 2019). The primary resources of ECMF include the program manual, worksheet, and technical guidelines. Other infrastructure certification programs such as LEED and Envision, use similar resources to provide guidance on the design and delivery of green infrastructure to consumers.

The design and plan for the delivery of affordable sustainable housing projects are tightly constrained finances leaving little room for inflating soft costs in hopes of reducing life cycle costs. Development costs are tied to risk levels, and correlations between user behavior and building technologies are complex leaving builder-developers uncertain about the risk involved with green technologies (Zhao et al., 2017). Variability during the utilization of energy models and simulations have introduced hazards in ECMF projects (Clevenger & Haymaker, 2006). Unforeseen outcomes have the potential to be alleviated during the delivery of affordable sustainable housing due to greater acknowledgment of how ECMF resources are used and user error (McCoy et al., 2015). EarthCraft has been shown to be successful, but improvements can still be made to increase utilization while also reducing the risk in a risk-adverse industry (Zhao et al., 2016).

Incorporating user experience (UX) methodologies into Civil Engineering design procedures can be beneficial in the delivery of infrastructure projects. The concept of

UX is best described as a person's experience with a system on all facets (Lallemand et al., 2015). UX is often considered human-centered design that aims to make systems usable and useful in interactive systems advancement. Usability is targeted through word recognition, grouping and color of interactions with related functions, adding displays with an abundance of text and icons, and writing logically structured manuals (Overbeeke et al., 2002). While the concept of usability mainly focuses on an objective approach of an interaction, UX explores emotional, subjective, and temporal aspects characterizing the experience between humans and technology (Lallemand et al., 2015). Using UX theories, experiences can be differentiated based on psychological needs fulfilled through technology use (Hassenzahl et al., 2010). UX has revolutionized the design procedures, making it easier to create innovative deliverables at a lower cost by more people.

The focus of Civil Engineering has mainly been on evaluating the usability of our projects' outputs and not the methods of generating those outputs (Sengers, 2018). Readability, legibility, order of information, and delivery platforms such as documents and interfaces are usability factors that can affect the resources utilized in engineering. As social and technological dimensions become more convoluted over time, utilizing usability studies could be beneficial to Civil Engineers in iterating our decision-making processes (Norman, 2013). By intertwining Civil Engineering and UX together, the effective and efficient utilization of tools and resources are assured. For green building certification tools or resources to be utilized successfully, it is vital that the understanding of users' needs is reflected by the tools or resources. Therefore, future research pertaining to green certification tools and resources should involve UX (Kim et al., 2013). This study aims to investigate ways of increasing the accessibility and utility of ECMF tools and resources.

METHODS

An exploratory case study was determined to be ideal to achieve the broad goal of investigating ways to increase the accessibility and utility of ECMF tools and resources. By conducting an explorative case study, we can analyze project specifications, user interviews, stakeholder interviews, and heuristic evaluations. The strengths and weaknesses of ECMF can be identified after a great deal of knowledge is unlocked about the green building certification program. The conceptual understanding that will be focused on in this case study will significantly enhance the broad goal of this research study.

Conducting an exploratory case study

The case study methodology is ideal for holistically exploring the contemporary experience of utilizing ECMF resources in which researchers cannot control (Yin, 2018). This exploratory case study consists of two phases: 1) qualitative usability analysis of the influence ECMF resources have on technology utilization and 2) qualitative analysis of builder-developer interview transcripts describing experiences using ECMF resources.

The usability analysis takes a deductive approach that leverages design theories by prioritizing accessible design standards. While the preliminary portion of this project is exploratory, there is great potential to transition from a general idea to specific theories that exist in separate domains (Fellows & Liu, 2015). In addition to the usability analysis of ECMF tools and resources, a sample was selected from criteria that included buildings' geographical location and sustainable construction practices.

Phase 1: Qualitative usability analysis of the influence of EarthCraft Multifamily resources

1.1 Usability analysis framework

The usability analysis framework links construction management theories and universal design concepts to serve as a basis for developing the framework needed for experimental user testing (Blythe et al., 2007). These concepts include project scale, scope, stakeholders, project delivery methods, interface design, and appropriate communication strategies (Retzlaff, 2008).

1.2 Heuristic evaluation methodology

Heuristic evaluation is a method for having individual evaluators perform an analysis that visualizes the state of a product in terms of usability and accessibility (Nielson, 1994). Evaluators, usually with backgrounds as specialists and experts, use industry-accepted guidelines for usability and prior experiences to complete the evaluations. For this research study, three UX experts will serve as evaluators. To determine usability, heuristic evaluations will be performed on ECMF tools and resources focused on the heuristics listed below (Nielsen, 1994):

- Visibility of system status
- Match between resource and the real world
- User control and freedom
- Consistency and standards
- Error prevention
- Recognition rather than recall
- Flexibility and efficiency of use
- Aesthetic and minimalist design
- Help users recognize, diagnose, and recover from errors
- Help and documentation

The tools and resources of ECMF that are analyzed in this study are, the program manual, worksheet, and technical guidelines. The major aspects of each resource that will be observed during the heuristic evaluations are navigability, page design, page layout, and content quality.

Heuristic evaluations are valuable when resources and time are limited (Kantner & Rosenbaum, 1997). Each evaluator spends approximately two hours during their evaluation sessions for this research project. Two hours allows the evaluator to thoroughly analyze ECMF tools and resources for the previously mentioned usability principles and elements. Each evaluator evaluates each tool and resource twice. The first time to get a feel for the flow of the tools and resources, and the second time to focus on key elements that capture attention. Violations to the heuristics are recorded during the evaluation process via the tabular tally system. In addition to counting the violations, the evaluators also rate the severity of the violations. Severity is defined as an expected impact on the user's experience.

After each evaluation session, the evaluator discusses heuristic violations and usability problems, as well as beneficial features of each tool or resource with the research team (Kantner & Rosenbaum, 1997). Common ground between the separate evaluator findings will be found and organized through group meetings with the three evaluators. The heuristic violations, usability problems, and beneficial features will be compiled into a rating scale where each is individually scored from 0% to 100% based on how evaluators view the effectiveness of each in the utilization of the tools and resources. The lowest percentage a violation or feature receives due to a lack of effectiveness in the tools or resources is 0% and 100% is the highest due to a high level of effectiveness. The findings from the heuristic evaluations will also be used to make changes to the tools and resources that will be utilized in the A/B testing phase.

1.3 Piloting Stage

There is a piloting stage before A/B testing sessions begin to determine the best experimental set up for study participants. The hardware and software are checked for performance to verify their ability to capture participants' varying experiences. After analyzing the two versions of the tools and resources, the participants provide feedback to the research team regarding their experiences as participants in this A/B testing.

1.4 A/B testing methodology

A/B testing is a method of isolating and testing factors that impact the performance of green building certification resources (Dixon et al., 2011). A/B testing allows for two different versions of ECMF tools and resources to be tested among groups of builder-developers and the usability of each version is compared. Version A of the tools and resources is the original version of ECMF tools and resources while Version B includes multiple improvements to the formatting and design of the original version. Version B is created from the findings of the heuristic evaluations. A/B testing will be conducted on the ECMF program manual, worksheet, and technical guidelines.

Builder-developers from previous ECMF projects used in studies (Zhao et al., 2017; Zhao et al., 2016) will be recruited to participate in the study. A sample size of 10 builder-developers with previous ECMF experience was determined to be ideal for this research study based on each of the builder-developers familiarity with EarthCraft. The builder-developers are asked to view both versions of ECMF tools and resources as if they were utilizing them on an actual company project. During each session of A/B testing, participants are also asked to fill out various sections of the ECMF worksheet while referencing back to the technical guidelines and program manual for assistance.

A script is followed during each session of A/B testing to ensure that each builder-developer is being presented with the same tasks and questions. This allows for each builder-developer to effectively analyze the two versions of ECMF without being influenced by the presenter's words or descriptions. The participants provide feedback regarding their experiences in a feedback section after analyzing the two versions of the tools and resources.

The A/B testing section of this study is considered to have a within-subject design, so a counterbalance is needed to offset a potential ordering effect. The first participant of the study first, analyzes the original version of ECMF tools and resources and second, analyzes the improved version of the tools and resources. The second participant of the study first, analyzes the improved version of the tools and resources and second, analyzes the original version of the tools and resources. This process of counterbalancing is repeated throughout the study for every two participants. If any of the participants' data is deemed insufficient to the collection of data or the results prove to be an outlier, the participant's data will be removed from the collection.

A/B testing sessions are held in a secluded media design studio on Virginia Tech's campus. These locations are ideal because they provide the builder-developers with a work environment similar to the environment they utilize on their projects. The locations also allow for adequate use of the equipment that will contribute to the success of the A/B testing sessions.

The equipment needed to complete an A/B testing session is a Blue Yeti USB Microphone, Camtasia 2019 software, and any computer that can display ECMF tools and resources. The participants speak directly into the microphone as they progress through the versions of ECMF tools and resources exemplifying a think-aloud method. The Camtasia 2019 software is utilized to document participants' voices and screens while they progress through the two versions of tools and resources. Compensation for participating in the A/B testing sessions will be provided in the form of food and beverages depending on the time of day.

1.5 Usability analysis of tools and resources

Following the completion of heuristic evaluations and A/B testing, a usability analysis of tools and resources will be organized to present the qualitative aspects of the data. The data from the heuristic evaluations and A/B testing will be analyzed in which specific features such as readability, legibility, hierarchy, and navigability are highlighted. The impacts and analyses of the resources will be recorded in a three-column table in Microsoft Excel as shown in Figure 1 below.

USABILITY ANALYSIS OF TOOLS		
Tools	**Function**	**Analysis of**
Program Manual	Provides steps to successful project delivery; Customizable program to meet needs of stakeholders	Bolded headings; Direct transitions to desired sections
Worksheet	Must be completed to show that a project qualifies for certification	Sections highlighted with colored backgrounds; Separate sheets highlighted by several colors
Technical Guidelines	Used in conjunction with Worksheet and explains for each line item	Bolded headings; Direct transitions to desired sections

Figure 1: Usability analysis of ECMF tools and resources

Phase 2: Qualitative analysis of builder-developers interview transcripts

2.1 Builder-Developer interviews

Builder-developers will be asked open-ended questions to provide a deeper understanding of how and why builder-developers access and utilize ECMF tools and resources. Open questions allow the respondents to reply in a narrative manner, in which the participants' experiences are highlighted (Fellows & Liu, 2015). Audio from the interviews is recorded and transcribed for analysis.

2.2 Interviewee selection

A total of 10 builder-developers who have previously used ECMF were selected to be interviewed on their previous experiences with the program. The interviewees are the same selected group of participants for the A/B testing sessions. In addition to their experiences with ECMF, the demographic profile such as age, education, and experience level of the interviewees will be recorded. The demographic profile provides insights into "who" is using ECMF resources (McCoy et al., 2015).

2.3 Interview questions

The questions for the interviews have not been finalized yet but a few draft questions are listed below:

1. How was each of the resources utilized during the project?
2. What were the challenges of using ECMF resources?
3. Could you describe moments of learning you had while using the resources?
4. Did any aspects of the resources stand out during usage?
5. How effective was each resource in the project delivery process?

The draft questions provided are expected to garner the experiences of builder-developers with ECMF tools and resources allowing for a better understanding of usability. It is of great importance to use the interview questions to create a narrative from the experiences of the interviewees during the recording of the interviews.

Order of Methodologies

A structured order of methodologies was created to give a visual representation of the methods of the research study. The methods are organized, as shown in Diagram 1 below, to maximize the effectiveness of each process in the research study. The structured order of methodologies provides further understanding of the processes involved with improving ECMF tools and resources.

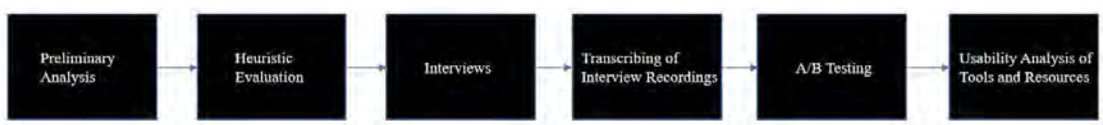

Diagram 1: Structured order of methodologies

Analysis of data

The data is organized so that the interview questions and respective responses can be viewed appropriately and in a manner that is easy to comprehend in a matrix format (Saldana, 2018). The participants' responses, feedback section, and interview transcripts will be coded using Dedoose, a qualitative analysis software. Initially, descriptive coding will occur on the transcripts to condense the data. Next, codes will be categorized into multiple themes that align with UX theoretical constructs. Data on the participants' experience is analyzed using narrative analysis and focused coding based on thematical similarity.

Results & Discussion

Analyzing ECMF resources for their capacity to utilize UX methodologies resulted in the following list of usability variables which show potential for improvement. The listed variables should significantly affect the utilization of ECMF resources.

- **Addition of hyperlinks**
- **Font colors**
- **Font sizes**
- **Layout of information**

Mockups of updates to ECMF resources follow to show how the usability variables are implemented into the resources to be tested in the next phase of this study.

The process overview of the program manual shows the steps of the process of getting ECMF certification as shown in Figure 2. Due to the extensive amount of content in the manual, a navigability issue occurs when the user manually searches for desired information. Hyperlinks to each of the steps in the process overview can be provided to address the issue. The links connect the user with the desired sections of interest in the manual. The interaction with the product should contribute to the overall pleasure found in the function of the product itself (Overbeeke et al., 2002). Satisfaction and required task time for users of the program manual will be significantly affected by this improvement.

EarthCraft Multifamily Project Process

Process Overview

All EarthCraft Multifamily Developers and Technical Advisors must follow a specific project process in order to certify EarthCraft Multifamily projects. All steps of the process must be completed, including individual unit and building-level inspections, in order for a project to be eligible for certification. Each step in the EarthCraft project process is defined in detail on the following pages.

Pre-Construction		Pre-Drywall		Project Closeout	
1	Project Registration	7	Kick-Off Meeting	13	Final Inspection(s)
2	Project Information Submittal	8	Kick-Off Meeting Report Submittal	14	Confirmed Energy Model(s)
3	Preliminary Energy Model(s) or Analysis of Prescriptive Compliance	9	Air Sealing Inspection(s)	15	Final Inspection Submittal
4	Preliminary Energy Model(s) Report Submittal(s) or Specifications reaching Prescriptive Compliance	10	HVAC Initial Diagnostics/Inspection(s)	16	Certification Submittal
5	EarthCraft Design Review	11	Insulation Inspection(s)	17	Certification
6	EarthCraft Design Review Report Submittal	12	Pre-drywall Inspection Submittal		

Figure 2: Process overview section of ECMF program manual

The addition of hyperlinks should also be utilized in the ECMF worksheet. Hyperlink additions in the worksheet support the theory of using links to overcome navigability issues (Cappel & Huang, 2007). To aid in the completion of the worksheet, hyperlinks connect the users of the worksheet to a desired section of the program manual as shown in Figure 3. Users are also connected to the technical guidelines through via hyperlinked text.

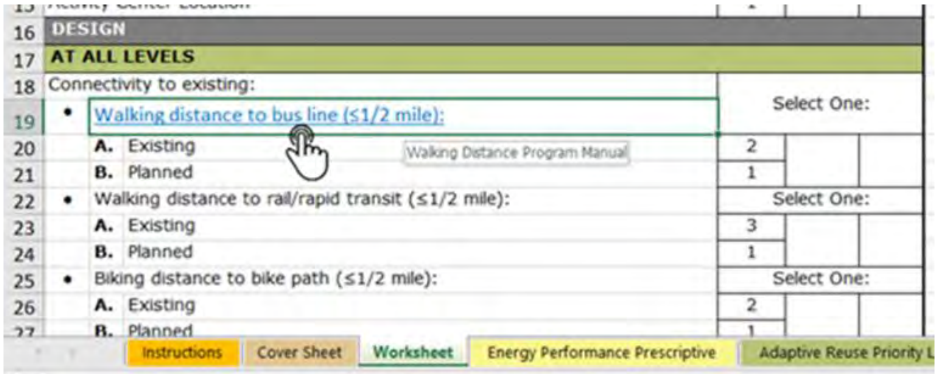

Figure 3: ECMF worksheet hyperlink to ECMF program manual

Font colors and sizes also have significant impacts on the utilization of ECMF resources. As users progress through tools and resources, font colors and appropriate sizes appeal to them. With various font colors, such as red and blue, the content within ECMF resources can be better distinguished to signify importance within the lengthy and wordy text. The blue color of the hyperlinks shows the user that there is another section of information available for viewing that is connected to the current section. Appropriate font sizes enhance users' abilities to progress through ECMF tools and resources in a continuously fluent manner. The layout of information in the content-rich resources can assist in guiding users to optimal decisions by strategically presenting the content in an order of importance or significance as shown in Figure 4. The table of contents of the technical guidelines lists the sections to follow in accordance with the worksheet.

Table of Contents

Introduction 4

Site Planning 12
Site Design
Site Preparation and Preservation Measures
Alternative Transportation Accommodations

Construction Waste Management 34

Resource Efficiency 38
Resource Design
Advanced Framing Products
Local, Recycled and/or Natural Content Materials
Building Reuse

Figure 4: ECMF technical guidelines table of contents

The concept of choice architecture is beneficial to this research study. Choice architecture is a creative method best described as multiple ways of presenting a choice to a decision-maker and the decision that is selected depends on how the choice is presented (Johnson et al., 2012). By strategically framing content and options in EarthCraft resources, stakeholders are nudged into making logical decisions. Factors that are expected to have contrasted impacts on the usability include but are not limited to seniority and years of experience. Preliminary findings of UX studies have shown that seniority and years of experience have notable impacts on usability (Lallemand et al., 2015).

In addition to usability, years of experience also affect how builder-developers view resources. Figure 5 below shows how experienced builder-developers potentially view the process overview of the program manual from Figure 2. The difference between Figures 2 and 5 is that Figure 2 provides a visual of how all new users view the process overview while Figure 5 visualizes how experienced builder-developers are familiar with the process and look for specific steps. The steps that are potentially neglected are marked out or blacked out in Figure 5.

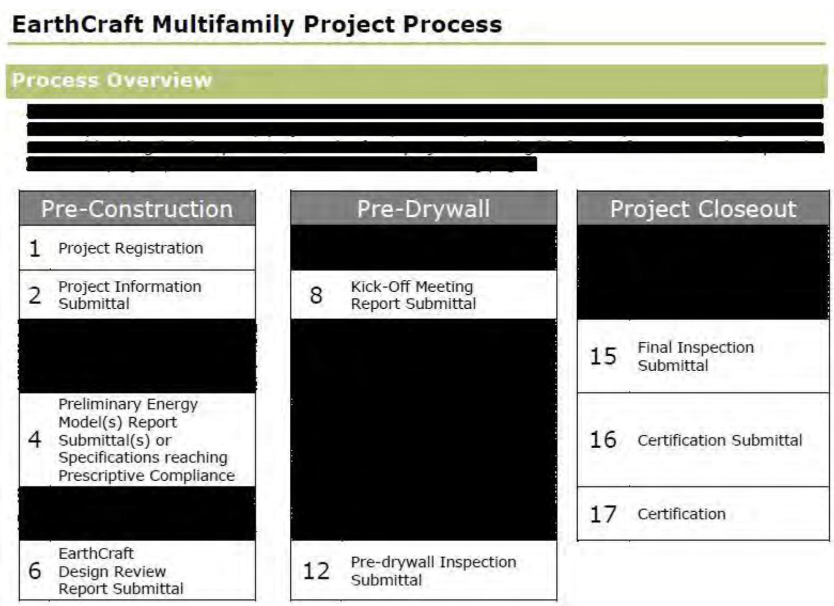

Figure 5: Experienced builder-developers' view of process overview section

Interviews for this study have not been concluded yet. Preliminary findings suggest that builder-developers often resort to a familiar process when utilizing resources due to status quo bias and satisficing. Focused coding will show the most prominent decision-making theories represented within our data. A code application analysis chart in Dedoose will be used to record the interview transcripts and codes occurring as shown in Figure 6 below. The number of times a code appears in each interview transcript is shown in the figure. For example, a 1 means there is one instance of a specific code appearing in a transcript, a 2 means there are two instances of a specific code appearing in a transcript, and so on. A complementary codebook will be assembled to supply the audience and future researchers with definitions and examples of every code used to comprehend the complex nature of the codes being used.

Media \ Codes	Design layout	Font color	Font size	Navigability	Totals
Participant 1.docx	1		2	2	5
Participant 2.docx	1	1			2
Participant 3.docx	1	2	1	2	6
Participant 4.docx	3		1	1	5
Totals	6	3	4	5	

Figure 6: Code application analysis chart of interview transcripts and codes

Conclusions

This research study provides improvements to the accessibility and usability of ECMF resources. The scope of this study is intended to follow seven features of user experience: useful, usable, desirable, findable, accessible, credible, and valuable. The seven features of user experience are structured as shown in Figure 7 below. The seven features are deemed beneficial in analyzing the usability of green certification resources in sustainable construction. Preliminary analysis shows that readability and navigation issues are present in ECMF tools and resources. Appropriate content and options are strategically framed to improve the accessibility of ECMF resources and enhance user decision-making through the concept of choice architecture.

Figure 7: Structure of seven user experience features

Multiple sectors such as community diversity, health, and environmental sustainability have been influenced by energy-efficient affordable housing. This research has the potential to provide intellectual merit by utilizing user experience methodologies to advance our understanding of improving the delivery of green buildings. By lowering the level of expertise necessary for sustainable infrastructure delivery, ECMF resources will allow for the involvement of a broader set of stakeholders. Improvements to ECMF tools and resources allow for inexperienced stakeholders to manage their roles in the project delivery process more effectively.

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BIM for parametric problem formulation, optioneering, and 4D simulation of 3D-printed Martian habitat: A case study of NASA's 3D Printed Habitat Challenge

Naveen Kumar Muthumanickam[1], Keunhyoung Park[2], Jose Pinto Duarte[1], Shadi Nazarian[1], Ali Memari[2], and Sven G. Bilén[3]

[1] Department of Architecture, College of Arts and Architecture, The Pennsylvania State University, 121 Stuckeman Family Building, University Park, PA, 16802. Phone Number (814) 863- 2450, Corresponding email: vrmnk@psu.edu.

[2] Department of Architectural Engineering, College of Engineering, The Pennsylvania State University, 104 Engineering Unit A, University Park, PA, 16802.

[3] School of Engineering Design, Technology, and Professional Programs, College of Engineering, The Pennsylvania State University, 213C Hammond Building, University Park, PA, 16802.

ABSTRACT

The design of buildings to be additively constructed using robots requires a paradigm shift during the design process. Using industrial robots to 3D print concrete structures imposes constraints on geometries that can be feasibly 3D printed. It is essential to consider the feasibility of 3D printing any geometrical structure during early stages of its design to avoid unnecessary revisions. Moreover, this new paradigm requires us to easily and efficiently compare and evaluate multiple design options to make informed decisions. These tasks mandate meticulous extraction of requirements from the design brief, parametric formulation of the design problem to include those requirements in the form of design variables and objectives; and generation and simulation of multiple design options and scenarios. This paper presents an overview of our efforts to leverage Building Information Modeling (BIM) for algorithmic problem formulation, optioneering, and 4D simulation in the process of designing a Martian habitat to be 3D printed as part of the NASA 3D-Printed Habitat Challenge Competition.

INTRODUCTION

An interdisciplinary team of researchers from the Pennsylvania State University participated in NASA's (National Aeronautics and Space Administration) 3D-Printed Habitat Challenge, in which multiple teams competed to push the state of the art of additive construction technology to design and build sustainable habitats for humans to live on Mars. The competition was hosted in multiple phases that included the design phase (Phase 1), structural member phase (Phase 2), and construction of an on-site sub-scale habitat phase (Phase 3) with multiple levels under each phase. Phase 3 included two virtual design levels and three actual construction levels. The virtual design levels emphasized leveraging Building Information Modeling (BIM) to design the habitat as well as the underlying construction process and logistics involved in its additive construction. The actual construction levels emphasized leveraging autonomous construction methods to additively construct parts of the habitat with progressive complexity ranging from foundations at the initial level; construction of a cistern with two required pipes that penetrated its thick wall and performance of a hydrostatic test during the second level; and a 1:3 sub-scale habitat design (a simplified version of the full-scale habitat design submitted for the virtual construction level) during the third level of the competition.

DESIGN BRIEF

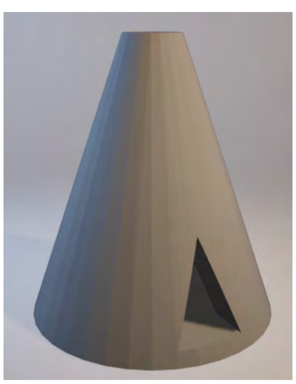
The habitat had to be designed for four astronauts with a minimum of 93 m^2 area comprising eating, work/lab area, recreation, sanitation, and sleeping spaces enclosed by pressure-retaining walls. The habitat should also include mechanical, electrical, and plumbing (MEP); environmental control, and life support systems (ECLSS); and entry/exit and viewing ports (based on habitability requirements from NASA-STD-3001, Volume 2). These systems had to be modeled at a schematic level of development (LOD 100) for the virtual construction level. The structural systems such as foundations, load bearing walls, and retaining walls had to be modeled to LOD 300 and analyzed before actual construction. The exterior surface of the habitat was to include one suit hatch of size 85 cm by 60 cm, one view port (located close to the suit hatch) of 50 cm in diameter (minimum), and one equipment/rover hatch of size 1 m wide by 1.5 m tall with the bottom edge located 0.5 m above the top of the foundation slab. Two 75-mm-diameter (minimum) penetrations, located at least 1 m apart from each other were to be made for combined communications–power–instrumentation.

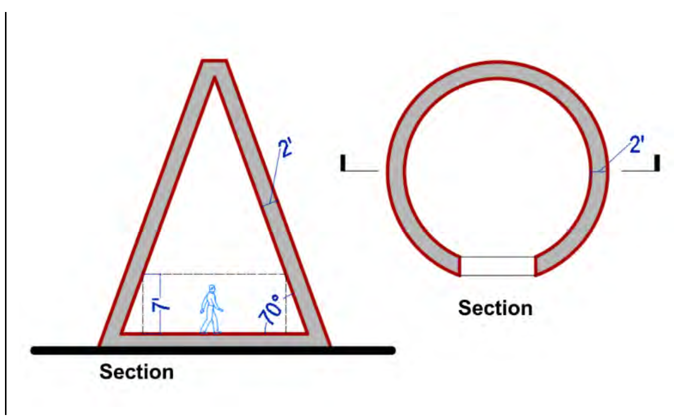
Apart from these functional requirements, the shelter designed for additive construction had to satisfy environmental requirements meant to simulate Martian conditions—its extreme temperature swings, severe cosmic radiation, reduced gravity, and 3D printing feed stock material (concrete in our case) in near-vacuum conditions. As a rule of thumb, the walls had to be designed to be a minimum of 0.6-m thickness (for most construction materials available on Mars) to shield harmful cosmic and galactic radiation from entering interior spaces.

DESIGN OF THE HABITAT

During the conceptual ideation stage, a circular profile was selected for the footprint of a single module of the habitat, as a circle helps distribute stress uniformly throughout the structure. Furthermore, these circular base profiles were designed into cylindrical forms transforming into conical extrusions towards the top to enclose the volume. Each volume was to be used as an independent module catering to the various spatial and programmatic needs such as lab/workspace, kitchen and dining area, food production area, and sleeping area. Each conical extrusion was envisioned to be a modular unit that can be replicated into many such modules and connected to each other sometimes using a connector or intersecting another forming a cluster of modules to cater to human habitation. At this juncture of the design ideation, the connectors that connect modules had to be designed to safety standards, acting as an environmental control barrier between modules in case of an emergency. Apart from such spatial requirements, the geometry of the modules or a cluster of modules contributing the Martian habitat had to satisfy environmental systems and structural design objectives. Furthermore, the angle of the conical extrusions, angle of the tapering portions in the connectors, and the geometry of the intersections of the module and the connectors were constrained by the printability (feasibility to 3D-print geometry) and the material behavior at such areas (Muthumanickam et al., 2020). Hence, a variety of options had to be generated parametrically and optimized for all such objectives and constraints. (This paper focuses on the parametric problem formulation and generation part and does not cover the multi-objective optimization part, which is covered in Muthumanickam et al., 2020.)

Initially, module design with circular profiles tapering towards conical extrusions were considered. The height and structural performance of the structure dictated the minimum height of the straight wall and the angle of taper of the conical extrusion. Later, various patterns of module distributions or arrangements were modeled and tested for their structural, environmental, and spatial adjacency performance. For the sake of scalability and modularity, three types of intersections were developed, such as modules overlapping each other at a distance, modules tangential to each other, and modules at a distance to each other.





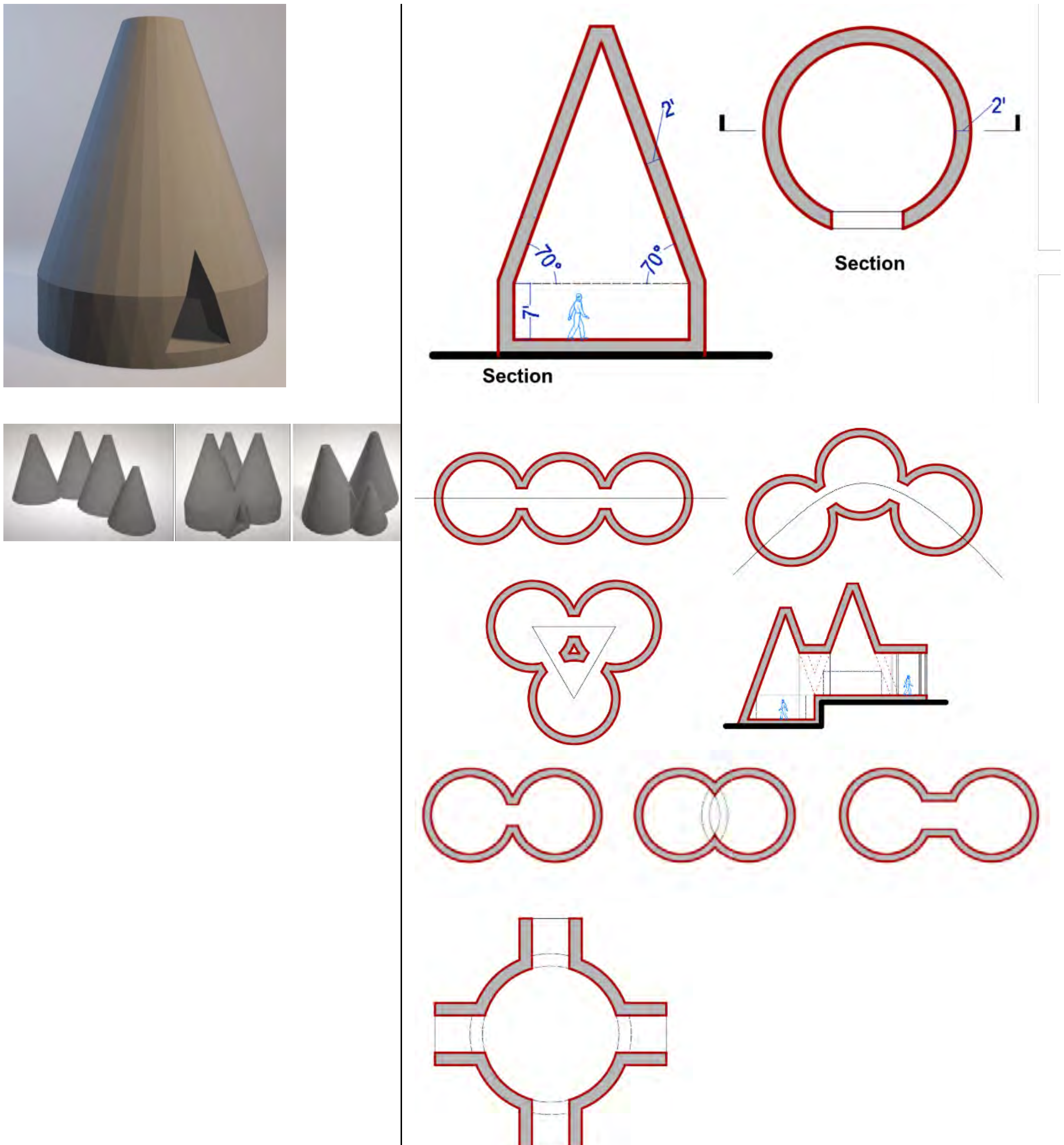


Figure 1: Conceptual design exploration of the Martian habitat modules, clustering of modules in various configurations, and design of connectors between modules.

1) Parametric Problem Formulation

For the sake of rapid generation of geometrical alternatives and optioneering of best possible design solution, all spatial requirements from the design brief, geometrical constraints imposed by the 3D printing setup (Watson et al., 2019), module-to-module intersection and connection rules, and material properties (Ashrafi et al., 2020) were encoded as parametric rules in Dynamo for Revit™. The parametric script was then used to develop the design of the habitat further and to incorporate the MEP and ECLSS systems to LOD 100, which would together act as a BIM of the Martian habitat. Simultaneously, the programmatic architectural requirements were generatively fit into all such options and evaluated for multiple objectives such as structural and environmental performances.

The parametric script in Dynamo was divided into the following sub-parts, with each sub-part containing several nodes executing geometrical manipulation tasks computationally to result in the overall habitat design. The sub-parts are, namely, input variables; floor plan generator and interior systems modeler; conical module modeler; connector modeler; entry/exit and safety system modeler; additive construction constraint solver; and application programming interfaces (APIs) to connect the BIM model to structural, environmental, and toolpath analyses tools (Figure 2).

Figure 2: Parametric script developed in Dynamo for Revit and its constituent sub-parts.

The input variables encompass a wide array of user input variables such as radius of the base profile of the module (r); distance between modules (d); angle between modules (α); height of straight walls (h_{ms}); overall height of the modules (h_0); tapering angle of the conical extrusion (α_m); wall thickness (t); connector sectional profile manipulators; width of connector (w); height of straight walls in connector (h_{cs}); overall height of connector (h_{co}); tapering angle of connector (α_c); width (w_c) and height (h_{es}) of entry and exit modules; penetrations in entry and exit modules; floor slab thickness (t_f); number of floors (n); number of crop shelves inside food production module; spacing between crop shelves; MEP routing variables (l_{mep}); usable area (a_u); and so on. Subsequently, these input variables were parametrically varied to create a huge set of multiple design options, which were then evaluated using various structural and environmental performance analyses, and toolpath simulation tools. The objectives and constraints for the objectives were mathematically formulated as shown below:

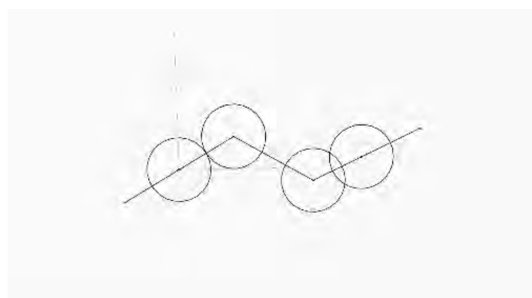
Objectives	Functions
max	$f_1(r, d, \alpha, h_{\mathrm{ms}}, h_0, \alpha_{\mathrm{m}}, t, w, h_{\mathrm{cs}}, h_{\mathrm{co}}, \alpha_{\mathrm{c}}, w_{\mathrm{c}}, h_{\mathrm{es}}, t_{\mathrm{f}}, n, l_{\mathrm{mep}}, \ldots)$
min	$f_2(r, d, \alpha, h_{\mathrm{ms}}, h_0, \alpha_{\mathrm{m}}, t, w, h_{\mathrm{cs}}, t_{\mathrm{f}}, n, l_{\mathrm{mep}}, \ldots)$
min	$f_3(t_{\mathrm{l}}, n_{\mathrm{l}}, \ldots)$

Constraints

such that
$t \geq 0.6$ m
$a_{\mathrm{u}} \geq 110$ m^2
where,
a_{u} is the minimum usable floor area prescribed per NASA habitatbility standards
f_1 is the compressive strength of the design
f_2 is the build cost based on construction material quantity
f_3 is the time taken to 3D print the entire structure

The mathematical formulation was scripted in Dynamo for Revit. The initial sequence of steps in the parametric design and modeling of the Martian habitat is shown in Figure 3.

Module arrangement and clustering



Spatial program modeler

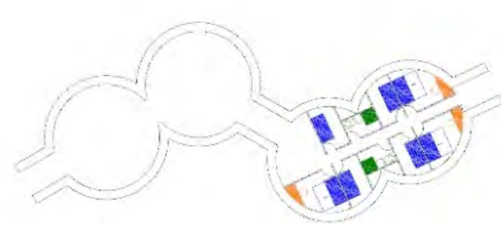


Figure 3: Initial sequence of parametric modeling involving module clustering and spatial programming in Dynamo for Revit.

2) Parametric Optioneering

The spatial program modeler was programmed to take into account the minimum permissible area for human habitation and this, in turn, dictated the overall shape of the module geometry, i.e., the radius of the module, height of straight wall, overall height of module, and the angle of taper. The upper and lower bounds for the taper angle for 3D printing concrete was identified by using a combination of structural analysis tools and physical experiments to test material behavior. Varying angles of small sample concrete structures were 3D printed using an ABB IRB 6640 industrial robot arm as part of the physical tests, and the material behavior was documented and analyzed to identify rate and type of deformations and material failure. These angles were then used as threshold ranges in the parametric script to generate modules of varying tapering angles, which were then tested for structural strength (compression and lateral loads). The maximum tapering angle and the number of beads in every layer of the 3D printed samples mutually dictated the performance of the gradually cantilevering taper of the modules that were to be 3D printed for the actual construction level at the competition venue. Figure 4 shows an example of such a test and Table 1 tabulates the results of these tests.

Figure 4: Physical experimentation of a sample concrete structure printed to test material deformation at 65-degree angle. The beads failing on the interior side can be seen.

Table 1: Tabulation of design options with varying taper angle and their associated module radius, overall height, usable area and height at 1:3 scale (for printing during actual construction level).

Options	Radius (m)	Distance(m)	Straight wall(m)	Height(m)	Area (Sq.m)	1/3rd height
60 Intersect	3.66	0.00	4.85	11.28	170.27	3.75901656
60 Tangent	3.66	0.00	4.85	11.28	171.88	3.75901656
60 Distance	3.66	3.05	4.85	11.28	178.32	3.75901656
70 Intersect	3.66	0.00	2.74	13.41	140.29	4.470181855
70 Tangent	3.66	0.00	2.74	13.41	141.90	4.470181855
70 Distance	3.66	3.05	2.74	13.41	148.35	4.470181855
65_Intersect	3.35	3.35	3.05	9.75	114.27	3.251041349
65_Tangent	2.99	0.30	4.27	11.28	111.58	3.75901656
65_Tangent Revised	2.99	0.30	3.66	10.36	93.00	3.454231434

Additionally, small concrete samples with varying edge configurations were also 3D printed using the same ABB IRB 6640 industrial robot arm to test the material deformation properties at edges and corners. The results and observations from such physical tests (Figure 5, top) were used as input threshold limits for edge conditions in the parametric script in Dynamo. The additive construction constraint solver nodes in the Dynamo script were used to parametrically incorporate the tapering angle and edge condition threshold values (observed from the physical experimentation) into the BIM of the Martian habitat. Multiple design options with varying combinations of these threshold values were generated automatically by the Dynamo script.

Figure 5: (Top) Physical experimentation of various edge configurations and the material deformation at the edges during robotic 3D printing. (Bottom) Failing of beads at interior side of tapering cone (marked in dotted yellow line). (Bottom right) Sectional view of module geometry at connector showing fillet edges

DESIGN OF THE CONSTRUCTION SETUP AND LOGISTICS

In addition to structural and environmental tools, data transfer APIs (sub-part of the Dynamo script) were used to transmit the resulting geometries and associated design data to slicing and toolpath analysis tools such as Cura and HAL for Grasshopper in Rhino. The toolpath for additively constructing all these geometrical options were generated and evaluated and the optimizer was used to identify the option that had the minimal printing time. Furthermore, the construction setup (robotic work cell) encompassing the equipment shown in Figure 6 was modeled in Revit. This model was then used for simulating the entire logistics of arrival and pre-printing setup as well as the toolpath motion planning of the robots (both 3D printing and window placement). Figure 6 shows the setup of the printing system in the designated 15.0 m × 15.0 m area in the arena, which includes the following:

1) Conestoga trailer with water tank, small silo, super sacks of dry mix (1.0 m^2, 1,458 kg)
2) Water tank (10,000-liter capacity) with water pump
3) Box truck with supporting equipment and spare parts
4) Large silo, AP-200 Lo-Pro (22.0 m^2), for feeding the dry mix into the smaller silo
5) Small silo, m-tec Picolo Silo (1.2 m^2, 500 kg), for feeding the dry mix into the Duomix 2000
6) Conveyor belt, m-tec Hurrican 160 (245 kg), to take the dry mix from the small silo to the large silo before printing starts, and could also be used to take the dry mix from the small silo to the Duomix 2000 during printing, if the Duomix 2000 hood gets out of order

7) Mixer and pump, m-tec Duomix 2000 (260 kg), a machine for mixing the dry mix with water and extruding, which includes a hood to connect directly to the small silo and a probe to control feeding
8) Robot 1, an industrial 6-axis robotic arm ABB IRB 6640-235 (3,375 kg), to guide the extruder nozzle along the generated toolpath and print the habitat
9) Robot 2, an industrial 6-axis robotic arm ABB IRB 6600 (3,320 kg), tasked with the placement of the prefab hatch components
10) Computers, one for each robot
11) Power outlets cluster, to which the power cords of the various equipment will connect
12) Robot controllers, one for each robot
13) Printing area, where habitat is printed
14) Safety fence, to delimit the area within the reach of the robots, where no one can go while robots are in automated operation mode; includes a light curtain on the edge from which the nozzle supervisor might enter the printing area if necessary, thereby automatically halting the robots
15) Loading platform, Skyjack, to load the large silo if Hurrican fails
16) Observation pole, equipped with GoPro camera to monitor printing
17) Prefab hatch components, to be placed by robot 2 during printing
18) Forklift, to unload equipment and material, to be supplied by the organization, and kept outside the working area.

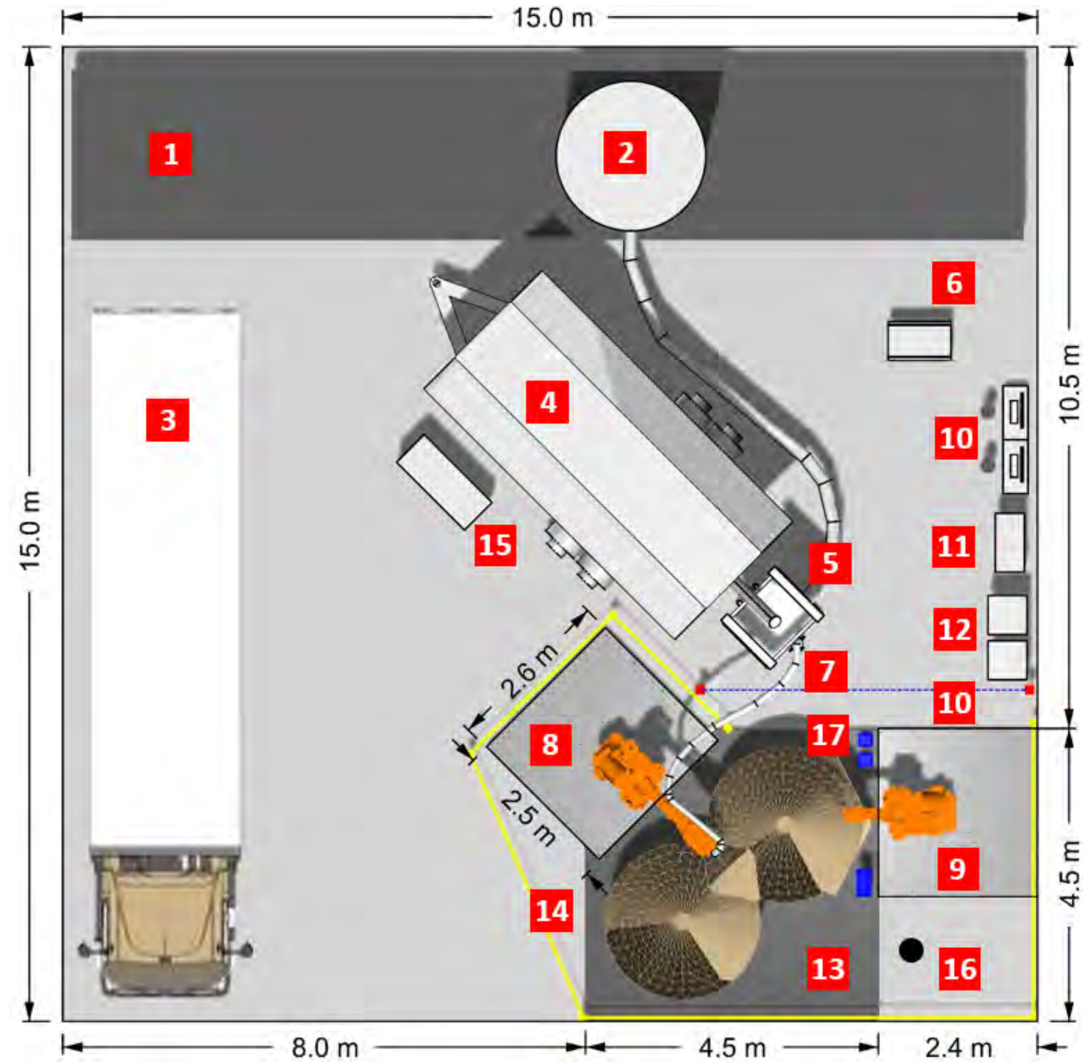
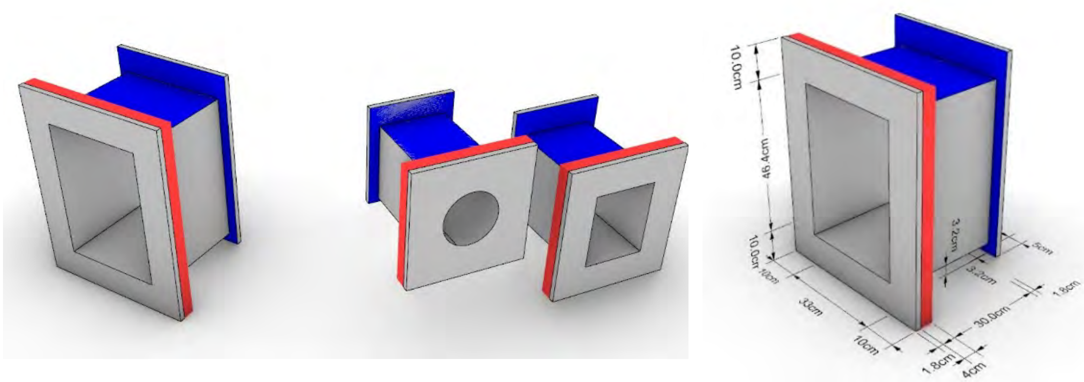


Figure 6: BIM of overall setup at 1:200 scale in the designated 15 m × 15 m area for actual construction level modeled in Revit

DESIGN OF CONSTRUCTION SEQUENCE – 4D SIMULATION

As mentioned before, a 1:3 sub-scale habitat design (simplified from the full-scale habitat design submitted for the virtual construction level) was to be 3D printed during the third level of the head-to-head competition (actual and final construction level). To ensure proper adherence to schedule and efficiency of automated operation of the robotic 3D printing process, a 4D simulation of the entire sequence of robotic construction and associated logistical operations was developed. The operation of two robots—one for 3D printing of the concrete wall structure and the other for placing penetration frames autonomously—presented a complex situation, in which it was crucial to coordinate the motion planning of the two robots to avoid potential collisions or damage to the uncured structure (fresh layers of 3D printed concrete). The design of the entry module, which had three penetrations with varying dimensions and positioned at various heights from the base, demanded detailed 4D simulation of the sequence of installation of the penetration frames (windows and hatches) to avoid such collisions. The openings had the dimensions shown in Figure 7b.

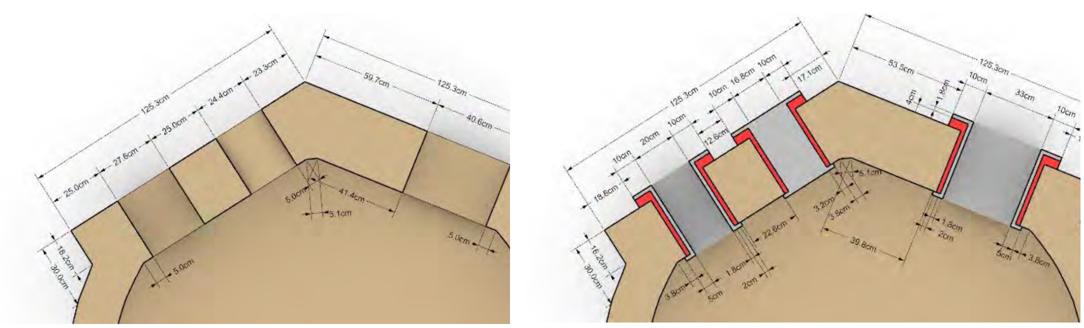
The window hatches were prefabricated as an assembly that contained the various hatches using 3/4″ (19 mm) plywood (Figure 7a). A soft sealant (e.g., a closed cell structure sponge or foam) was applied onto the inner sides of the inner flanges, the bottom, and the top of the component, as indicated in blue in Figure 7b. Upon placement of the hatches in position, an expanding foam sealant (15 Board Foot Polyurethane 2-Component Spray by Dow) would then be injected into the inner side of the outer flanges on the next day, as indicated in red in the diagram below.



a b

Figure 7: (a) Models of the three hatches (b) zoomed in model of the rover hatch showing the sealing strategy: blue indicates the previously applied soft sealant, and red indicates the expanding foam injected on the next day.

Figure 8 shows the plan and 3D frontal view of the sub-scale habitat showing the location of the openings, including the structural aluminum frame of the hatch components. The second ABB robot arm was used to lower these components in the respective openings as soon as the final height of each opening was reached when printing the walls sequentially in the following order: first the suit hatch, then the view port, and finally the rover hatch as shown in Figure 9.



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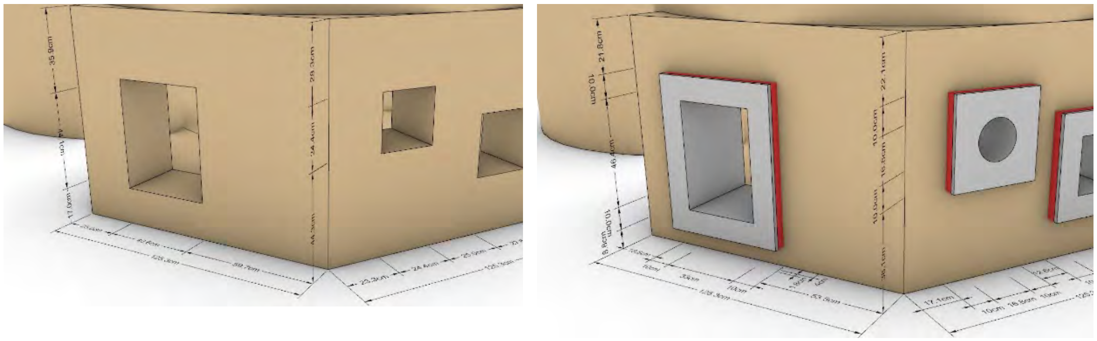

c d

Figure 8: Location of exterior penetrations designed for Construction Level 3 in plan (a and b) and in elevation (c and d).

In addition, Figure 9 describes the procedure to follow in the placement of each hatch frame. We have considered 2.0-cm tolerance on each side of the component (i.e., making the opening in the printed wall 4 cm wider than the component itself) to avoid any contact with the fresh concrete during the insertion process. With reference to Figure 9, once the hatch was safely in place, the robot gently pressed it against the inner surface of the wall, moving it forward toward the outside, until the inner flanges made contact with the inside face of the wall, thereby leaving a 4-cm gap between the outer flanges and the outside face of the wall. The next day, when concrete had hardened, the front gap was filled with injected expanding foam applied by the robot. When the wall was printed to the top of the first opening, the suit-hatch component was placed given the detailed description above. Printing continued covering the top of the first component and when the wall reached the top of the second opening, the view-port component was placed. Printing continued, covering the view-port hatch until the wall reached the top of the third opening, and then the rover hatch component was placed. The printing continued thereafter to complete the habitat.

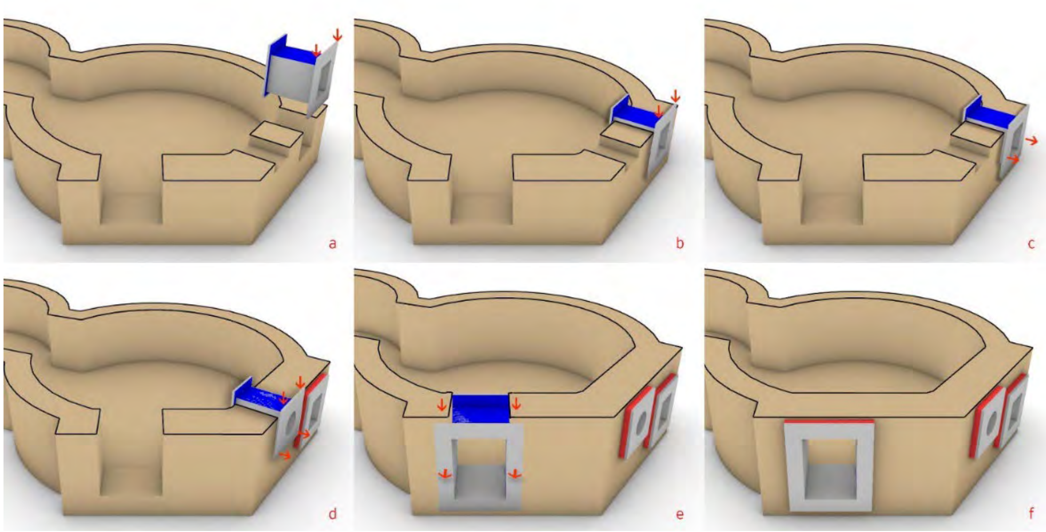

Figure 9: Construction sequencing regarding placement of hatch components.

Figure 10 shows a 3D model of the habitat design with the cold joints designed to account for the interface between hardened concrete and wet/freshly printed concrete after an intermittent stoppage in 3D printing.

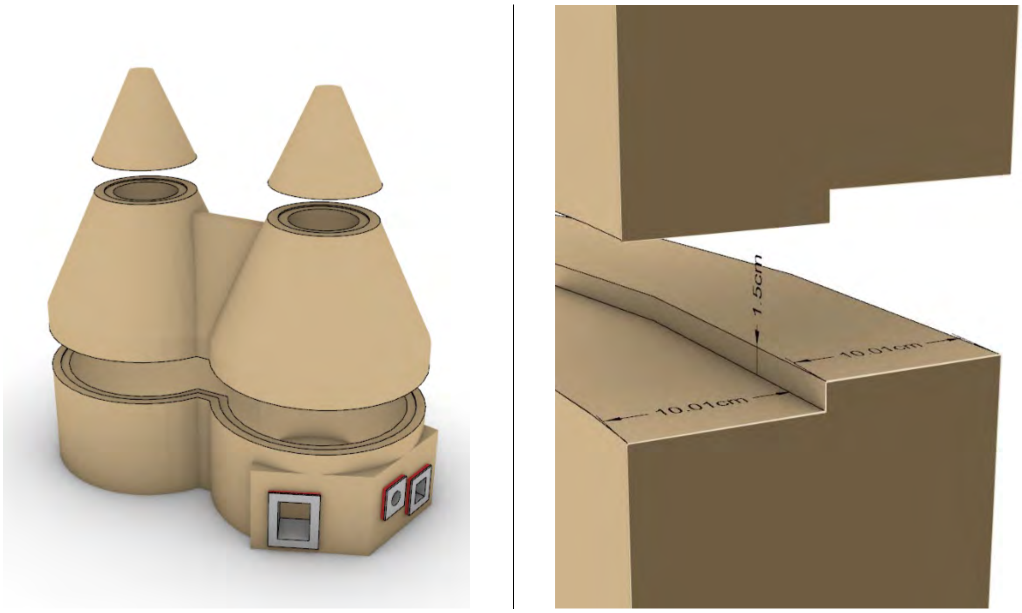

Figure 10: 3D model of the habitat design (left), exploded axonometric showing the location of cold joints (middle) and section of the cold joint interface (right).

Figure 11: Final 3D printed concrete structure at the actual construction level.

CONCLUSION

Hence, a unified BIM platform tied to various analysis and simulation tools was used extensively, not just for the design of the Martian habitat, but also both in the design of the building and associated details as well as the construction sequencing and 4D simulation to be able to 3D print the world's first fully enclosed and tapered concrete building at architectural scale without any support structures. This accomplishment was possible due to the use of the BIM platform combining generation, evaluation, and optimization capabilities, which enabled one to identify the most appropriate solutions for two very different environments, Earth and Mars. This platform encoded the relationships between material, printing, and design aspects, making it possible to develop in parallel the design of the shelter, the printing system, the printing setup, and the construction process, embodying what one could call a holistic design approach. The development of this platform was supported by extensive experimental testing that enabled one to identify the relationships between the variables associated with the three aspects mentioned above, as well as the interval of values that each variable could take. The experimental testing covered partial aspects of the design such as, maximum printing angle, sharp corners, window placement and sealing, coordination of the printing and window placement robots, among others. This testing led to a successful printing of the sub-scale shelter in the head to head competition. However, the effort of printing the whole shelter was not completely seamless as it also revealed some shortcomings, such as, over extrusion in some areas, bigger material deformation than anticipated, offset of the printing toolpath between various printing sessions, among others. These shortcomings had a negative impact on the autonomy of the process and will require additional research to be overcome.

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LIFE-CYCLE COST AND CARBON FOOTPRINT ANALYSIS FOR LIGHT-FRAMED RESIDENTIAL BUILDINGS SUBJECTED TO TORNADO HAZARD

[1] Pramodit Adhikari

[2] Hussam N. Mahmoud

[3] Aiwen Xie

[4] Kathrina Simonen

[5] Bruce R. Ellingwood

[1] Graduate Research Assistant, Department of Civil & Environmental Engineering, Colorado State University, Ft. Collins, CO, 80523
[2] Associate Professor, Department of Civil & Environmental Engineering, Colorado State University, Ft. Collins, CO, 80523
[3] PhD Candidate, Department of Architecture, Harbin Institute of Technology, Harbin, Hei Longjiang, China, 150090
[4] Associate Professor, Department of Architecture, Univ. of Washington, Seattle, WA, 98195
[5] Professor, Department of Civil & Environmental Engineering, Colorado State University, Ft. Collins, CO, 80523

ABSTRACT

Light-frame wood building construction dominates the single-family residential home market in the United States. Such construction is susceptible to damage from extreme winds due to hurricanes in coastal areas and tornados in the Midwest. The consequences of such weather phenomena on residential construction can be severe and are likely to increase in the coming decades as a result of increases in urbanization and economic development and the potential impacts of changing climate in hazard prone areas. Current building practices generally do not consider building *resilience* or *sustainability*. Post-disaster building reconstruction or replacement following a natural disaster should enhance subsequent building performance without compromising the environment. This paper explains how a balance between resilience, sustainability and cost might be achieved in design and rehabilitation of residential building construction for tornado hazards.

KEY WORDS

Fragility; residential buildings; resilience; sustainable construction; tornadoes.

1. Introduction

More than 90% of the U.S. housing market is comprised of light-framed wood building construction. Such buildings are attractive to home buyers and developers because of their low cost (Maloney et al., 2017), but are susceptible to damage from extreme winds. The impact of damage on such structures and the social and economic wellbeing of a community can be severe (Kuligowski et al., 2014). For example, tornadoes have caused an average of nearly $8 billion per year in economic losses (Heberton, 2014), making them one of the most significant among natural hazards in terms of impact. Measures to increase building resilience to reduce the impacts from tornadoes have an effect on their cost and carbon footprint. Not all measures to enhance resilience are sustainable in the usual sense of the term (Hall & Ashley, 2008); improvements to building resilience should also be sustainable in terms of their use of natural resources. Human activities have increased the level of carbon dioxide in the Earth's atmosphere from 338 ppm to 411 ppm since 1980 (Lindsey, 2018). Residential buildings in the U.S. contribute about 20% of total greenhouse gases emissions ("Annual Energy Outlook", 2019). This figure accounts only for direct CO_2 emissions. If the entire life-cycle of the building is considered then this figure is likely to be higher.

Current building codes, with their focus on providing adequate levels of occupant safety and health, (Vaughan & Turner, 2013) rarely address issues related to resilience and sustainability; moreover, most building developers and homeowners are concerned more with keeping initial costs as low as possible rather than minimizing life-cycle costs. This focus on initial cost may have an adverse impact on the resilience and carbon footprint of a building during a life cycle of 50 to 100 years, during which it may be exposed to extreme winds. Instead, residential building costs should be based on a life-cycle analysis to ensure both resilient and sustainable residential building design and construction practices. This paper presents a life-cycle analysis methodology for examining tradeoffs between cost and carbon footprint of owner-occupied single-family dwelling of light-frame wood construction. Cost and carbon foot-print functions are formulated which enable the initial construction cost, repair and maintenance costs, and damage cost due to the random occurrence of tornadoes to be amortized over the life cycle of the building. This paper shows that when the life cycle of a typical home is considered, the decisions involving home construction or home repair following a tornado to enhance resilience and minimize carbon footprint differ significantly from those made on an initial cost basis.

2. Theory and Methodology

The life-cycle of a building can be represented by Figure 1 below. Its total life-cycle cost depends on the decisions taken at the times of initial construction, routine maintenance, and repair or reconstruction following wind-induced damage. In the life-cycle analysis of residential buildings presented herein, the focus is on damage costs; indirect economic losses, morbidity and mortality are not considered because of the difficulties in assigning costs to these factors.

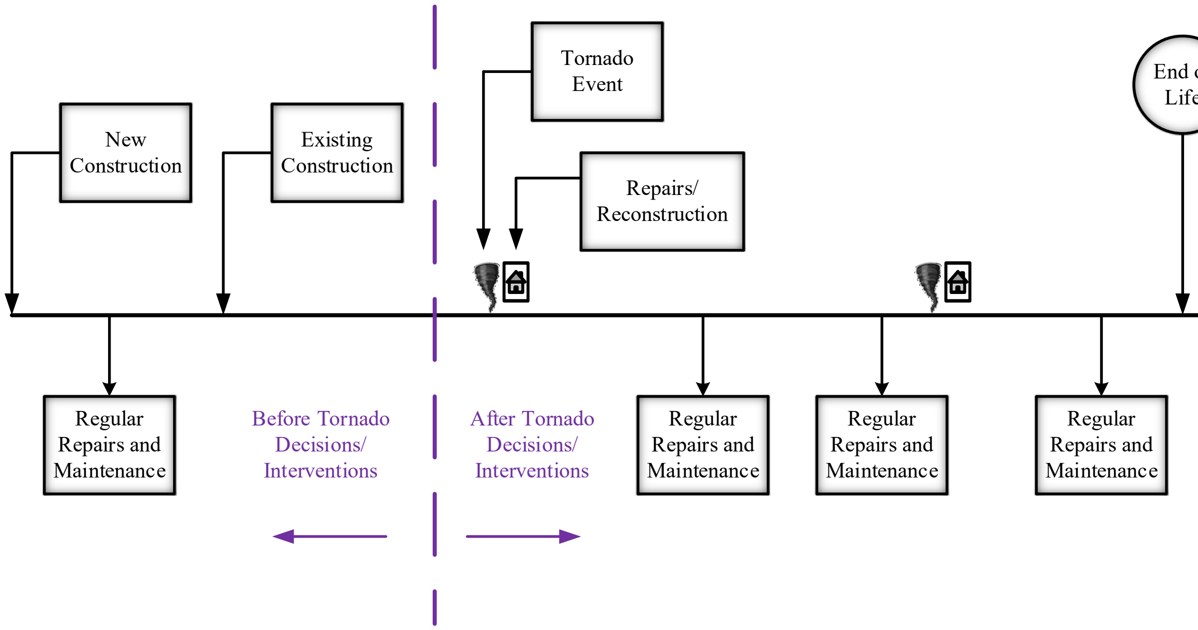

Figure 1 Representation of building life-cycle

2.1. Assessment of Life-Cycle Cost and Carbon-Footprint

2.2.1 Expected Life-Cycle Cost

The present value (PV) life-cycle cost, of the building exposed to a scenario tornado with 3-sec gust wind speed, *v*, includes initial cost, regular repair/maintenance cost, and costs of repairing damage following the occurrence of a tornado, respectively:

$$PV_{cost}(v) = C_0 + \sum_{i=1}^{n} \sum_{j=1}^{k} \frac{C_{j,rm}}{(1+d_c)^{n\Delta t}} + \sum_{j=1}^{k} \frac{C_{j,T}(v)}{(1+d_c)^{T_{tor}}} P_j(v) \quad (1)$$

Here, C_0, C_{rm} and $C_{j,T}$ are the initial cost, regular repair and maintenance cost for the repairs at time t, and tornado repair. Maintenance/repair and damage costs are incurred at *n* regular intervals, Δt. while the tornado can occur at random time, T_{tor}, during the service life of the residence. The failure cost depends on *v* and T_{tor}. All costs are discounted to present value, where the discount rate is d. The damage to component j is described by the fragility, P_j, described subsequently in Section 3.

2.2.2 Total Carbon-Footprint

The carbon emissions, measured in kilograms, are also discounted to present value because the carbon dioxide emitted today will have a long-lasting impact (Tol 2019), but the discount rate, d_m, might be different from that used for cost.

$$PV_{carbon}(v) = M_0 + \sum_{i=1}^{n} \sum_{j=1}^{k} \frac{M_{j,rm}}{(1+d_m)^{\Delta t}} + \sum_{j=1}^{k} \frac{M_{j,T}(v)}{(1+d_m)^{T_{tor}}} P_j(v) \quad (2)$$

Here, M_0, $M_{j,rm}$ and $M_{j,\mathrm{T}}$ are the carbon emissions due to initial construction, regular repair and maintenance and hazard repair, respectively.

2.2.3 Decision Variables

A single-story building with 1200 ft^2 (30 ft x 40 ft footprint) and without basement (Figure 2) is considered with the following design (or decision) variables which are the building components summarized in Table 1. We chose to focus on structural and nonstructural components and systems, deferring the inclusion of home appliances and heating, ventilating and cooling systems for a later study.

Table 1 Standard and Enhanced Building Components

Components	Standard Condition	Enhanced Condition	Nominal Strength Increase (Maloney et al., 2017)
Roof Shingles	Class D asphalt shingles	Class H asphalt shingles	3.5(74 psf –181 psf)
Roof Panels	6x12 Spa/8d nails/SPF rafters	6x6 spacing/W-L rafters/ 10D nails	3.5(63 psf – 222 psf)
Windows and Doors	DP 25	DP55	2.2(40 psf – 80 psf)
Wall Panels	1/2" gypsum wall board on the interior and 1" thick stucco on the exterior	No change	1(No change)
Rafter-Sill Connection	3-16d box toenail	H2.5 clip	4.6(750 lb – 3446 lb)
Foundation Connection	½" bolts, 6’ o.c.	5/8" bolts, 2’ o.c.	3

Figure 2 Typical single-story archetype

3 Tornado Fragility Curves

3.1 Performance Limit State

The probabilities of damage to structural and nonstructural components and systems of a light-frame wood building exposed to tornado effects in Eqs (1) and (2) are determined by their fragilities, defined as the conditional probability of failure as a function of the 3-sec gust wind speed, v. To determine these damage state probabilities, a limit state is defined as,

$$g(x, v) = R - (W(v) - D) \qquad (3)$$

in which R = component or system resistance, D = dead load, and $W(v)$ = wind load as defined in *ASCE Standard 7-16* (ASCE, 2016):

$$W(v) = q_h(v)\ (GC_p - GC_{pi}) \qquad (4)$$

in which $q_h(v)$ = velocity-related pressure and GC_p and GC_{pi} = aerodynamic coefficients for the exterior and interior surfaces of the building (ASCE 7, 2016). The function $g(\ )$ is negative when the limit state occurs. When wind effects cause uplift or suction on building surfaces, W generally acts in a direction opposite to D. Thus the component or system fragility, $P(v)$, is:

$$P(v) = P[R < W(v) - D|V = v] \qquad (5)$$

In tornado damage assessment, it is common to assume that the building is located in open-country exposure (Exposure C in ASCE 7) because the boundary layer and surface roughness effects are not well understood for tornadoes (Maloney et al., 2017). Tornado wind loading is determined by Method 1 in Commentary section C26.14 of *ASCE Standard 7-16*.

3.2 Tornado Fragilities for Building Components and Systems

The tornado fragilities were determined for each of the six building components and systems identified in Table1. The wind pressures in *ASCE 7-16* depend on the location on the building envelope, higher (localized) pressures occurring at edges of walls, and at the eaves, ridges and edges of roofs. The fragilities define the dependence of component failure probability, required to evaluate Eqs (1) and (2), as a function of 3-sec gust wind speed, v. The fragilities for shingles, roof sheathing, doors/windows and wall sheathing are based in the aerodynamic coefficients for components and cladding in *ASCE 7-16*, while those for roof-wall and wall-foundation connections are based on the aerodynamic coefficients for main wind force-resisting systems. An illustration of fragilities for roof shingles is presented in Figure 3 for the three roof zones in *ASCE 7-16*; fragilities for the other components take on a similar appearance. The tornado fragilities utilized in the life-cycle analysis are based on average wind pressures, in which the averaging is performed by weighting the wind pressures by the individual areas over which the wind acts.

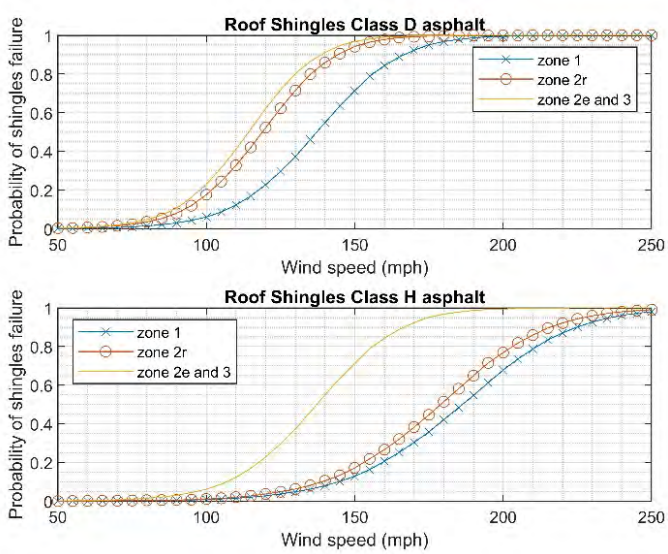

Figure 3 Illustration of Fragilities – Roof Shingles

4 Life-Cycle Cost and Carbon-Footprint Analysis

The cost and environmental impact of different building construction depends on the dimensions, materials and techniques used. In this study, we use materials identified in the RS Means Residential Cost data (2018) and Athena Impact Estimator (2015), which is a tool for predicting the impact of global warming potential, to match the building products in Table 1. The standard-quality construction is representative of practices in the Midwest US. The enhancements of roof shingles, roof panels, wall panels and rafter-sill connection were considered by Maloney et al. (2017) and were aimed at making the building more resistant to extreme winds. The costs estimated from the RS Means data include costs of material and labor costs/square foot. An allowance was added for damage to interior contents, based on the extent of damage to the building envelope, e.g., 100% damage to the shingles on the roof may result in 20% damage to flooring due to ingress of rain; 100% damage to the exterior wall panels may result in 10% damage to flooring due to breach of the building envelope. Such assumptions are approximate but avoid the need for actual testing. The carbon footprint (kg) was determined from the Athena Estimator. The cost of manufacturing, transport and construction/installation for each component is included in the cost and carbon footprint.

The procedure for evaluating Eqs (1) and (2) can be illustrated by considering damage to roof shingles. Suppose that the 3-sec gust wind speed is 120 mph. Using Eqs (3) – (5), we find that 48.7% of the roof shingles must be replaced for standard-quality construction (and 2.8% for enhanced quality construction). The cost for standard quality is $4,977 while the carbon footprint is 737 kg ($179 and 23 kg, respectively for enhanced quality construction). Repeating this calculation for all six components, we find that the total cost at a wind speed of 120 mph is $12,623 and the total carbon footprint is 51,562 kg for standard-quality construction ($11,499 and 39,393 kg, respectively for enhanced quality construction).

In this study we have two life-cycle objectives associated with the building to minimize: cost (in dollars) and carbon footprint (in kg). Problems with multiple objectives often do not admit single solutions that optimize both the objectives unless the objectives are dependent. While sophisticated mathematical techniques are available for such problems (e.g., Chang 2015), the problem considered herein involves a relatively small number of decision variables and distinct options; thus, a simple sort and rank method is used to obtain a solution for illustrative purposes.

5. Illustration of life-cycle analysis of single-family residential building

We illustrate the life-cycle analysis for the single-family residence in Figure 2 and consider the decision variables summarized in Table 1. To simplify the analysis while preserving its fundamental features, we make the following assumptions:

- The single-family residence is assumed to be of standard-quality construction, and has an expected service life of 100 years (Ianchenko et al, 2018)
- We neglect the costs associated with routine maintenance (Eqs (1) and (2)) for simplicity. Such costs can be easily anticipated in comparison with damage costs due to a tornado.
- Tornadoes occur randomly in time, with the probability of either zero or one tornado strike in 100 years being substantially higher than the probability of two or more strikes. Thus, we assume, for simplicity that a tornado can strike a residence only once in 100 years. The occurrence of the tornado is assumed to be uniformly distributed within the service life of the residence; 50 realizations of each tornado scenario in order to compute the expected PV.
- We consider a series of tornado scenarios defined by their 3-sec gust wind speeds.
- The discount rate for expected cost is 3%, consistent with the rate of return on long-term financial instruments.
- The discount rate on carbon footprint is 1%, since the future impacts of climate change are highly uncertain beyond around 2050, and the assumption of a higher discount rate would shift the burden to the future generations (Lee and Ellingwood 2015).

The total life-cycle costs and carbon footprint as a function of 3-sec gust wind speed are illustrated in Figures 4 and 5, respectively.

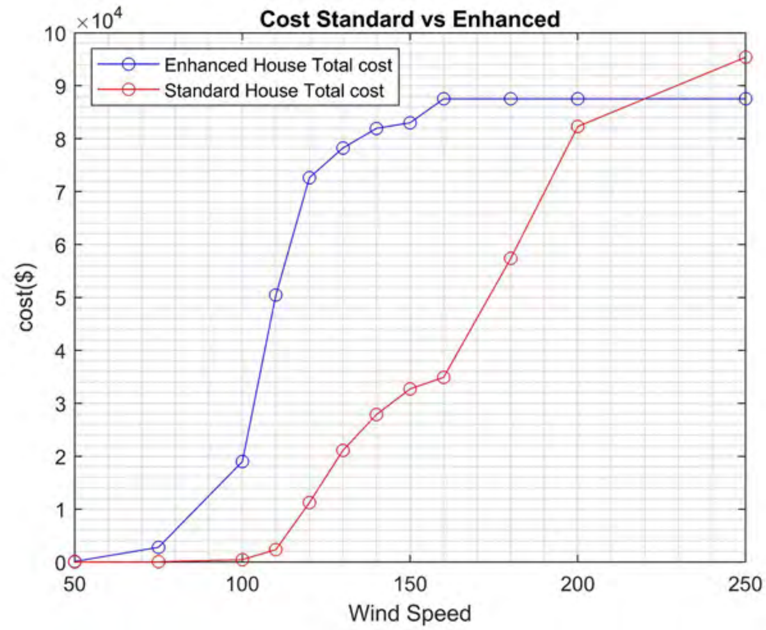

Figure 4 Cost: Standard vs Enhanced

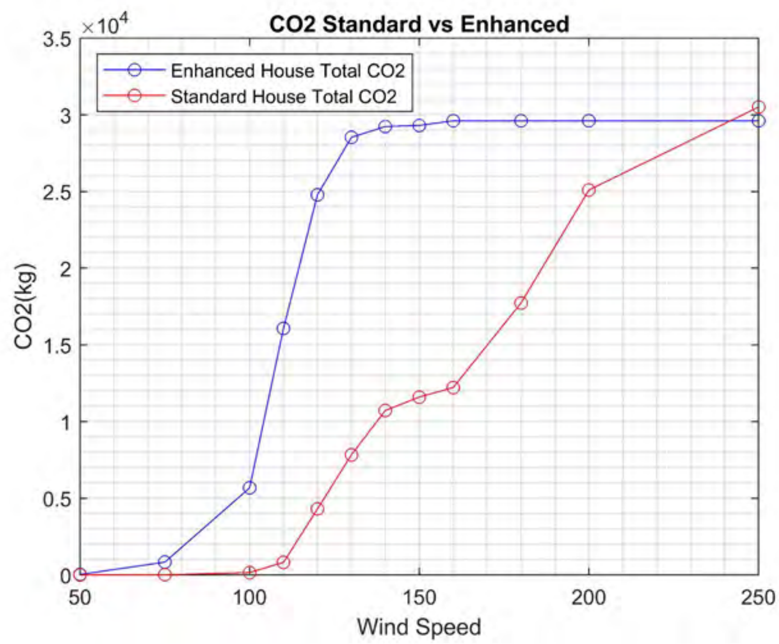

Figure 5 CO2: Standard vs Enhanced

One can easily see the benefits of enhanced construction on expected cost; the small difference in initial cost is overshadowed by the savings resulting from enhanced performance during tornadoes at wind speeds between 100 mph and 250 mph. One sees a similar result in Figure 5 describing the reduction in carbon footprint for enhanced construction, for the same reason. Figures 6 and 7 show that there is a relatively strong positive relationship between cost and carbon footprint for two specific wind speed scenarios, due to the small values of probability of failure for enhanced components compared to standard components. This indicates that enhanced construction practices will always pay off over the service life of a single-family house, provided that other contributors to carbon footprint, such as home appliances and heating/ventilating/air conditioning systems are not taken into account. For a wind speed of 120 mph, the savings in cost over a 100-yr life using the enhanced construction would be $11242, while the reduction in carbon footprint would be by 12168 kg.

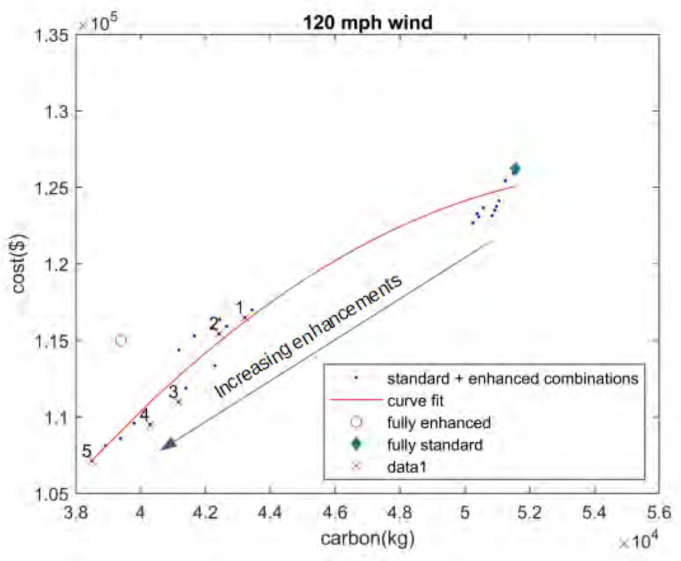

Figure 6 Carbon vs Cost: different combinations of enhancements

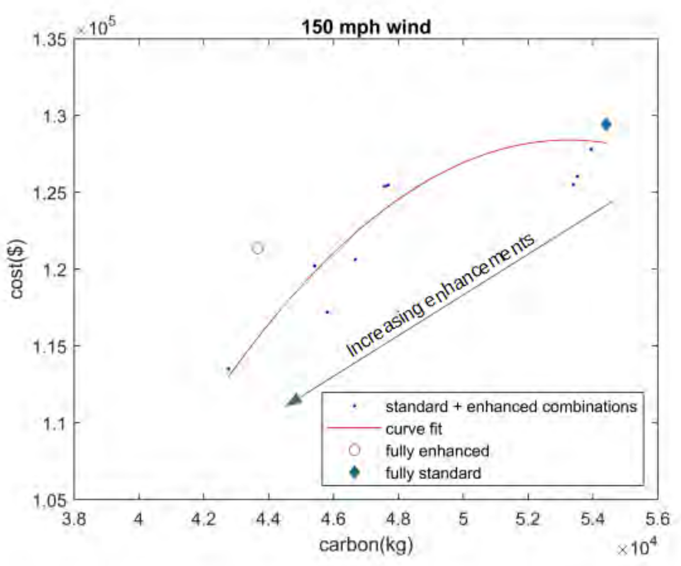

Figure 7 Carbon vs Cost: different combinations of enhancements

Some of the repair combinations between standard and enhanced components, marked 1 through 5 in Figure 6, after the standard building is subjected to a tornado with wind speed of 120 mph, are shown in Table 2:

Table 2 Some of the Repair Combinations for 120 mph wind speed

	Roof shingles	Windows/Doors	Roof Panels	Rafter-Sill Connection	Foundation Connection
1	Standard	Standard	Standard	Enhanced	Enhanced
2	Standard	Enhanced	Standard	Enhanced	Enhanced
3	Standard	Standard	Enhanced	Enhanced	Enhanced
4	Standard	Enhanced	Enhanced	Enhanced	Enhanced
5	Enhanced	Enhanced	Enhanced	Enhanced	Enhanced

6. Summary, conclusions and recommendations for further study

Our study has shown that having a “initial-cost mentality” in residential building construction is not justified and investing in enhanced building quality will be very beneficial in the long term. Including other variables like furniture, appliances, mechanical fixtures, etc. in our problem might give us tradeoff between enhanced and standard components in our building. Studies to investigate these other factors are in progress.

Acknowledgement

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Mitigating the Potential of Overheating in an Earth-masonry Shell House Situated in Johannesburg through Passive Design Strategies

R. A. Bradley[1]

[1]Lecturer, School of Civil and Environmental Engineering, University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, Gauteng, 2000. (+27) 11 717 7127, ryan.bradley@wits.ac.za.

ABSTRACT

There is renewed interest in earthen masonry as it offers several benefits over more traditional building materials, such as: sustainability; low embodied carbon and energy; good thermal and climatic performance; and affordability. A prototype house, featuring earth-block masonry vaults, was built in Johannesburg to assess the potential of incorporating sustainable materials into affordable housing in South Africa. The double-story house also integrates interlocking masonry (mortarless), which was manufactured from recycled building rubble. Of specific consideration in this paper is the thermal performance of the structure during the summer months. Furthermore, several passive design strategies were assessed following the CIBSE TM52: 2013 overheating guidelines. The guidelines evaluate of the risk of overheating against three criteria, which provide limits on the severity and frequency of overheating. The ground floor spaces were not assessed on the basis of overheating criteria because the indoor operative temperature did not exceed the maximum acceptable temperature (T_{max}) during the monitoring period (Jan 2018 – Mar 2018 and Oct 2018 – Mar 2019). In contrast, the first-floor vaults occasionally exceeded T_{max} due to the large surface area exposed to direct solar radiation and its low surface albedo (maroon paint). These maroon colored vaults overheated, failing two of the three criteria, without ventilation. Natural ventilation and painting external surfaces white were especially effective at reducing the potential of overheating in the first-floor vaults. Specifically, ventilating the space in the late afternoon and evening reduced the number of hours above which indoor temperatures exceeded T_{max}. None of the overheating criteria were failed when the vaults were painted white.

Keywords. Earth masonry housing; sustainability; shell roofs; overheating

INTRODUCTION

The thermal performance of smaller residential buildings is largely governed by the characteristics of the building envelope. Moreover, the extent of heat flow through roofing is especially important in this regard, e.g. Morton *et al.* (2005) attributed occasional overheating in a house situated in Scotland to the greater amount of solar radiation received by the roof as well as its low thermal mass. The significance of heat gain and/or loss through roofing is addressed in several building standards through specification of minimum total R-values for standard assemblies. For clay tile and metal sheet roofs, SANS 10400-XA: 2011 gives minimum total R-values ranging between 2.7 m^2.K/W and 3.7 m^2.K/W – depending on the climate zone. Thermal insulation is essential for these typical *low-mass* roof assemblies to achieve the above-mentioned R-values. Unfortunately, much of the informal, as well as formal, low-cost housing infrastructure in South Africa do not meet the minimum performance requirements of SANS 10400-XA: 2011. These issues are illustrated in a study by Naicker *et al*. (2017), in which indoor temperatures were measured in 100 low-cost houses situated in five suburbs of Johannesburg. Specifically, none of the houses evaluated had any form of roof insulation, and the majority of informal and post-apartheid (post-1994) government-built houses (i.e., Reconstruction and Development Programme [RDP] houses) did not have ceilings. A peak indoor temperature of ~ 40°C (104°F) was measured within aforementioned RDP houses between 18 Feb 2014 - 12 May 2014 (Naicker *et al.,* 2017). This period is characterized as a more comfortable part of the year in Johannesburg. Another aspect contributing to the poor thermal performance of low-cost housing is that single-leaf imperial brick (~ 105 mm) walls are used for habitable portions (Naicker *et al.*, 2017; Makaka and Meyer, 2006). SANS 10400-XA: 2011 recommends a minimum masonry unit width of 140 mm (total R-value of the walling > 0.35 m^2.K/W) within the deemed-to-satisfy framework.

In this paper, the summer performance of a house incorporating earthen masonry roofing is examined. A masonry shell roof, unlike conventional assemblies, relies on high thermal mass to mitigate excessive heat gain/loss through the envelope. Although it must be said that good thermal insulation can be achieved by using a greater section thickness. High thermal mass is beneficial throughout the year in the South Africa, and this is especially true for Johannesburg (Conradie, 2012; Climate Consultant 6.0, University of California, Los Angeles). Masonry roofs have been employed for centuries in regions such as Egypt, Iran, and many other parts of the Middle-East (Dabaeih *et al*., 2015; Hadavand *et al*., 2008; Fathy, 1973). The thermal performance of high-mass roofs, in these hot arid regions, has been also examined by several researchers, with some reporting that vaulted roofs are superior to flat roofs (Dabaeih *et al.,* 2015; Hadavand *et al*., 2008). Dabaeih *et al*., (2015) compared flat and curved roofs in a numerical study, and reported that spaces covered by a vault produced lower average indoor temperatures. The source of the advantages associated with vaulted roofs are described below.

1. *Reduced area exposed to direct solar radiation due to self-shading for part of the day*. However, sloped roofs having greater surface area may absorb more radiation during certain times of the day, and year, than flat roofs covering the same plan area (NBRI, 1987). The geometry of the roof and its orientation are of principal importance in this regard, e.g. Tang *et al.* (2006) recommend that vaults be orientated north-south facing and Runsheng *et al.* (2003) showed that heat gain through shallower east-west facing vaulted roofs is similar to that for a flat roof.
2. *Larger convection heat-transfer surface*. Generally, a curved roof has a larger convection heat-transfer surface, allowing it to be more easily cooled than a flat roof covering the same floor area (Dabaeih *et al*., 2015). Hadavand *et al.* (2008)

calculated reduced daily heat flow through vaulted roofs due to superior cooling at night, and early morning, in the presence of wind.

3. *Thermal stratification of indoor air*. Hadavand *et al.* (2008) note that air heated within vaulted buildings, gathers under roofs, resulting in thermal stratification of indoor air (i.e. temperatures are cooler where persons will inhabit the space).

Another factor contributing to the improved performance of vernacular masonry roofs is the thermal inertia associated with their heat capacity and thickness (i.e. > 250 mm). In contrast to these structures, several dozen shells built in the South African interior comprise of only a single-leaf section roughly 105 mm thick (Figure 1a – 1e). These diminutive sections, in combination with the solar exposure of the envelopes, raise concerns regarding the performance of several inhabited masonry shells. Some of these shells are also covered with dark paints (Figures 1d and 1e), which would cause increased heat gain when elements are sunlit. Similarly, the shells assessed in this paper comprise of a single-leaf section, albeit 50% greater than those shown in Figure 1, and coated with a dark maroon paint. These characteristics led to unsatisfactorily high indoor temperatures (Bradley *et al.*, 2019), so passive techniques were implemented to improve the thermal performance. The effectiveness of high surface albedo and natural ventilation are discussed in this paper.

(a) Parabolic roof **(b) Catenary roofs** **(c) Hemispherical dome**

(d) Domes (light tan and dark brown surfaces) **(e) Domes (gray surface)**

Figure 1. Several thin masonry shells situated in the South African interior

EXPERIMENTAL ARRANGEMENT

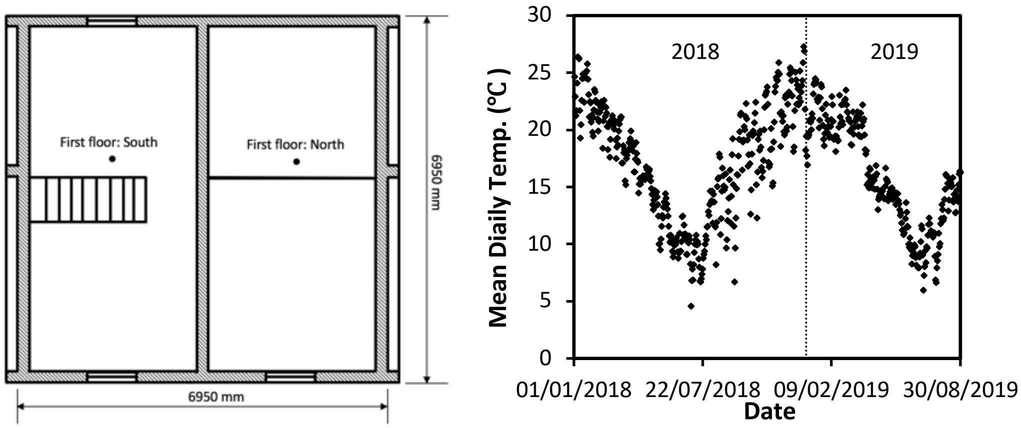
Prototype affordable house. The house is situated on the east-campus of the University of the Witwatersrand, Johannesburg, South Africa (~1700 m above sea level; coordinates of 26°11'09"S 28°01'30"E). The reader is referred to Gohnert *et al.* (2018) for the materials specifications and details of the structural design. The load and non-load bearing walls are built from dry-stack interlocking blocks, manufactured from recycled building rubble; whereas, the vaults comprise compressed stabilized earth blocks (CSEBs) in a traditional mortar. The thickness of the shell, including internal plaster, and vertical walls are ~170 mm and 220 mm, respectively. External surfaces of shells were covered with either dark maroon or white paint during the study period (Figures 2a- 2c). The first-floor slab is 170 mm deep, and comprises a rib and block system.

Instrumentation. Operative temperature (T_{op}) was measured within the building using ~40 mm diameter black globe thermometers. Further information regarding the instrumentation and setup is presented by Bradley *et al.* (2019). Operative temperature represents the combined effect of air temperature, mean radiant temperature as well as air movement, as a single quantity. The location of the globes, relevant to the discussion presented in this paper, is illustrated in Figure 3a. Temperatures were measured 1.1 m above the floor, per the recommendations of ASHRAE 55 (2010). Several black globe thermometers were also used to assess the spatial (plan and elevation) temperature variation in the south vault. Data was recorded every 15 minutes with an Agilent data-acquisition unit (Agilent Technologies Inc., Santa Clara, California). The outdoor air temperature was measured in a continually shaded region on the south-facing side of the building.

(a) 1st Jan – 29th Oct, 2018 (b) 6th Dec – 28th Feb, 2019 (c) 29th Oct – 5th Dec, 2018

Figure 2. Surface color during 2018 and 2019

Monitoring period. The summer monitoring period fell between 1st January 2018 – 31st March 2018 and 1st October 2018 – 28th February 2019. Summer in Johannesburg is between October through to March (Dyson, 2009). Figure 3b shows the mean daily outdoor temperature corresponding to a period between 1st January 2018 and 31st August 2019. The summer months monitored were hot, with many days having mean temperatures above statistical historical records. The South African Weather Service (SAWS) issued several heat wave warnings during the monitoring period; namely, in early January 2018, mid-November 2018, and early and late December 2018. SAWS declare a heat wave if the maximum temperature is expected to meet or exceed the average maximum temperature of the hottest month by 5°C, for that particular location, as well as persisting in that mode for 3 or more days (SAWS, 2018). The present threshold is 32°C for Johannesburg (SAWS, 2018). Outdoor temperatures in excess of 32°C were measured, on at least three consecutive days, for the periods 6th – 8th January 2018, 13th – 18th November 2018, 4th – 6th December, and 25th – 27th December at the prototype house. The highest outdoor temperature was measured on the 26th of December 2018 (34.3°C/93.7°F).



(a) Black-globe thermometer positions **(b) Mean daily temperatures**

Figure 3. Experimental and monitoring details

PERFORMANCE CRITERIA

Overheating criteria. The Chartered Institution of Building Services Engineers London (CIBSE) publish a comprehensive set of guidelines for assessing the risk of overheating in naturally ventilated buildings. Although these guidelines were developed for buildings in the UK and Europe, they have been applied to assess buildings in tropical, subtropical and temperate climates (e.g., Bhikhoo *et al*., 2017). The CIBSE guidelines assess of the risk of overheating against three criteria, which provide limits on the severity and frequency of overheating. The building, or internal space, is said to overheat if it fails any two of the three criteria outlined in Table 1. These criteria are defined in terms of ΔT, which is the difference between the indoor operative temperature (T_{op}) and the maximum acceptable temperature (T_{max}) - see Equation 1. The specifics of these criteria are summarized in Table 1, and for further information the reader is pointed to CIBSE TM52:2013.

$$\Delta T = T_{op} - T_{max} \text{ (rounded to the nearest whole degree)} \tag{1}$$

Table 1. Overheating Assessment Criteria

	Assessment criteria	Limit
Criterion 1	Percentage of occupied hours during which $\Delta T \geq 1$°C	Up to 3% of occupied hours
Criterion 2	Daily weighted exceedance (We) in any one day > 6°C.h (degree.hours)	0 days
Criterion 3	Maximum temperature level (T_{upp}) $\Delta T > 4$°C	0 hours

The maximum acceptable temperature (T_{max}) was calculated following the procedure outlined in BS EN 15251 (BSI, 2007). CIBSE suggest that designers should aim to remain within Category II (Normal expectation) limits prescribed in BS EN 15251 (BSI, 2007), which sets an acceptable temperature range of ±3°C about the comfort temperature (T_{comf}) for naturally ventilated buildings. The adaptive comfort model used in this standard expresses the comfort temperature through its relationship with the outdoor temperature. BS EN 15251 gives the following equation to estimate the comfortable temperature (T_{comf}) in naturally ventilated buildings:

$$T_{comf} = 0.33\ T_{rm} + 18.8 \text{ (where } T_{rm} > 10\ °C\text{)}, \tag{2}$$

where T_{rm} is the exponentially weighted running mean temperature (°C) for the day under consideration. This calculation puts higher importance on the most recent days. The equation for the determination of the running mean temperature is given below:

$$T_{rm} = [1-\alpha]\{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots\} \tag{3}$$

where α is a constant and T_{od-1}, T_{od-2}, T_{od-3}, etc. are the daily mean temperatures for yesterday, the day before, and so on.

The potential for overheating within the prototype house is assessed here, admitting that the influence of internal heat gains from people and appliances were not considered entirely. Some spaces were occupied on several occasions during the period, and heat gains from electrical sources were considered to estimate their influence on indoor operative temperature. Realistic heat gains from people and lighting, etc., had little influence when the space was naturally ventilated. Also, no attempt was made, on the majority of summer days, to inhibit direct solar radiation through the east and west-facing windows. The resultant solar heat gains certainly contributed to higher measured indoor temperatures. In South Africa, maximum solar radiation is transmitted through east and west-facing windows in the summer (NBRI, 1987). Furthermore, the penetration of solar radiation though west-facing windows occurs in the afternoon, when spaces are usually most susceptible to overheating. Due to the uncertainty in internal and solar heat gain (through windows), a conclusive deduction on overheating is not made. Rather, the criteria are implemented to highlight potential problems with certain spaces, and examine the effectiveness of several passive strategies to improve comfort.

RESULTS AND DISCUSSION

Overheating assessment. The ground floor spaces were not assessed on the basis of overheating criteria because the indoor operative temperature did not exceed T_{max} during the monitoring period (Jan 2018 – Mar 2018 and Oct 2018 – Feb 2019). In fact, the majority of peak daily operative temperatures were consistently lower than T_{comf}; apart from those measured during several periods of prolonged heat (e.g. Figure 4). In distinction from these spaces, T_{max} was exceeded on a number of days inside the maroon colored vaults during summer (e.g. Figure 4). Consequently, a high surface albedo paint and natural ventilation were employed to reduce indoor temperatures within these spaces. The effectiveness of the two aforementioned passive techniques were evaluated using the CIBSE overheating criteria. It should be noted that these criteria are assessed based on when a space is occupied, and that by varying a room's occupied hours or classification (e.g. bedroom versus living room) one could obtain dissimilar conclusions from the overheating assessment, i.e. either overheating or not overheating. In this study two occupancy patterns were supposed; namely, continually occupied and only occupied between 8:00 PM and 6:00 AM (i.e. a night-time space). Tables 2 and 3 show the results of the overheating assessment for the aforesaid occupancy periods.

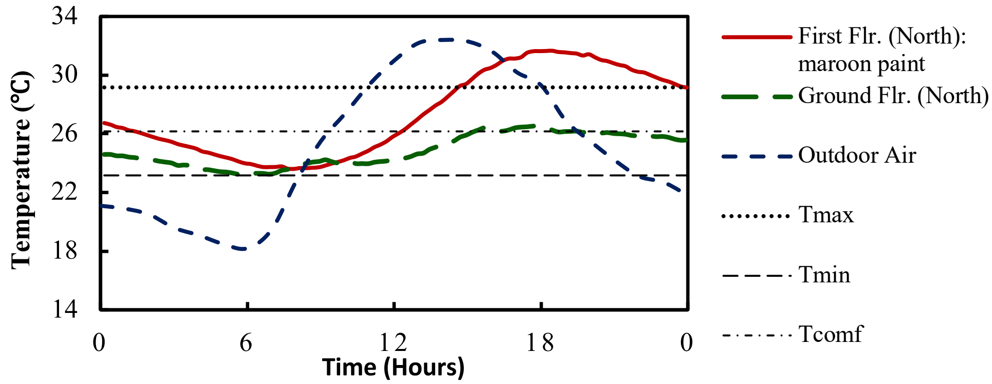


Figure 4. Temperatures on 16 Nov. 2018: Maroon roof coating; windows closed

Table 2. Overheating assessment: assuming continually occupied

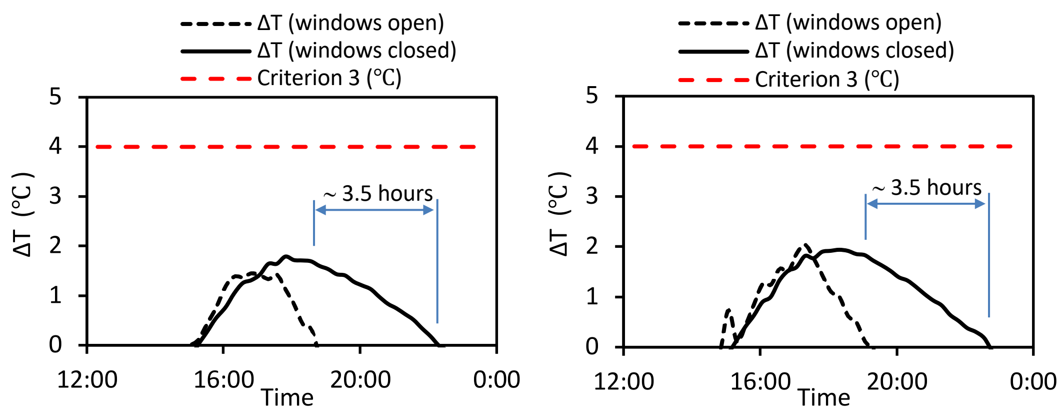
	Max T_{op}	Exceed T_{max}	Criterion 1	Criterion 2	Criterion 3	Overheat
Maroon surface, windows kept closed (101 days)	32.4°C (90.3°F)	Yes	Fail (3.8%)	Fail (We=19.25°C.h)	Pass (ΔT=3°C)	Yes
Maroon surface, windows kept open (56 days)	32.0°C (89.6°F)	Yes	Pass (1.4%)	Fail (We=8.25°C.h)	Pass (ΔT=3°C)	No
White surface, windows kept closed (82 days)	28.6°C (83.5°F)	No	*NA*	*NA*	*NA*	No
White surface, windows kept open (61 days)	31.1°C (88.0°F)	Yes	Pass (0.2%)	Pass (We=2.25°C.h)	Pass (ΔT=1°C)	No

Table 3. Overheating assessment: assuming occupied between 8 PM and 6 AM

	Max T_{op}	Exceed T_{max}	Criterion 1	Criterion 2	Criterion 3	Overheat
Maroon surface, windows kept closed (101 days)	31.9°C (89.4°F)	Yes	Pass (2.2%)	Fail (We=6.25°C.h)	Pass (ΔT=3°C)	No

*** T_{op} did not exceed T_{max} for all other cases (i.e. the overheating assessments are not applicable).**

Maroon surface. Table 2 shows that the continually occupied vaults overheated when the windows were kept closed during the afternoon and evening. If these rooms were designated as night-time spaces (i.e. bedrooms), occupied between 8:00 PM and 6:00 AM, then only Criterion 2 was exceeded on 17th of November 2018 (Table 3). When the spaces were naturally ventilated, and assumed occupied at all times, then Criterion 2 was failed on several occasions in January 2018. In contrast, the naturally ventilated first-floor spaces did not exceed any of the criteria when designated as bedrooms. It is evident that Criterion 2 was the most likely to be violated for these maroon-colored vaults – see Tables 2 and 3. Opening the windows in the late afternoon and evening greatly reduced the risk of spaces failing Criteria 1 and 2. (Figures 5a and 5b). On these two occasions, natural ventilation reduced the period that $T_{op} > T_{max}$ by as much as 3.5 hours. Furthermore, these figures show that temperatures did not exceed T_{max} after 8:00 PM, and this same result was true for all days during which windows were open during late afternoon and early evening.



(a) 27th October **(b) 28th October**

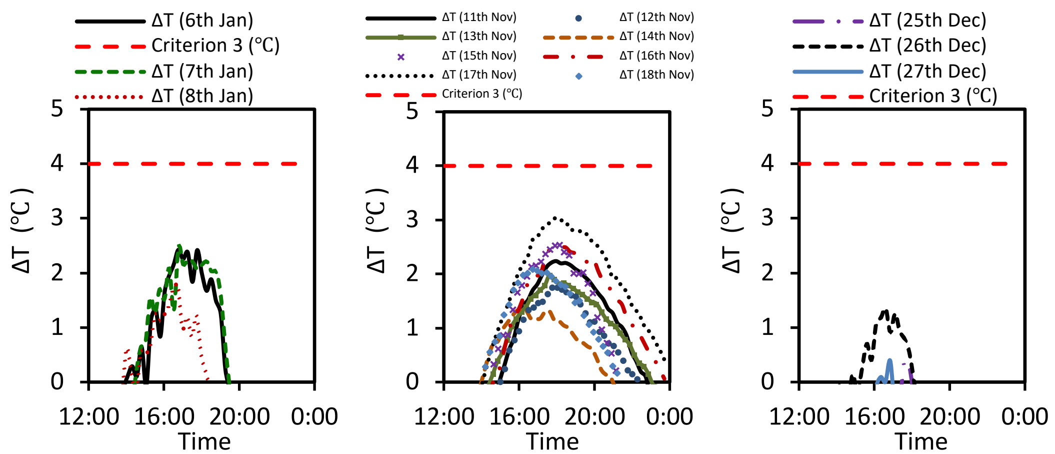
Figure 5. Assessment of Criteria 2 and 3 in Oct. 2018: Maroon surface

The effectiveness of cross-ventilation (Table 2 and 3) is attributed to a large outdoor diurnal temperature range, building layout, and the positioning of fenestration. Windows are equally sized, situated on opposite sides of the buildings, and face the direction of the prevailing wind (wind comes from the east during the summer months in Johannesburg). Furthermore, the vaults have a long narrow floor plan, without any internal partitions, which assists with cross-ventilation – particularly in temperate and hot-humid climates (Climate Consultant 6.0).

The results of the third overheating assessment, unlike the first and second, were not markedly affected by ventilation. For example, the peak temperatures were of similar magnitude in the unventilated and naturally ventilated spaces (e.g. Figures 5a and 5b). More critically, and although Criterion 3 was not violated during the assessment, the measured peak operative temperatures were only within 1°- 2°C of exceeding ΔT = 4° (Figures 6a – 6c). It should be highlighted, once more, that the above difference (1°– 2°C) excludes the potential increase of temperature associated with internal heat gains. This close pass of Criterion 3 is especially concerning because it is an upper limit, which covers extreme weather conditions (e.g., heat waves) and future climate situations. The authors of the South African Risk and Vulnerability Atlas

(Department of Science and Technology, 2010) report, based on projections obtained from a dynamic regional climate model (Engelbrecht *et al.*, 2009), that future warming is expected to be the greatest over the interior of the country. This same model, assuming moderate to high growth in greenhouse gas concentrations, shows that temperatures may increase in the South African interior by around 3°C by mid-century. Based on the above considerations, as well as the overheating assessment presented in Table 2, a masonry shell thickness of 175 mm in combination with a low emissivity surface is unsuitable if the space is occupied during daylight hours.

White surface. Painting the shell white, and ensuring windows were closed from mid-morning through to the late afternoon, kept the operative temperature below T_{max}. This strategy has been used extensively in places with hot-dry climates, such as the Middle East, to keep indoor spaces cool and/or reduce cooling demand. The performance of the white coating was also far superior to its maroon counterpart when the space was ventilated during the day; improvements were observed regarding all three overheating criteria, including a reduction of ΔT (Table 6 & Figure 6). However, the indoor operative temperature exceeded T_{max} on several occasions in late 2018 but these ventilated spaces still passed all three overheating criteria.



(a) Maroon, windows open (b) Maroon, windows closed (c) White, windows open

Figure 6. Overheating assessment during heat waves in Jan., Nov., and Dec. 2018

Painting external surfaces white was extremely successful at mitigating overheating; however, markedly lower indoor temperatures were recorded for this surface condition during the winter (Bradley *et al.*, 2019). Passive solar heating is tremendously beneficial in the South African interior where winters are predominated by sunny and clear weather. On several occasions in mid-winter, the indoor temperatures within the maroon colored vaults were sufficiently high during the evening that artificial heating was not necessary (Bradley *et al.*, 2019. Based on the performance of the white surface condition in the winter it is unlikely that adopting high albedo paints over uninsulated masonry shells is beneficial in Johannesburg (Although Johannesburg is only a few hundred kilometers from the Tropic of Capricorn, its high elevation means temperatures are several degrees cooler than neighboring cities). The results presented in this paper highlight the significance of surface albedo on the thermal performance of spaces enclosed by thin masonry shells.

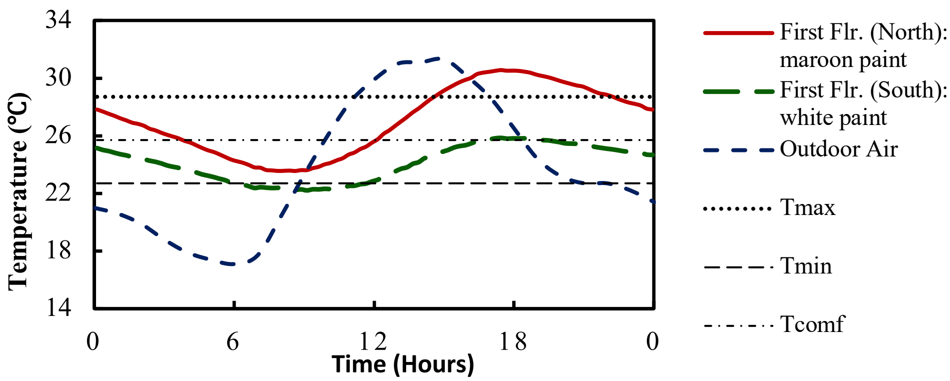
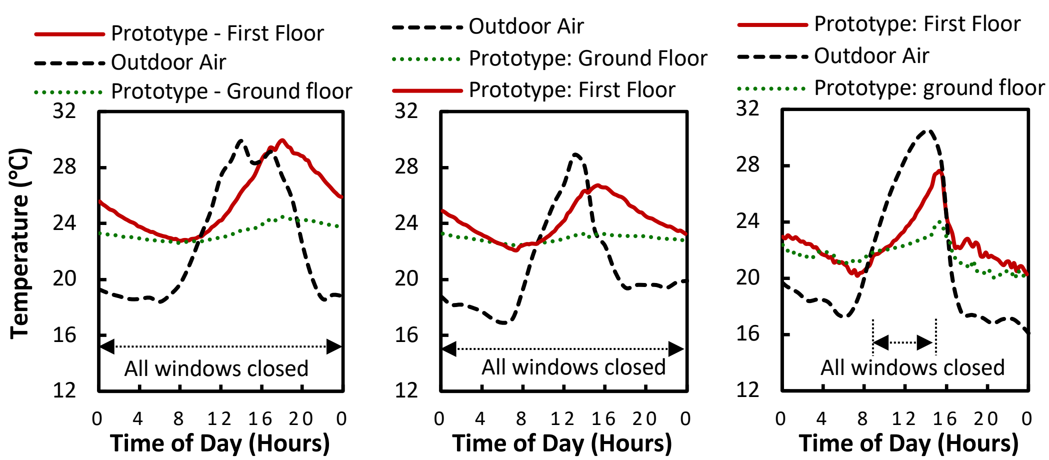


Figure 7. Temperature range on 30th October 2018, windows closed

Benefits associated with the summer climate. Johannesburg's rainfall predominantly occurs in the summer months, and the accompanying cloud cover assists in reducing direct solar heat gain through exposed parts of the building envelope. Heat induced thunderstorms also occur regularly on the Highveld during summer (Engelbrecht and Landman, 2010), which moderate temperatures in the late afternoon and evening. For example, 28% of peak summer days (1st January 2018 – 28th February 2018 and 1st November 2018 - 28th February 2019) monitored had some afternoon and/or evening rain. These short duration rain storms cooled the masonry envelope (Bradley *et al.* 2018), leading to lower indoor temperatures. This effect is highlighted by comparing Figure 8a (no thunderstorm) and Figure 8b (with an afternoon thunderstorm). An even greater reduction of indoor temperature was observed when windows were open during these storms, e.g. the indoor temperature in the first-floor vault (south) fell by ~6°C during a brief thunderstorm on 28th September 2018 (Figure 8c).



(a) 3rd Feb 2018: mostly clear (b) 6th Feb 2018: storm (c) 28th Sep 2018: storm
Figure 8. Operative temperatures on days with/without thunderstorms in 2018

Temperature variation with height. Two additional black globe thermometers were positioned at 2 m and 3 m above the floor of the south vault to assess the variation of temperature with height. Figure 9 shows the diurnal temperature range at 1.1 m, 2 m, and 3m meters for the white and maroon colored surfaces (windows kept closed). It is apparent that peak temperatures, corresponding to the dark surface, increased with height above the floor. Furthermore, the peak operative temperature measured at 3 m was typically ~3°C higher than that at 1.1 m within the maroon colored vault. Several factors likely contributed to the observed disparity, such as: warm air rising and collecting under the apex of the vault and the closer proximity of the uppermost black globe to the masonry envelope. Additionally, internal and external surface temperatures increased from the base to apex of the maroon colored shell in spring and summer (see Bradley *et al*., 2018), which is indicative of higher heat gain through the upper portion of the shell. For example, Figure 10 shows the minima and maxima internal surface temperatures, from southern base to apex, on a hot day in January, 2016. In contrast to the dark surface condition, there was practically no difference between operative temperatures measured within the vault painted white (Figure 9), and only minor variation between surface temperatures. These observations point toward the dual effect of a shallow inclination and low surface albedo on the high rate of heat gain through the envelope in Johannesburg, and that their combination is the cause of the vertical temperature variation.

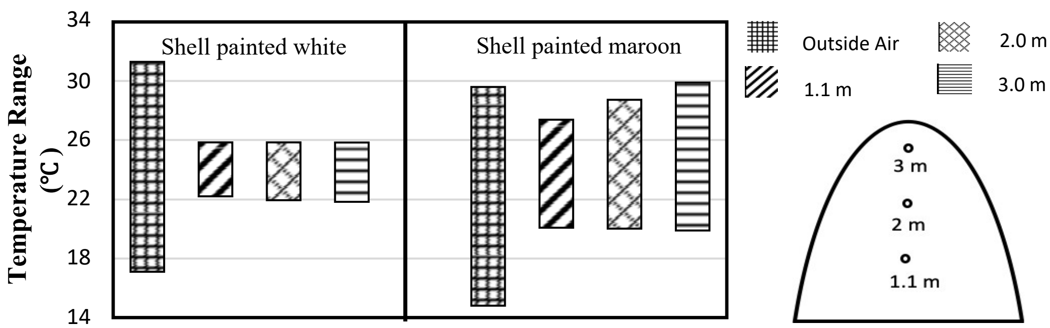


Figure 9. Temperature range at 1.1 m, 2.0 m and 3.0 m above the floor

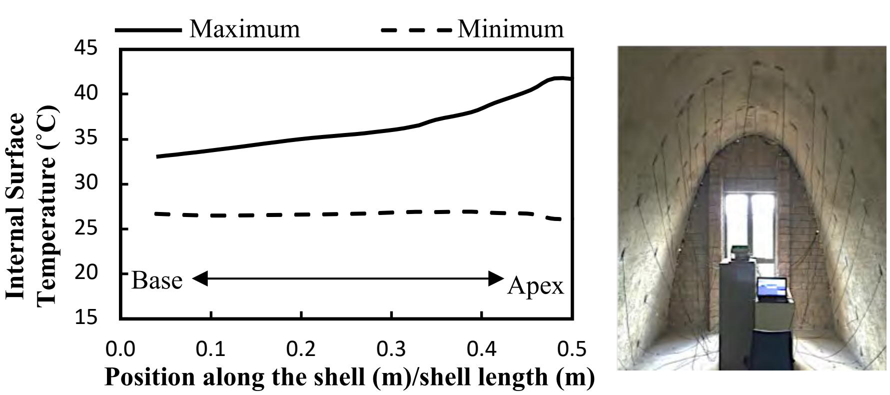


Figure 10. Maxima and minima internal surface temperatures on 30th January 2016

To examine the aforesaid postulate, the software package OPAQUE 3 (University of California, Los Angeles) was applied to examine the influence of surface inclination on heat gain/loss through the shell envelope. Several inclinations of a CSEB masonry section, having either low or high surface albedo, were considered. The materials parameters assumed in the analysis are shown in Table 4; thermal properties for soil:cement blocks were provided by the manufacturer (Hydraform). The internal temperature was fixed at 20ºC and Sol-air temperature (an empirically derived temperature of a surface in sunlight) was automatically calculated by OPAQUE 3 using data from the weather-file for Johannesburg. The weather-file was created using Meteonorm software package. The surface absorptivity (the proportion of the incident solar radiation absorbed by the surface) corresponding to a high and low albedo finish was assumed to be 0.26 (white paint) and 0.70 (dark maroon paint), respectively. Several assumptions were made in these analyses, such as a constant indoor temperature of 20ºC, but the exercise was still valuable to elucidate the experimental observations presented in Figure 9.

Figure 11 shows the range of heat loss and gain for several surface inclinations of CSEB masonry envelope, with R-value as per Table 4, for a typical summer's day. When the exterior surface had high absorptivity, i.e. the maroon paint, significant disparity between peak heat gain values corresponding to the vertical and horizontal inclinations was observed (Figure 11). In contrast, the difference was negligible for the low surface absorptivity coating. These analyses reveal that the proportion of incident solar radiation absorbed by the shell, and consequent heating of the indoor space, is affected more by inclination when the surface albedo is low.

Table 4. OPAQUE 3 R-value calculation

Material	Thickness (mm)	Density (kg/m^3)	Thermal cond. (W/m.K)	Heat capacity (kJ/kg.K)	R-value (m^2.K/W)
Outside air film					0.04
CSEB masonry	150	1900	0.72	0.85	0.21
Cement:sand plaster	25	1500	0.50	1.00	0.05
Inside air film					0.12
Total	175				0.42

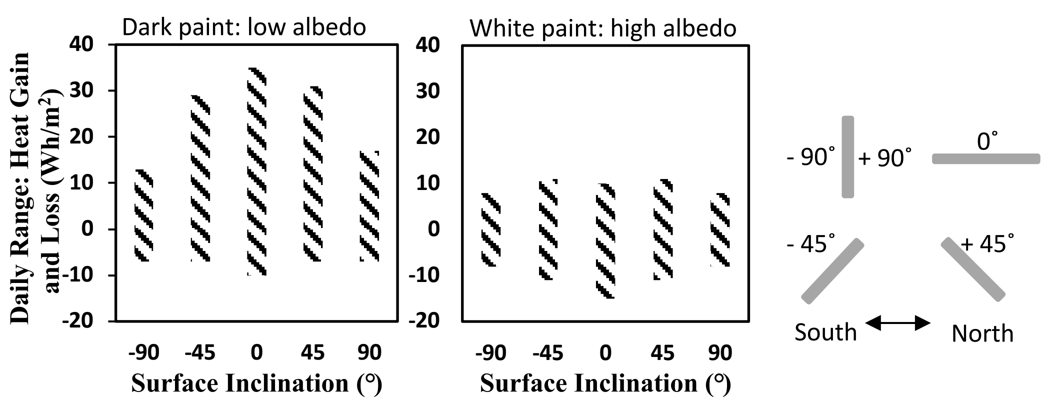
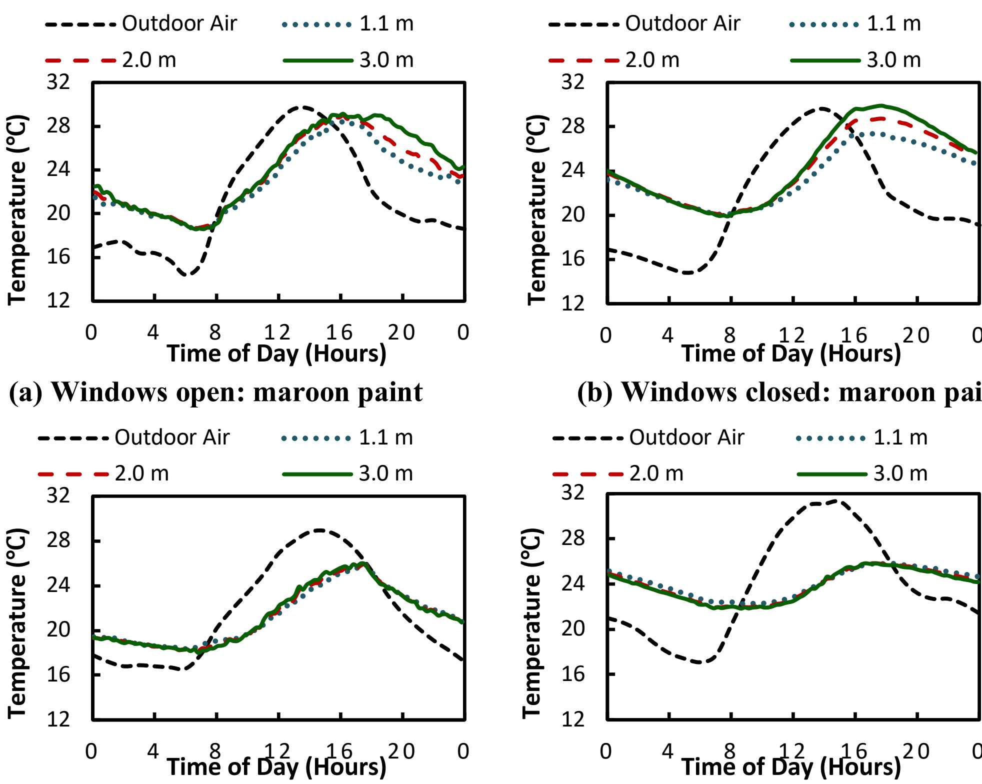


Figure 11. Comparison of diurnal heat gain/loss for low and high albedo surfaces: Jan

When windows were left open, the maximum difference between the upper and lower black globes was also about 3°C in the maroon colored shell (Figure 12a). However, unlike the gradual separation observed with windows kept closed (Figure 12b), the temperature disparity changed abruptly in the early evening. Prior to this sudden divergence, the temperature difference between upper and lower measurement points was mostly less than 1°C. Again, there was only marginal temperature variation with height within the shell painted white - irrespective of whether windows were open or closed (Figure 12c and 12d). In the case of the dark surface condition, i.e. maroon paint, it is of significance that operative temperatures recorded at 1.1 m were typically a few degrees cooler than those measured at 2m and 3m during the evening (when occupants are most likely to be at home).



(a) Windows open: maroon paint **(b) Windows closed: maroon paint**

(c) Windows open: white paint **(d) Windows closed: white paint**

Figure 12. Exterior and interior temperatures on several summer/spring days

CONCLUSIONS

This paper presents the results from an in-situ overheating assessment of a house incorporating CSEB shell roofing. The shells were initially coated with a dark maroon paint, which led to these spaces overheating when unventilated (i.e. failing at least two of the CIBSE overheating criteria). Subsequently, natural ventilation and high albedo paint were investigated as a means to improve the thermal performance of these spaces. Naturally ventilating the spaces in the late afternoon and evening greatly reduced the period that indoor operative temperatures exceeded the maximum acceptable temperature (i.e., better performance regarding CIBSE Criteria 1 and 2). It was particularly effective when the spaces were designated as bedrooms because temperatures did not exceed T_{max} after 20:00 hrs. The same could not be said if the spaces were assumed occupied in the afternoon, since natural ventilation, per se, had little effect on the magnitude of peak indoor temperature during this period. Painting external surfaces white, and keeping windows closed during the afternoon, was the most effective passive measure for mitigating the potential of overheating. However, additional heating would be required during Johannesburg's sunny and clear winter due to reduced passive heat gain through the envelope. These results highlight the need for further study and consideration of additional passive design measures.

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Double-skin ventilated glass façades. An overview of concepts, product systems, realized examples.

S. Brunoro[1]

[1]Researcher, Department of Architecture, University of Ferrara, via Ghiara 36, Ferrara, Italy, 44121. + 39 0532 293633, silvia.brunoro@unife.it.

ABSTRACT

Double skin façade systems are employed increasingly, mainly in high profile buildings being touted as an exemplary green building strategy. It is a new technology that is more often found in North European countries, even if in the last ten years also in Mediterranean Countries this totally glazed envelope had large diffusion.
The aim of the paper is to improve the definition of the double-layer ventilated glass façade concept, illustrate a proposal for the classification of the concept technologies and ventilation criteria, supported by existing examples, in order to improve the understanding of the general principles of the double skin façade system and the possibility of application both in cold than in hot climates.

INTRODUCTION

A Double Skin Façade is based on the notion of exterior walls that respond dynamically to varying ambient conditions, and that can incorporate a range of integrated sun-shading, natural ventilation, and thermal insulation devices or strategies. Early solar passive design exemplified in the "*trombe*" wall, can be considered as a precursor to modern double skin systems [*Diproise et altr.,1999*].
A typical double glass envelope system comprises a layer of single glass and a layer of double-glazing, separated by an air space. Each of these two façade is commonly called skin. The ventilated air cavity - having a width that can range between several centimeters to about a meter – is located between these two skins. The air cavity can be heated by the sun to create a warm buffer zone that protects interior zones in winter, or can be configured to function as a thermal chimney in summer utilizing the stack effect to remove excess heat. The Double Skin Façade is based on the notion of exterior walls that respond dynamically to varying ambient conditions, and that can incorporate a range of integrated devices: operable sun-shadings, natural or forced ventilation devices, heat absorber. [*Loncour et altr., 2004*]
From perspectives of both knowledge and budget, double skin systems are often beyond the scope of most commercially driven projects. The question arises as to whether or not double skin buildings truly are more environmentally responsible and sustainable, mainly in the Mediterranean climate context where summer overheating is the main issue, and where cooling requirements are higher than the insulation ones.
Before the energy crisis of the 1970's, the use of glass in envelopes was mainly focused on aesthetics, as it was estimated that they didn't need to be ecologically responsive to

the environment. Since energy costs were low, the inefficiency of the fully glazed building, with large heat gain and heat loss, resulted in more operation for the heating or the air-conditioning system.
Following the oil crisis of the 1970's, the fully glazed envelope was criticized due to its energy inefficiency: this led the building industry to develop new products such as photosensitive and photochromic glass, and new coatings such as reflective or selective (Low-E), anti-reflection, angular selective, etc. Many of these new technologies have helped in reducing energy consumption in buildings with large glass area. Moreover, glass has become an important feature in architecture: its many desirable qualities, including light transmission, and aesthetic appearance, make glass one of the almost indispensable materials in use today. With this belief, the intelligent double layer glass façade is being used frequently in Europe [*Krewinkel, 1998*].

Figure 1. A fully-glazed double-skin ventilated glass façade in the refurbishment of an existing building. Torno International Headquarters in Milan (Italy)

The main purpose of the double glass envelope is to balance the desire for daylight and outdoor view with the concerns for heat gain and loss. The air cavity is heated by the sun to create a warm buffer zone that protects interior zones in winter, while in summer it is configured to function as a thermal chimney utilizing the stack effect to remove excess heat.
In addition to the energy savings, the double envelope system has other potential benefits such as acoustic control, water penetration resistance, and improved office atmosphere because of the view and utilization of daylight. The double skin system also offers a choice for renovation of existing building facades to transform into more energy efficiency buildings (Figure 1).
A double skin façade can be classified according to: building construction, kind and direction of ventilation in the air cavity [*Oesterle et altr., 2001*]. The purposed classification is below summarized in the next two sections. The aim of this paper is to

provide an advancement of knowledge in the field of the dynamic high-efficient envelopes, that can improve the overall energy balance of the building by reducing thermal losses, gaining solar energy and provide passive cooling: the so -called ventilated double skin glass façades.

CLASSIFICATION OF DOUBLE SKIN FAÇADE SYSTEMS BY TYPE

In a double layer façade configuration, glass "skins" are separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. According to the typologies of constructions, double layer façades can be classified in three types: Full – height façades, Divided by space (corridor) façades, and Single-elements (cells) façades [*Brunoro,2006*].

Full – height (undivided) façades

In full height façades, the air space is undivided: the air cavity is vertically continuous across the entire facade to draw air upward using natural physics principals (hot air rises – Figure 2).

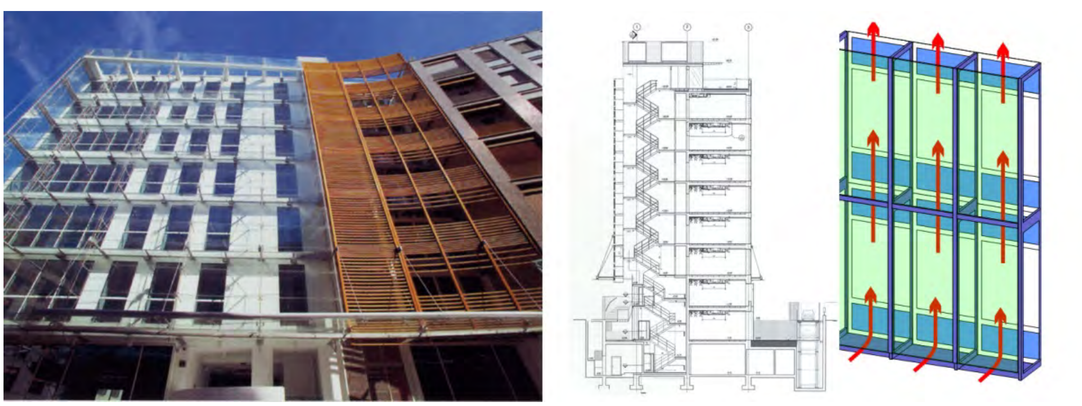


Figure 2. Full height façade

The undivided façade benefits from the stack effect. On warm days, hot air rises at the top of the air space. Openings at the top of the cavity throw out warm air and cooler replacement air is drawn in from the outside. However, in very hot and humid climates, offices on the top floors can suffer from overheating due to the low pressure and accumulation of hot air in the cavity adjacent to their space. For this reason, mechanical devices such as engines are desirable. In this configuration, the interior windows can be operable for ventilation or not. In most cases, some windows are fully opened, or "vasistas", this favors the inlet of natural fresh air in the rooms. Generally the undivided air space can be practicable allowing people to occupy this environmentally variable interstitial space. The atria/air cavity can be used for maintenance, and also programmatically for green balconies: plants are used in these spaces to filter and moisten the air as well as act as shading devices.
In the continuous cavity, grates at each floor level allow the access to the interior of the space for cleaning. Any louvers that are located within the cavity must be able to be moved to facilitate access. These still permit airflow through the space but provide a

platform upon which to stand when cleaning the cavity floor by floor. In some instances, where there has to be occupation of the air space for cleaning, the interior clear dimension is usually in the 600 to 900 mm range.

Corridor façades

Corridor façades (Figure 3) are divided into vertical or horizontal bays across the wall, to optimize the stack effect, by drawing air across the façade through openings allowing better natural ventilation. In this typology, the divided air space can reduce over-heating on upper floors as well as noise, fire and smoke transmission.. However, the shaft façade becomes problematic for fire-protection, sound transmission and the mixing of fresh and foul air.

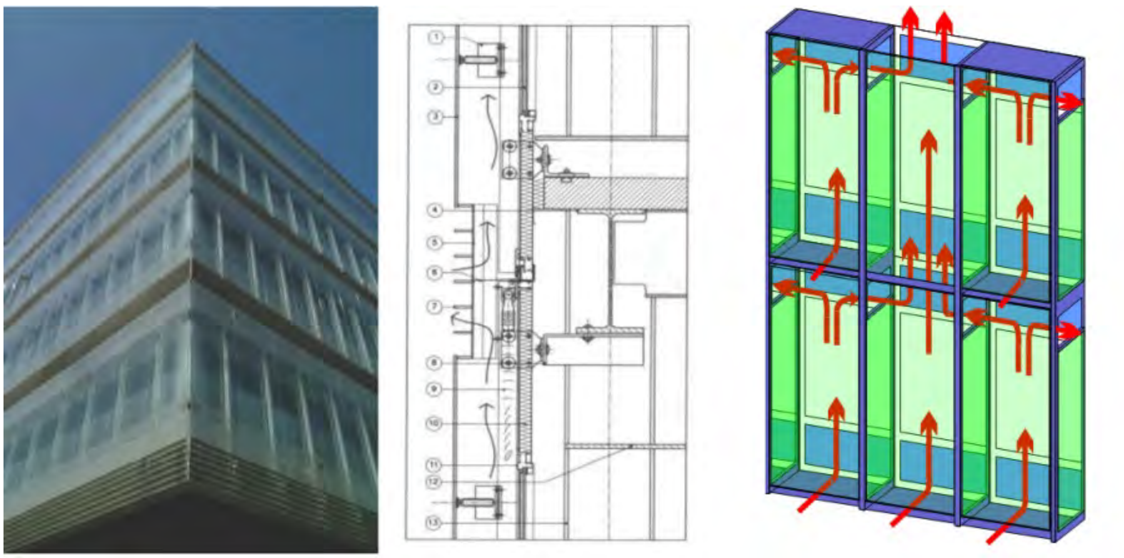


Figure 3. Corridor façade

Single-elements (cells) façades

A typical strategy of the double skin façade is to compartmentalize the buffer zone into separate regions with air supplied by grilles or vents at each level or individual zone (Figure 4).

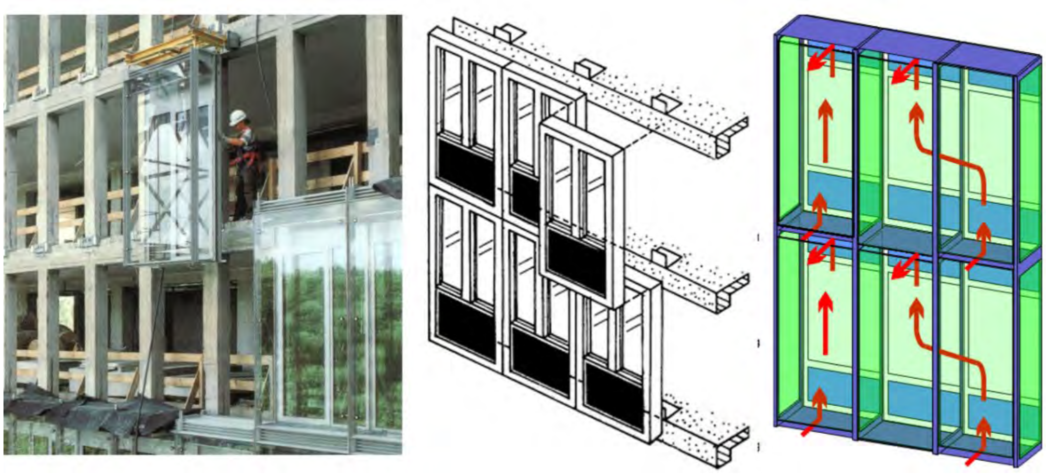


Figure 4. Cell façade

Double layer façades made by cells have a high prefabrication grade, as in general, single elements (one floor high) are ready to be installed. Floor-by-floor divisions add construction simplicity of a repeating unit and in turn can produce economic savings. Cell façades have fresh air and exhaust intakes on every floor allowing for maximum natural ventilation. This compartmentalization eliminates the impact of noise, sound, smoke and heat transfer from one section, level or room to the next area. This is more desirable also for fire-security, as the air cavity is divided into small zones. The use of vents or grilles allows for the control of the incoming air by reducing air speed, protecting from rain and reducing noise transmission from the exterior. It is this control that allows occupant access to natural ventilation in high-rise constructions.
In this type of façade, the dimensions of the air cavity is small (about 20 to 35 cm): this is because of the floor- height and the correct proportion for the stack effect. Cleaning is done from within the office space and requires that interior window panels open fully to provide adequate access for cleaning.

CLASSIFICATION OF DOUBLE SKIN FAÇADE SYSTEMS BY VENTILATION

The stack effect (or chimney effect) is a phenomenon related to the rising of hot air, which is lighter than cold air. Applied to a double skin glass façade, the concept of stack effect is expressed by the air movement in the cavity between the two skins. The air in the cavity is hotter than outside, and has a tendency to escape at the top of the cavity. The ventilation of the cavity may be totally natural, fan supported (hybrid) or totally mechanical. The width of the cavity can vary as a function of the applied concept between 10 centimeters to more than 1 meter. The width influences the physical properties of the façade and also the way that the façade is built.

Natural ventilation can provide an environmental friendly atmosphere and reduce the requirement for mechanical ventilation. On the other hand, natural ventilation may create a door-opening problem due to pressurization. Besides, if the air path is not appropriately designed, the solar heat gain within the façade cavity will not be removed efficiently and will increase the cavity temperature. This is mainly true in Mediterranean climates, where the risk of overheating is tangible.

Natural ventilation

In the naturally ventilated double façade system, the air flows into the cavity by two means: wind pressure and/or the stack effect [*Ding et altr.,2005*]. Wind pressure typically dominates the airflow rate. If properly designed, wind flowing over the façade can create pressure differences between the inlet and outlet inducing air movement. Without wind, the cavity can still be ventilated due to the stack effect. As air flows into the lower inlet, it is heated and becomes less dense and lighter. As a result, air will flow into the inlet and out the outlet while removing heat. Because there is the potential for stack-driven and wind-driven pressures to be counteractive, the air path and exterior openings need to be correctly sized and configured to insure the stack effect pressures and wind-driven forces are additive. A correct ratio is estimated in 1:2 (outlet the double of inlet). Otherwise, the preheated airflow in the cavity will tend to radiate to the interior, and opening the inner layer window in summer will introduce a burst of hot air

These are comprised of a single layer of glazing placed on the exterior the main façade of double-glazing. The single-glazed outer skin is used primarily for protection of the air cavity contents (shading devices) from weather. With this system, the internal skin offers the insulating properties to minimize heat loss. The outer glass skin is used to block/slow the wind in high-rise situations and allow interior openings and access to fresh air without the associated noise or turbulence. Windows on the interior façade can be opened or not. In general they are openable, while ventilation openings in the outer skin moderate temperature extremes within the façade.

Mechanical ventilation

In urban environments, natural ventilation systems may also experience significant problems of noise transmission and pollution and may result in uncomfortable indoor environments in extreme weather conditions. Therefore, a natural ventilation system is more suitable in suburban areas with temperate weather where the airflow in the cavity will be close to the indoor air condition.

In double layer glass façades with mechanical ventilation, the air space between the two layers of glazing becomes part of the HVAC system. Air is forced into the cavity by mechanical devices: the air rises and removes heat from the cavity and continues upwards to be expelled or re-circulated. The heated "used" air between the glazing layers is extracted through the cavity with the use of fans and thereby tempers the inner layer of glazing while the outer layer of insulating glass minimizes heat-transmission loss. Fresh air is supplied by HVAC and precludes natural ventilation. Air is not pumped in directly from the outdoors, for this reason there is potentially less risk of condensation and pollution in the cavity. Also, because the forced ventilation systems allow the building to be sealed, they provide more protection from traffic noise than naturally ventilated systems. In areas with severe weather conditions or poor air quality, the forced ventilation system can keep conditions in the buffer zone nearly constant to reduce the influence of the outdoor air to the indoor environment.

The placement of the glass can vary, depending on the ventilation system. The choice of the glass type for the interior and exterior panes depends on the typology of the façade. In case of a naturally ventilated façade, an insulating pane (= thermal break) is usually placed at the interior side and a single glazing at the exterior side. In case of a façade ventilated with indoor air (mechanical ventilation), the insulating pane is usually placed at the exterior side, the single glazing at the interior side.

Because of the different ventilation source, the thermal performance, like cavity heat removal rate and glass surface temperature, of these two systems may vary as well.

Hybrid ventilation

There is also a “compromise” between natural and mechanical ventilated double layer façades: hybrid systems. In general, in this type of ventilation, natural ventilation is used as far as possible, and the mechanical ventilation is only triggered when the driving forces of the natural ventilation become inadequate and no longer make it possible to achieve the desired performances. Generally, a remote system permits the shift to one type of ventilation to another in an automatic manner, on the basis of a controlled an algorithm.

On Figures 5-6-7 Different types of ventilation of Double skin façade are showed.

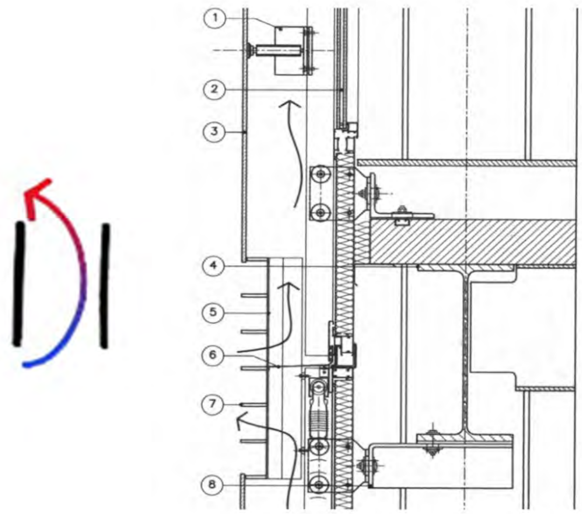


Figure 5. Naturally ventilated façade. The air in the cavity flows for wind pressure or chimney effect. Inner skin can be openable or not.

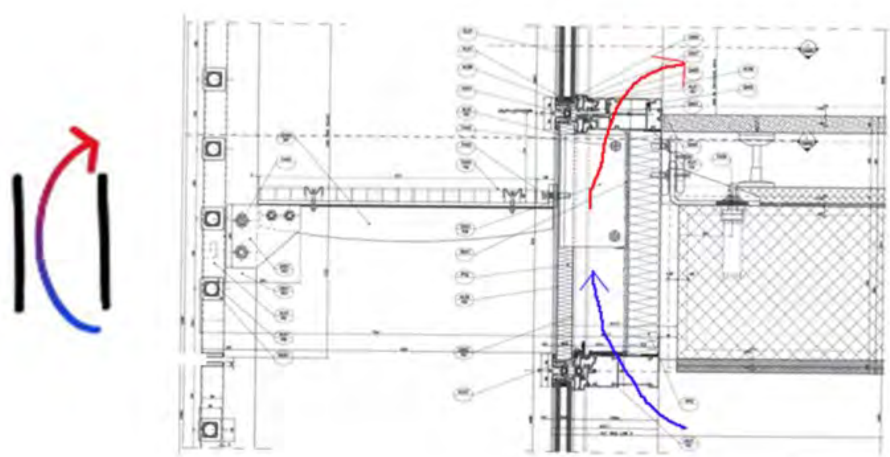


Figure 6. Mechanical ventilated façade. Air is forced into the cavity by mechanical devices: the air rises and removes heat from the cavity and continues upwards to be expelled or re-circulated.

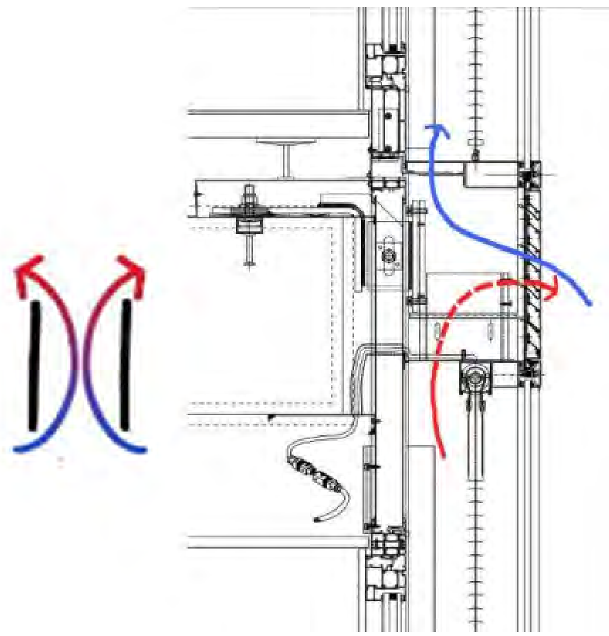


Figure 7. Hybrid ventilation, when both conditions are mixed.

Ventilation direction in the cavity

Another criterion of classification is the ventilation direction, that refers to the origin and the destination of the air flowing in the ventilated cavity. This can be applied to the type of ventilation (natural, mechanical, hybrid) above mentioned.

There are different approaches:

1. A building with its own separate heating, cooling and ventilating system, where a second skin is added to the façade. The cavity of the double skin façade is only ventilated to the outside and is built to reduce noise, contain solar shading and light redirection devices.
2. A building, where the heating, cooling and ventilating system of the building is integrated into the double skin façade, e.g.: by ventilating the building using the cavity of the double skin façade.

It is also possible that a façade can adopt several ventilation directions at different moments, depending on what devices integrated into the façade permit it (for example operable openings). The following ventilation directions can be listed:

Outdoor - Outdoor

In this ventilation mode, the air introduced into the cavity comes from the outside and is immediately rejected towards the outside. The ventilation of the cavity therefore forms an air curtain enveloping the outside façade.

Indoor -Indoor

The air comes from the inside of the room and is returned to the inside of the room or via the ventilation system. The ventilation of the cavity therefore forms an air curtain enveloping the indoor façade.

Mixed ventilation Outdoor –Indoor (Air supply) or Indoor - Outdoor (Air exhaust)

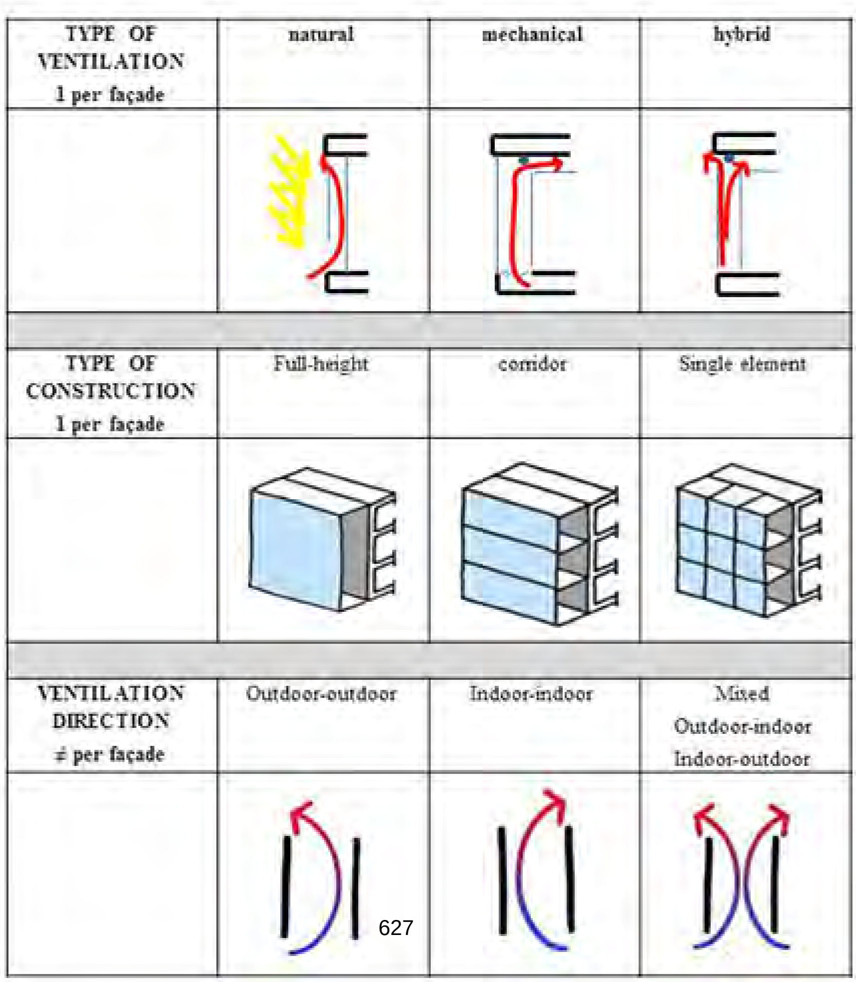
In the case of mixed ventilation, the air movement of the façade is created with outdoor air. This air is then brought to the inside of the room or into the ventilation system. The ventilation of the façade thus makes it possible to supply the building with air.
In indoor-outdoor systems, the air comes from the inside of the room and is evacuated towards the outside. The ventilation of the façade thus makes it possible to evacuate the air from the building.
Combinations between different kinds of classification (by type, by ventilation, by direction) are illustrated in Figure 8.

TYPE OF DEVICES

Solar shadings

"*Good lighting of the workplace is one of the main factors of indoor comfort that can positively influence health and productivity of office personnel. Natural light, its variations and its spectral composition are of great importance for well-being and mental health. Natural light is a fundamental component of our life, helping our body to produce vitamin "D", an important anticancer element*." [*Straube, 2001*]

The control of solar heat gain in a double skin glass façade is obtained through the use of shading devices in the air cavity, typically horizontal blinds. Blinds are situated in the cavity of the double skin facade and protect the building from the solar heat gains or play the role of the pre-heater for the ventilation air. The absorbed solar energy is transformed to the passing air by convection or by radiation to the neighboring surfaces. Several configurations for these horizontal blind shading devices exist; they



can either be fixed elements or operable units that are either controlled by the occupant or by sensors within the building. External shading devices are the most efficient means of reducing solar heat gain, but they are expensive because of installation costs and safety concerns, anyway the totally full-glazed façade aesthetic is changed.

Figure 8. Classification of Double layer lass façade by type

Moreover, they are typically fixed and not usually effective for all sun angle conditions especially with low sun angles in the morning or late afternoon. Also to reduce maintenance, the air cavity offers protection for the shading devices.

The geometry (mainly width and height of the cavity) and the properties of the blinds (absorbance, reflection and transmission) may affect the type of air flow in the cavity. When designing a Double Skin Façade it is important to determine type, size and positioning of interior and exterior openings of the cavity since these parameters influence the type of air flow, the air speed and the temperatures in the cavity.

The double skin façade with its increased glazing coverage improves the access to daylighting in the space. Also important to daylight penetration is floor to ceiling height and floor plan depth. The increased daylighting component of the completely glazed façade can introduce excessive glare and heat at certain times of the day. These increases require further measures in design to combat their negative effects. Solar shading devices are designed into the air space to decrease solar heat gain through the glazing and reduce the amount of glare caused by the increased access to daylighting.

Green in the cavity

In general the temperature of the blinds is high, which is an advantage in the cold period but disadvantage in the hot period. To decrease the cooling loads of the building new ideas for shading system are considered. Green in the cavity has the ability to dissipate absorbed solar radiation into sensible and latent heat. These are mostly related to the thermal, aesthetic, psychological, comfort level, and sound attenuation point of view. In general green in the cavity create more effective shading system than blinds. A research project at TU Delft aimed in defining the thermal performance of the double skin façade with plants. [*Stec W.J, et altr, 2005*]

Further simulations of the total building proofed that plants can contribute to the creation of comfortable indoor climate and saving energy.

The study proves that the Installation of plants in the double skin facade allows for reduction of the cooling capacity by almost 20%. A similar result was noticed for the energy consumption of the cooling system.

Figure 9. Different kind of solar shadings in Double skin glass façades. On the

left: venetian blinds (Johnson wax building, Milan, Italy) In the center: textile curtains (Gsw Headquarters, Berlin, Germany) On the right: green shadings (Bayerische landesbank, Frankfurt)

DOUBLE LAYER GLASS FACAES IN MEDITERRANEAN CLIMATE

The concept of regional response in building design leads to solutions that would further enhance concepts of sustainability by promoting climatic responses such as solar availability, weather patterns, urban design considerations, and other issues that deal with specific regional differences versus a technological solution that operates on universal conventions.

The double layer glass façades system is a sustainable design solution born in Northern Europe to maximize daylighting with integral solar heat gain control, to heat production and exchange by potential green house effect in the buffer zone. Overheating, as a minor problem, is solved by blinds and buffer zone. Natural ventilation reduces air-conditioning loads. This is why it is necessary to question if the system is exportable with good results in Mediterranean Countries.

The thermal performance of double façade systems depends on many factors. Because the interactions among these variables are complex, the energy savings and cost/benefit of these systems are not well established.

For the climate of Mediterranean Countries, the control of solar gains in the building design is important during the summer periods. Therefore double skin facades may lead to overheating during the summer months if there is no appropriate façade design, ventilation technique building orientation and provision of shading. [*Hamza, 2004*]

The Mediterranean climate encourages the use of natural ventilation. However, in the last decades, it is noted an increased use of air-conditioning due to high ambient air temperatures and high internal gains both in large office buildings than in residential buildings.

The buffer zone allows for the increased use of the perimeter zone of the space that typically requires heating or cooling mechanisms against the exposed glazing. Also, with the use of improved solar heat transmission values for glazing the absorption and reflection of heat can be manipulated to minimize solar heat gain. This can be accomplished through the use of what is referred to as ‘spectrally selective glazing’.

The increased daylighting component of the completely glazed façade introduces excessive glare and heat at certain times of the day. These increases require further measures in design to combat their negative effects. Solar shading devices are designed into the air space to decrease solar heat gain through the glazing and reduce the amount of glare caused by the increased access to daylighting.

The air space and integrated solar shading devices control the solar heat gains that would typically require the use of mechanical means of air conditioning and air extraction.

Another problem that can occur in hot and humid climate regards naturally ventilated façades where the low pressure can reduce the stack effect in the air cavity. In Mediterranean Countries, the warm and wetter climate compared to the Northern European Countries, makes it difficult to think of the possibility of exploring a natural ventilated façade in all its performance potential. [*Hamza, 2005*]

Sometimes, to avoid overheating and condensation phenomena, electrical fan are provided to favor the flow of ventilation in the case of low-pressure and air stagnation

at the top of the air cavity. Due to the warm and humid climatic conditions typical of the Mediterranean area, it is preferred to avoid the natural ventilation trough the cavity, keeping the inner skin closes and obtaining the comfort conditions through the air conditioning (indoor-indoor) [*Brunoro,2006*]:
The maximum performance obtainable from a double-skin façade in Mediterranean climate is strongly linked to the integration with HVAC system. The main advantage will result in lower operating costs, due to the increased thermal performances of the envelope.

CONCLUSIONS

"*A double-skin façade also reduces heat losses because the reduced speed of the air flow and the increased temperature of the air in the cavity lowers the rate of heat transfer on the surface of the glass. This has the effect of maintaining higher surface temperatures on the inside of the glass, which in turn means that the space close to the window can be better utilized as a result of increased thermal comfort conditions*" [*Compagno, A., 1995, p. 94*]

The thermal performance is a primary consideration of selecting a double envelope system. Because of the different ventilation source and directions, the cavity heat removal rate and glass surface temperature, may vary as well.
Main conclusions on adopting high-performing double layer glass envelopes can be listed as follows:

- All types of Double Skin Façade offer a protected place within the air gap to mount solar shading and daylight enhancing devices, which then can be used whenever necessary and thereby reducing the cooling load;
- One of the main advantages of the Double Skin Façade systems is that they may allow natural (or fan supported) ventilation, which will reduce the use of electricity for ventilation;
- In winter the cavity forms a thermal buffer zone which reduces heat losses and enables passive thermal gain from solar radiation, which will reduce the heating load;
- May enable natural ventilation and night time cooling of the building's thermal mass, which will reduce the use of electricity for ventilation and the cooling load;
- Noise reduction from motor traffic, enabling natural ventilation without noise problems.

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Nine Cases in the Integration of Off-site Construction Practices

Carlo Carbone[1]
[1] Associate professor, Université du Québec à Montréal, 1440 rue Sanguinet, Montreal, PQ, Canada, H3C 3P8, 514-714-1554, carbone.carlo@uqam.ca

Abstract

Since industrialization every sector of production has benefited from technical advances and greater productivity. Building construction has not followed the same evolution and remains in certain cases fairly archaic. Currently, in response to manpower shortages and the need for more sustainable practices, construction seems to be evolving toward a greater use of off-site construction. Factory production is being proposed to radically reform construction and to generate quality buildings, produce safer working conditions and generally attain superior efficiencies. Funded by the Société d'Habitation du Québec, our study sought to elucidate some of the potentials and challenges of integrating off-site construction strategies into the Société's project delivery methods. The SHQ is responsible for the construction and operation of social and low-cost housing in Québec. Based on nine documented case studies designed and built from 2010 - 2018, in Canada, the USA, Norway and the Netherlands we discovered impacts on the whole project ecology and the need to reform processes to achieve results. The successes in integrating manufactured building sub-assemblies and systems demonstrated that the traditional Design – Bid - Build ecology embodies conflict and entanglement between on and off-site practices. Within our sample size, nine projects, only those with a holistic approach, involving all stakeholders early were able to optimize production and knowledge sharing at every level, from planning to construction. The required process overhaul was also confirmed in projects that deploy BIM to integrate and coordinate all stakeholders. The paper will demonstrate and focus on the benefits of particular methods. Conversely, it will also show that without reviewing the overall project ecosystem the risks associated with prefabrication appear to be the same as for conventional construction and sometimes all the more difficult to deal with since delivery methods are not harmonized and responsibility not adequately or clearly distributed among stakeholders.

Keywords

Architecture; Off-site construction; Prefabrication; Industrialization; Project delivery methods; Building construction; Building information modeling; Integrated design processes

Background

Demographics in industrialized countries along with ecological imperatives are fostering a renewed consensus about building. Off-site construction and prefabrication can help rationalize construction by reducing labour and waste while optimizing scheduling and by providing a direct and streamlined process between design, manufacturing, construction and operation of buildings. These premises have existed since the beginning of the twentieth century, but have only marginally succeeded in integrating everyday construction (Smith and Dale 2017). Construction in many cases remains an entangled, arduous and unrepeatable undertaking with much of its disparate components manufactured off-site but without a harmonious and coherent strategy for their on-site organization and assembly.

Amid a reintroduced interest in the potential relationship between factory production and architecture, this study surveyed how manufacturing methodologies could provide patterns for architecture and construction's advancement. This research was initiated with a simple question: What are the challenges and potentials of integrating factory production in construction today? This research contract conducted between September 2018 and April 2019 was mandated by a branch of the Québec government in reaction to what is seen as the construction industry's current stagnation. The industry in Québec as a whole has long ignored potentials of off-site construction relegating it to a marginal portion of production.

The construction industry in Québec (Canada's French speaking and second largest province) in many ways parallels the industry in all of North America as a great number of small or medium sized businesses compete for projects, usually based on costs[1]. More than 95% of the active companies within the construction sectors (residential, commercial and industrial) have 10 employees or less. This small business model discourages innovation as companies lack the time and resources to choose, explore, study or move toward innovative processes. The dominating model of the one-off project producing artisan counts for the overwhelming majority of entrepreneurs in the industry.

Reacting to this artisan model and productivity problems that are beginning to percolate everyday construction while targeting a greener industry, the Québec government has set up a number of initiatives to question archaic project delivery methods and encourage sustainable practices. One initiative, Vision 2030, aims to increase uptake in off-site construction by investing in the prefabricated building sector and its companies (SHQ 2018).

The Société d'Habitation du Québec (translated as the Québec Housing Authority) is behind this particular initiative and has financed a number of research and prototype projects to showcase new technologies in timber construction. While describing new potentials for timber the initiatives also provide a framework for building codes to assimilate tall timber construction. The Vision 2030 initiative contributes to the governments sustainable action plan on three fronts, firstly increasing modular construction which is regarded as a greener construction method, secondly by encouraging a digital revolution by small manufacturers who lack resources and thirdly by creating a larger more competitive export market for Québec's manufacturers (SHQ 2018). Along with building, managing and operating a large social housing stock, the SHQ finances research and production and is leading a cross industrial awareness about the need to reform construction methods (CPQ 2018). The current and ongoing research described in this paper financed by the SHQ studied and compared local and global projects and was undertaken in September 2018 within a partnership between the Pomerleau Industrial Research Chair in Construction Project Innovation at Montréal's École Polytechnique and the Université du Québec à Montréal's Pre[FABRICA]tions research lab.

The government's Vision 2030 proposal identified the prefabricated building sector as an ensemble of companies already involved in off-site construction and having the potential to showcase its capacities and create a fertile environment for cross collaboration within the

1 Available only in French, the cited statistics were retrieved on August 22, 2019 from a government website at https://www.metiers-quebec.org/portraits/batiment1.htm

industry. The prefabricated building sector in Québec also in many ways parallels the industry in North America as a whole. About sixty companies are producing either stick frame panels or lightweight timber volumetric. Three large companies are responsible for the majority of units produced while many are producing 20 or less units per year. The sector in Québec is composed of small artisanal producers, manufacturing modules, panels or houses in the factory as they would on-site (Robichaud, Julien and alt 2015). The climate-controlled setting combined with some standardization of procurement, cutting and framing are about the only elements that are generally in use. Still the industry's experience with off-site methodologies is regarded as a potential motor for the rationalization of the construction industry.

Construction's industrialization in Québec led to the development of on-site timber platform framing and flat slab reinforced concrete as the two mainstream systems for residential stock built every year. Prefabrication and off-site construction's use remain fairly marginal, relegated to the manufactured house or temporary school additions. In terms of innovation, Habitat 67 in Montréal, the establishment of a Schokbéton franchise in the late 1960s and their subsequent construction of the Olympic Stadium in Montréal remain the archetypal achievements against which prefabrication is unfairly defined and often evaluated. Only recently with greater communication and knowledge-sharing about of how off-site construction could lead to sustainable building practices has the industry began to take a more rigorous look at itself.

Research objectives

Endeavouring to increase uptake in the use of off-site construction is not new in North America. It seems that every generation takes on the challenge of increasing construction's productivity by looking to the factory.

The five main partners in this research project, Université du Québec à Montréal, Polytechnique Montréal, Pomerleau Inc, SHQ and a local architectural firm Saia, Barbarese, Toupouzanov Architects, were brought together with a common objective: understanding the possibilities of off-site construction and the necessary on-site mechanisms to facilitate their integration. This research objective determined a comparative study of local and international construction projects that would draw attention to current issues. The comparative analysis of nine projects highlights the diversity of current practices and their constraints within a rapidly evolving industry; Yesterday's prefabrication is being replaced with more energetic project delivery methods, which require far more symbiotic relationships between stakeholders and reform age old tensions between on and off-site construction (Kieran and Timberlake 2004). The comparative analysis addresses five topics driving prefabrication's current rebirth:

- systems: How are off-site construction systems evolving ?
- integration: How are the systems integrated in overall project ecology?
- BIM (building information modeling): Is BIM a driving force for the more streamlined use of off-site construction?
- project delivery: Are there specific project delivery methods that are more conducive to harmoniously integrating off and on-site construction?
- on and off-site construction synergies: What are the specific difficulties considering that each project requires coordination between what is normally referred to as traditional construction and factory produced sub-assemblies?

Methodology

Comparative analysis is an acknowledged methodology in architectural research (Groat and Wang 2002). As demonstrated by Haraguchi (1989) it allows for each case to contribute to an overall theory regarding a particular theme. Each of our nine cases addresses in its own way the above-mentioned areas of investigation. In accordance with the SHQ's request, projects included both local and international cases to effectively compare local issues to what are generally considered as more innovative contexts but with analogous industry dynamics.

In choosing projects that employed off-site construction, boxes, panels and pieces (Dietz and Cutler 1971) were isolated as conventional production methods. In addition to these traditional avenues, we searched for projects that explore digital technologies, computer modelling or BIM as an integrating factor for off-site construction. Examples of multi-trade prefabrication (Smith and Dale 2017) reflecting a paradigm shift within the industry where chosen to question the design-bid(lowest bidder)-build methodology which is still the prevalent project delivery method in Québec.

For each case, a particular system, component or sub-assembly was examined from the standpoint of its incorporation within the project ecology. While framed by the five objectives mentioned previously the analysis looked for impacts on budget, timeline, worker conditions, and effects on the building's ecological footprint. Our analysis included a series of interviews conducted between January 11, 2019 and February 27, 2019 with various project stakeholders. The interviews focused on a diversity of aspects, helped complete the literature review for each case and affirmed what worked and what hadn't worked according to a specific viewpoint.

The comparative analysis, table 1 at the end of the paper, highlights some preliminary conclusions, project ecology constraints, and where further research is necessary. The nine projects and some of their particularities are described below in chronological order. The published report is available on-line in French where each case is presented in depth.[2]

Nine case studies

1- 2010 - Miami Valley Hospital (Dayton, Ohio, USA - 2010 – NBBJ architects – Skanska-Shook)

- ***Multi-trade prefabrication and near site prefabrication*** (Smith and Dale 2017)

Inaugurated in 2010, the 484,000 square foot hospital expansion is a veritable vehicle for innovative construction strategies. The 12-storey cardiology center provides 178 rooms and a capacity for 72 more. The addition includes a new entrance hall for patients and visitors and two levels of underground parking along with other services. Developed by NBBJ architects and built by a consortium of Skanska and Shook Construction, the building's design and construction incorporate virtual design and construction through BIM modelling used to enhance stakeholder coordination (NBBJ, 2010).

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[2] see report at the following link
https://www.dropbox.com/s/99y28hv7he7mq02/Rapport%20final.pdf?dl=0

In terms of off-site construction processes, Skanska sourced a former furniture manufacturing plant near the project site (about 10 miles from the construction site). The building's various components and subassemblies were digitally modelled and assembled inside the factory, then delivered and installed on site. In addition to the toilet pods and modular head walls other elements that were assembled off-site include: A unitary curtain wall and mechanical ceiling racks fully coordinated in the factory.

Building information modelling was the principle integration tool for all project elements. The shared digital model was a platform for design development and adjusting elements in real time according to developing site conditions. Patients' rooms are composed of a set of four sub-assemblies pre-assembled in the factory and put together on site to form party walls: headboard wall, toilet pod, case work and utility shaft combine to form the service spaces, a type of utility wall which divides the rooms. Each sub-assembly is standardized and repeated. Information modeling and full-scale mock-ups were essential to develop these mass-customized prefabricated parts to ensure they worked well in the giant 3d jigsaw puzzle.

The *near-site prefabrication* and *multi-trade prefabrication* model involved an increased amount of design work upstream, close collaboration and clearly defined contractual prescriptions between the various stakeholders. Skanska defined each stakeholder's and trade's roles in terms of accountability from factory assembly to on-site delivery and system coordination. The project's success according to Marty Corrado (interview 21-01-2019), the site's superintendent was contingent to the use of digital modelling as a tool for collaboration.

2- Residence Heterington (Malartic, Québec, Canada - 2013 – Trame Architecture et Paysage – Constructions Pepin et Fortin)

- The service core revisited

The Hetherington Residence is located in Malartic, in Abitibi-Témiscamingue, a northwestern region of Québec. The region's economy is based on logging and mining and operates Canada's largest open-pit gold mine.

Trame Architecture + Paysage, a firm well-versed in Québec's low-cost social housing standards explored a variety of building systems before deciding on the Noyo service core (noyau in French means nucleus). Looking to improve on-site logistics, the firm proposed the use of this normalized utility core module developed by Mobilfab. The firm also envisioned the service core as a way of rationalizing construction for northern Québec's short construction season (Fortier D. interview. 21-01-2019). The Noyo's development and marketing was, previous to this use, supported by the Quebec Housing Authority's research funding program. The concept redirected a manufacturer's existing process, mainly related to producing site construction trailers, to manufacturing service cores that met the government's prescriptive social housing criteria (Fortier D. interview. 21-01-2019).

Prefabricating service cores to simplify coordination dates back to the beginning of the twentieth century. In this same spirit, Mobilfab's Noyo incorporates kitchen and bath with all the mechanical and electrical elements in a transportable container format manufactured in lightweight timber. Once delivered the core would simply be plugged into the conventional construction system. Employed only once, as far as we found, the success and validation of the Noyo concept appears to be contingent on a variety of independent and unpredictable elements: differing construction tolerances and competing trades on and off-site defined an entangled relationship between modular offsite construction and the traditional stick framing. While not complex, the contractual relationships must be thoroughly coordinated before on-site assembly. This was not the case for Hetherington and ended up causing work delays and quality issues, which plagued the project from its design to its operation (Fortier D. interview. 21-01-2019). Further, these undetermined interfaces and contractual obligations between on and off-site trades ended up eating up any savings that could be made in the factory. Digital modelling at the onset and a type of design-build formula could have simplified coordination. In this case, the undefined crossing points in the specifications between on and off-site assemblies limited any productivity gains.

3- El sol Science and Arts Academy (Santa Ana, California, USA - 2014 – HMC Architects – Bernard Construction)

- The kit-of-parts for quick delivery

El sol Science and Arts Academy is a privately funded primary school Santa Ana, California. The South Campus expansion consists of the construction of a 15,000 square foot two-storey building. Serving as a permanent solution to housing its increasing population and to replace the mobile classrooms that had been popping up on their site. The expansion project was also an opportunity for the school to showcase some of their core values: innovation and sustainability (Daviss M. interview. 29-01-2019). Aligned with these ideals Project Frog Kit proposed an easy and simplified streamlined construction process for school administrators. In addition to the usual criteria (cost, schedule, sustainability), adaptability to further additions also argued for Frog's modular approach.

Project FROG's (Flexible Response to Ongoing Growth) business model combines a standardized and modular construction kit, current design tools and manufacturing technology to simplify the design and construction process. Established in 2006, the various components of the Frog kit can be likened to a kind of toy building set which could be assembled in a variety of designs. In the project delivery, Project Frog becomes a key stakeholder, uniting design with manufacturing, delivery and assembly of modular components.

The Kit's key benefits in the project were efficiency, specifically speed of construction, which in the case of a school offers potential to increase student population and return to normal operation, thus increasing revenues by decreasing time (Willison R. interview. 29-01-2019). While the kit's standardized modular design precludes total architectural freedom, the design and assembly process leads to a completely harmonized and coordinated building process reducing waste by made-to-measure and just-in time delivery. New players such as FROG are leading an upheaval in the construction industry where digital modelling and integrated components are placed at the centre of the project ecosystem untangling what has become arduous coordination activity between design and construction stakeholders.

4- Treet (Bergen, Norway - 2015 – Artec AS architects – FM Gruppen Strand AS)
– the power floor for standardized units

Treet, Norwegian for tree is a 14-storey timber residential building. Its structural system is based on a simple but effective idea of stacking standardized modular volumetric units without any reinforcement. Architects (ARTEC) and project engineers (Sweco) designed a superstructure that repeats an artificial foundation «the power floor» (Abrahamsen and Malo 2014). on the 5th and 10th floors. This rather simple innovation divides the overall building into three four-storey flat "sandwiches" supported by fourteen-storey columns. The megastructure's vertical, horizontal and diagonal bracing members make up a vertical truss. Elements are calculated to burn, char and slow combustion for 90 minutes without collapsing (Abrahamsen and Malo 2014). The mega – truss pillar supports the power floors, which then act as a shelf onto which the independent dwellings are positioned. The independent modules/flats offer optimal acoustic insulation and fire resistance as they don't share walls as is the case in more conventional residential construction. Transported from Estonia the four modular unit floors required only three days for stacking. The "power-floor" is a major contribution circumventing the habitual reinforcing required for stacking units. This simplifies factory logistics.

Virtual modeling and the involvement of all stakeholders from the beginning of the project have reduced risks and errors habitually associated with construction (Abrahamsen and Malo 2014). Focussing on designing the project as a coherent assembly of prefabricated elements and systems also reduced the risks associated with coordination. The experimental nature of the project arguably impedes its advances in more generalized use, however the argument made for the use of standardized modules for tall buildings avoids module uniqueness (reinforced or adapted according to each unit's position within an overall structure) which is remains an unsettled question for both production and construction of tall modular buildings.

5- Patch 22 (Amsterdam, Netherlands - 2016 – Lemniskad Consortium architects and builders)
- a «master builder» for streamlined design for assembly and disassembly

Located in a revitalized industrial sector in Amsterdam-North, Patch 22 designed and built by the Lemniskade consortium composed of architect Tom Frantzen and engineer Claus Oussoren is an eample of design for disassembly principles applied to building construction. The competition entry displays' the designer's ideal of an integrated project concept from financing, to design, to construction and to operation considering each project phase in a coherent action plan for the building's entire lifecycle (Frantzen T. interview. 27-02-2019).

The mixed-use building combines a commercial ground floor with open plan flexible floor plates to create a vertical and horizontal loft typology that could be zoned, planned and adapted to new uses over time. The building garnered international interest when it won the World Architecture Network (WAN) award in 2016. The 30-meter tall mass timber structure is both a symbol of the sector's renewal and symbol of a sustainability objectives applied to a an overall project ecology.

The Slimline floor, a prefabricated structural solution for adaptable building systems, creates a network of open spaces below one's own flat for mechanical systems. An example of Open Building practices, the separation of infrastructure from infill through the Slimline floor makes it possible to completely redesign interior systems of any flat without affecting its neighbours (Frantzen T. interview. 27-02-2019). A coordinated effort between architect, engineer, builder and municipal stakeholders to optimize adaptability over time commanded a completely integrated approach to building and argues for a type of master builder and industrialist who identifies stakeholders, shares knowledge, defines responsibilities in a collaborative project methodology.

6- Loggia Saint- Lambert (Saint-Lambert, Québec, Canada, 2016, BTAE architects, Gestion Rodier)

- extra-large modular to compete with flat slab concrete

A distance of 8km, as the eagle flies, from Habitat 67 and located in Saint-Lambert, a suburb of Montreal, the four-phase project is located between a Golf course and an industrial railway. Along with its potential for redevelopment the site was chosen for its proximity to the manufacturer, about 50 miles from Bonneville Industries, who in this case was also the project developer. A simple modular design by BTAE (Blouin Tardif Architecture - Environment), the 241-rental-unit development was intended as a showpiece for modular construction. The project is composed of independent volumetric boxes that are stacked to shape the overall massing. The envelope stitching, masonry and metal cladding were fitted on-site after the modules were assembled. The volumetric modules some of which are **16x70** feet were delivered, staged for lifting and assembled on site. Only one hour was required to lift and install two modules (Bonneville G. interview. 11-02-2019). This pretty impressive time lapse was a major selling point as the modules are 90% factory completed. Their manufacturing tolerances and on-site variations made service, corridor continuity and mechanical coordination more difficult than first imagined. Stitching the modules together to achieve high quality air and vapour barriers, important in any climate, had not been correctly contractually distributed among stakeholders before construction, causing both extra costs and delays which ended up eating away at any efficiencies linked to the quick and easy modular stacking (Blouin A. interview. 22-02-2019).

The first phase of a series of four buildings, one of the main challenges of this type of construction was the just-in-time management of delivery, storage, staging, protection and assembly of huge boxes on site. The plant’s proximity and the availability of a large staging area for the modules certainly helped to reduce the risk in this project, however difficult weather conditions including a mid-December storm caused damage on many non-installed modules, which had to be corrected and repaired before installation (Bonneville G. interview. 11-02-2019).

Certified in the factory according to the CSA A277 standard, the units are validated before leaving the factory which facilitates the whole process of quality control. The 90% factory made and controlled units make it possible to imagine a gain of efficiency on the building site, estimated at about eight weeks on this project compared to a concrete flat slab construction. However undetermined crossovers between on and off-site trades were the cause of conflicts and delays.

7- 461 Dean Street (Brooklyn, New York, USA, 2016, SHoP architects, Turner and Skanska)

- mass customized tall stacked modular

Identified in 2016 as the tallest modular building in the world, the project was completed in Brooklyn with publicised conflicts, cost and schedule overruns. Designed by SHoP Architects, this 32-storey building built in Pacific Park part of the regenerated Atlantic Yards shipyard. The 363 flat residential complex includes retail space on the ground floor, a fitness center and other community services (Farnsworth and Edelson 2018).

The 930 prefabricated stacked steel modules are braced by a steel superstructure, a type of racking system for attaching and assembling the manufactured units. The project builders and manufacturers imagined an ambitious future for modular construction. The 930 modules were assembled in a factory located in a former industrial area of Brooklyn. Localized production would simplify logistics both for manufacturing and assembly and according to project objectives would reduce construction costs by 25% and reduce construction time by 20% (Bagli 2016). The great theoretical advantage of modular construction over a traditional timeframe is the ability to produce units even before completing the foundations. The staggered timeline allows multiple tasks to take place concurrently.

The BIM model was the focal point of the project's ecosystem as each element of the structure, the modules and their services were modeled upstream before their production taking care of any irregularities before they showed up on-site. The very customized design of 225 unique modules created certain logistical constraints. The plant was separated into several production bays producing specific units for each subsequent floor; making production somewhat of a mega jigsaw-puzzle arguably lacking enough repetition to be completely cost effective.

The development of modular architecture applied to high-rise structures that go beyond the status of simple prototypes is not simple. Since the mid-twentieth century, many have proposed modular as an ideal response to housing problems. Projects have often remained one-off prototypes (Davies 2005). Dean Street offers an up-to-date window on the enduring challenges. In this case, what seemed to be a perfect storm (establish a factory near the site, give the architects design freedom and establish a first builder/manufacturer partnership for the largest modular tower in the world) produced some important lessons: modular construction imposes certain conceptual, constructive and manufacturing constraints that must be known and integrated from the outset by all stakeholders and considered in the agreements that bring them together. The chosen project delivery method must also allow for on-site adjustment as no matter how precise the factory is, the site will always require and impose its logistical conditions.

<u>8- Brock Commons</u> (Vancouver, British Columbia, Canada, 2017, Acton Ostry, architects, Urban One Constractors)

- integrated project delivery by virtual design and construction (VDC)

Part of the University of British Columbia's more recent development, Brock Commons includes student housing and services for a population of over four hundred students. This simple tower repeats the same floor plan over 17 levels. Each floorplate is a linear scheme of flats divided by a central corridor. The 18-storey structure is a hybrid of mass timber floors (glulam posts and cross laminated timber panels) anchored to a concrete podium and braced by reinforced concrete vertical cores. The structure was erected in just 10 weeks; its site cast concrete equivalent would have required 18 weeks.

An integrated project delivery method, the university through its real estate developer branch, UBC Trust, mandated all stakeholders. Designed as part of the 2013 Wood Buildings Demonstration Competition, the tallest mass timber building in the world[3] was completed in 2017. Since timber is still being studied and examined by regulating bodies in Canada as an alternative to reinforced concrete, all wood components have been encapsulated, either with a concrete topping or layers of gypsum board (Acton R. interview. 11-01-2019).

The building uses prefabrication for its internal timber structure and for its panel envelope system. The lightweight steel-framed metallic panel system was also developed to act as a protective barrier during construction. The timber floor plates were erected two at a time and protected from inclement weather by two floors of wall panels.

An estimated cost premium of 7% was calculated by comparing the project with traditional reinforced concrete construction. Required by code, the gypsum and concrete coatings account for 60% of this additional cost. It is in terms of planning that the project's process stands out. The assembly sequences for mounting the structure and installing the envelope combined precise modelling, full-scale mock-ups, and a virtual construction process to reduce the planned schedule by 2-months. Stakeholders identified a nine-week gain on a similar concrete structure. It is certainly possible that the 7% premium could be significantly reduced if a similar strategy were used for a similar and subsequent project, allowing stakeholders to learn and apply the lessons learned to another building (Acton R. interview. 11-01-2019).

According to Russel Acton, the principle architect, protecting the timber structure from moisture was one of their main concerns. Making it part of the design criteria from the outset significantly reduced the risk that moisture content would affect the structure. The differential movement between the reinforced concrete and the timber structure also requires more research; many components had to be readjusted accounting for the actual axial shortening of columns as calculated theory differed from what was actually observed on-site, the columns didn't shrink as calculated and had to be cut. The use of VDC models allowed designers, trades and client to discuss and react in real time allowing many of the logistical kinks to be cleared before on-site assembly (Acton R. interview. 11-01-2019). On-site assembly was also further optimized during construction making it possible for the upper floors to be put together much quicker than the lower ones.

9 - East Pier Project (Boston, Mass. USA, Boston, 2018, Lessard Design Inc, Cranshaw Construction)

– harnessing the factory to solve labour shortages

Located on the southern edge of East Boston, these two buildings sit on adjacent lots pointing to Boston Harbor. Buildings 5 and 6 employ similar building systems. Building 5, a 5-storey structure, has 137 flats, while Building 6 has 159 flats distributed over 5 floors. The housing units range from 476 square feet of micro-units to 1489 square feet of family units. In both buildings, the flats are organized around a common hallway. The property developer / owner Rosedale Property company was also the general contractor for the project (Houde C.W. and Grondin J. interview 24-01-2019). Our interest in the project specifically focused on the production of the

[3] At the time it was built – the race for tallest timber is ongoing

structure's lightweight stick-framed wall panels. The prefabricated panels, manufactured some 520 km away in a factory in Québec, were outsourced by the framing contractor as framers are increasingly difficult to contract in the Boston area (Houde C.W. and Grondin J. interview 24-01-2019).

Prefabricated stick-built wall panels for platform construction have been successfully deployed in the industry for a long time. Lightweight timber panels are arguably the most successful modular building system in North America. For East Pier, American Structures from Thedford Mines Québec (520 km from the site) was commissioned to produce the wall panels and provide all the structural components including floor beams and roof trusses (Houde C.W. and Grondin J. interview 24-01-2019). American structures' production is geared toward this specific building component. The panels for interior partitions and structural walls are simple to assemble and offer the flexibility of on-site coordination as one side generally remains accessible.

American Structures is one of Québec's successful producers in operation since 2002, and has been active in the United States for eight years; their process has not changed much and is based on the non-automated construction of stud and sheathed panels without the integration of any other systems. While it would be possible to imagine a more complex panel, the company identifies the agility and flexibility of its approach as a way to respond to a highly developed sector in Canada and the United States (Houde C.W. and Grondin J. interview 24-01-2019).

An interesting note which would require further investigation: as the sub-trade subcontracted his production to a manufacturer, any potential economies, except for overall project productivity, made though off-site construction are not clearly transferred to the client. The off-site construction strategy is not considered in design as it is simply adapted as it would to any platform structure. This type of prefabrication although not new, elucidates the manner in which many efficiencies have been integrated in construction. The integration of the prefab panel could be a model for studying what other elements could be pre-assembled and easily integrated in project ecology to gain similar efficiencies.

Discussion

Since industrialization, the decline of productivity in the construction sector relative to other production industries has argued in favor of a greater use of manufactured construction systems. Many have reasoned that industrialization in construction would parallel the advances made in other industries (Kelly 1951; Sullivan 1980; Herbert 1984). In addition to productivity gains, the benefits of factory production of architectural systems are well known: waste reduction, climate-controlled environments, improved health and safety conditions, and potential improvement in construction logistics (McGraw Hill Construction 2011). In addition to these real observable and confirmed benefits, it has been argued that prefabrication or off-site construction should theoretically reduce the time spent on site and reduce costs. The principle is quite simple as the reduction in time due to task overlapping should lead to a time equals money savings.

The nine cases presented in this report illustrate the diversity of processes, ecologies and strategies employed today to shift construction toward greater quality and efficiencies. The study's primary goal was to highlight the issues, challenges and potentials of integrating factory production into the construction ecosystem. A secondary objective was to identify themes that could be the subject of more specific research in a second phase of the study. The nine cases reaffirmed the already known advantages of prefabrication, however they also portray a certain entanglement between on and off-site strategies. Whether prefabricated or not, the traditional process of splitting design and construction into two stages linked by a bid is an important risk factor and amplified in the case of a process using off-site construction, as a shared responsibility between the plant, the site and the various stakeholders must be defined from the onset. The divergent tolerances of the plant and the site are one of the specific areas of conflict that require more collaboration to facilitate on-site systemic coordination. Collaboration must be facilitated by a contractual model and delivery method that allows teams to react during a project's evolution. Integrated project delivery methods are a step in the right direction, but must evolve into an integrated design and build strategy to bridge the divide between stakeholders concerned with specific phases be it design or construction.

Conclusion

At present, the quest for increased productivity is certainly affected by a decline in the skilled work force. The lack of specialized trades is already being felt in multiple contexts and is putting financial strain on projects. Factory work does not guarantee an absolute reduction in costs or manpower, but allows simpler and ideally repetitive processes to be built into projects. Repetition of systems, components and a degree of standardization remain important for successful integration of off-site construction. Although the manufacturing and design tools make it possible to imagine significant customization, repetition remains a tool for optimizing logistics.

We started this study with a simple question: What are the challenges and potentials of prefabrication today? The analysis allowed us to construct a more ambitious question: what would be an idealized embodiment of projects that combine on and offsite construction strategies?

The nine cases pointed to a fundamental and thorough revision of the traditional design-bid-build process. Cooperative models, multi-trade prefabrication, using virtual design and construction and strategies that relied on a hybrid relationship between stakeholders seemed to offer more opportunities for successes.

To invoke a prelude to further research, three cases convey very singular delivery methods: Brock Commons and Patch 22 with completely integrated teams showcase the role of a master builder who orchestrates the entire project from its financing to its operation; this process sets the rules at the beginning of the project and seems to minimize conflicts. A return to the master builder concept seems simplistic, but Skanska's approach to Miami Valley Hospital demonstrates the full potential of the process. The multi-trade and near-site prefabrication appear to lead to a type of master-factory-industrialist requiring a more collaborative construction culture.

Comparative analysis

Project/year	Miami Valley Hospital 2010	Heterington 2013	El-Sol 2014	Treet 2015	Patch22 2016	Loggia Saint Lambert 2016	Dean Street 2016	Brock Common 2017	East Pier Boston 2018
type of mandate	private	public - SHQ	public + private	private	public competition	private	private	public - university	private
off-site construction Strategy	«multi-trade» «near site»	service core	«kit of parts»	Hybrid volumetric	service floor	volumetric	volumetric	custom wall panel	lightweight timber panel
principle stakeholder for integration	Skanska, General Contractor	Architect / Mobilfab (manufacturer)	Project FROG (kit manufacturer)	IPD	IPD	manufacturer Bonneville industries	Full Stack Modular, manufacturer	UBC Trust, university's developement branch	Subtrade - framer
impact on project productivity	+	+/-	+	+	+/-	+/-	-	+	+
determinate factor	shared responsibilities + BIM	tolerances + non collaborative trades	BIM for streamlined design and construction	BIM + IPD	IPD from planning to operation	tolerances + non harmonized on and offsite	250 of 900 singular modules	IPD + BIM + VDC	just-in-time delivery
position in project ecology	BIM, FACTORY → planning, bid, construction, operation	planning, bid, construction, operation	FROG → planning, bid, construction, operation	SYSTEMS, COMPONENTS → planning, bid, construction, operation	ADAPTABILITY, COMPONENTS → planning, bid, construction, operation	MODULES → planning, bid, construction, operation	MODULES → planning, bid, construction, operation	SYSTEMS, COMPONENTS → planning, bid, construction, operation	WALLS → planning, bid, construction, operation
integration method	BIM + IPD	standard drawings	BIM + IPD	BIM + IPD	IPD + standard drawings	standard drawings	BIM	BIM + IPD	standard drawings
what we learned	préfabrication spécifique au projet. USINE de production	inflexible / «product driven prefab»	FROG a new stakeholder	Powerfloor for stacking repetitive units	Design for disassembly and lifecycle	30 minutes for a 90% complete 16'x70' module	localized production - potential for site regeneration	performance spec for increased exploration	labour shortages
further research required	project delivery method	the future of service cores ?	how configurators could work ?	assembly details	monitor life-cycle	assembly details	customization and on-site harmonisation	delivery method	Project economies ?

Table 1: Comparative analysis summary

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Evaluating Missed Opportunities for Energy Savings in Residential Buildings Using Mixed Mode Ventilation

Huyen Do[1], Kristen S Cetin[2]*, Omar-Hesham Elsherbiny[3], Liping Wang[4]

[1]The University of Danang - University of Science and Technology, Danang, Vietnam
[2]Michigan State University, East Lansing, Michigan, USA
[3]Iowa State University, Ames, Iowa, USA
[4]University of Wyoming, Laramie, Wyoming, USA
*Corresponding Author, cetinkri@msu.edu

ABSTRACT

Residential buildings consume a significant amount of electricity, representing nearly 40% of total electricity use in the United States. These buildings are most commonly designed to be mechanically rather than naturally cooled, heated and ventilated. As such, in all seasons, and in particular in transition seasons, homes use the HVAC system even when the outdoor conditions are conducive to natural means of heating, cooling, or ventilation, i.e., the outdoors is cooler than indoors in the cooling season or warmer than indoors in the heating season. The occurrence of these conditions represents a missed opportunity to reduce HVAC use if appropriate smart technologies were implemented in buildings to allow for mixed-mode ventilation. This research assesses the occurrence of unused opportunities for natural ventilation, and evaluates the energy savings opportunity from reduced HVAC use, using data collected on HVAC system operation and indoor and outdoor temperatures for 28 homes in Austin, TX from 2015 to 2017. The results indicate that 3% - 35% of the HVAC runtime in the spring transition seasons, and 11% - 35% of runtime in the fall transition seasons could benefit from mixed mode ventilation, resulting in strong opportunities for HVAC energy savings. The results of this work provide motivation to further study this opportunity and consider the use of smart technologies to facilitate reduce energy use of residential buildings.

Keywords: energy savings, residential buildings, mixed mode ventilation

INTRODUCTION

Buildings in the U.S. continue to consume a significant amount of the total electricity and energy used in the United States. Significant efforts have been made by in both the public and private sectors to help improve the efficiency of the U.S. buildings stock. Many programs target the single largest end user in the U.S. which is the heating ventilation and air conditioning system (HVAC), of which, depending on the climate zone, a significant portion of energy and electricity can be attributed. Since nearly 100% of commercial buildings both heat and cool their building, and 100% and 83% respectively of residential buildings heat and cool their homes, HVAC is a significant player in our U.S. building stock.

One way to avoid the use of mechanical heating and cooling is through the use of operable windows to provide natural, rather than mechanical, ventilation, heating and cooling to the building stock. In many places, building codes mandate a certain percentage of operable area (e.g. 2.5%- 5% of the floor area in NYC (Urban Green Council 2009), 0.53 m^2 in Denver (O'Hara 2017) for residential buildings, in particular for emergency escape and rescue windows. However, as compared to Europe, the U.S. uses very little natural ventilation in buildings. For commercial buildings in particular, many building systems are not designed to have operable windows.

Given this fairly standard practice of limited opening and closing of windows, occupants and building owners are used to using heating and cooling all times of the year, including cooling in the summer when it is cool at night, and heating in the winter when it is warm enough during the day. Thus even if the outdoor temperature is cooler than the indoor temperature in the cooling season, and even if the outdoor temperature is warmer than the indoor temperature in heating season, most residential building use their HVAC system. This represents a missed opportunity that could be utilized if the appropriate smart technologies were implemented in buildings to enable this to occur. In a limited number of cases, building designers have utilized this opportunity in buildings – such as the ESIF (Energy System Integrated Facility) (Sheppy et al. 2015) at the National Renewable Energy Laboratory which has operable windows which allow for natural ventilation. Occupants in ESIF are alerted to if it is beneficial to open their windows for natural ventilation using a computer-installed Application which is active on the employees' desktop. However, this is a commercial building rather than a residential building.

The ventilation method that combines natural ventilation and conventional mechanical HVAC systems is called mixed-mode ventilation. The utilization of such a system can help to minimize HVAC energy consumption and satisfy the requirements of indoor air quality and thermal comfort through the implementation of appropriate control strategies for operable windows and mechanical systems. The mixed-mode system is commonly classified into three categories including 'change-over', 'concurrent', and 'zoned' (CBE. 2015). 'Change-over' refers to the mixed-mode method where a building switches between natural ventilation and mechanical system operation. 'Concurrent' refers where both natural ventilation and mechanical systems can operate at the same time in the same thermal zones. 'Zoned' refers to the method where natural ventilation and mechanical systems serve different thermal zones individually.

Recent research has been conducted on operational control strategies for mixed-mode buildings. Spindler and Norford (2009) optimized control strategies for natural ventilation and fan-assisted ventilation in a mixed-mode building based on thermal predictions using a developed data-driven thermal model for mixed-mode buildings. Hu and Karava (2014) developed a model predictive control framework using particle swarm optimization (PSO) for window opening position, fan assist and night cooling schedule. Both studies emphasized the operational strategies using for natural ventilation and fan-assisted ventilation. Zhao et al. (2016) developed an occupant-oriented model predictive control system using 'change-over' mixed mode ventilation using EnergyPlus building energy simulation program coupled with Matlab via MLE+ (Bernal et al. 2012). May-Ostendorp et al. (2011) developed a 'concurrent' mixed-mode building model using natural ventilation in conjunction with a rooftop VAV air handler units extended from the DOE reference commercial medium-size office building model. A model-predictive control framework was developed for a mixed-mode building using PSO optimization to control the window state (i.e. opened/closed). The simulation results were used to extract decision rules using a statistical approach. Wang and Greenberg (2015) investigated the impacts of mixed-mode ventilation on building energy use for a medium-size office building using EnergyPlus. Temperature-based control strategies for "change-over" and "concurrent" mixed-mode ventilation were implement in EnergyPlus using an Energy Management System (EMS) module. HVAC energy savings of 17–47% was predicted using mixed-mode ventilation for the case study building in summer. It was concluded that key control parameters such as window operation availability setpoint and window opening fraction should be optimized to maximize energy savings.

These studies are limited to temperature-based operation and focused on commercial buildings only. No previous studies have established optimum control operation strategies for mixed-mode ventilation for single family homes. There is an essential need to provide a practical solution to how to design and operate mixed-mode ventilation system in a manner that will ensure maximum energy savings and enhance indoor air quality for single-family houses. Thus in the research, we take advantage of a large set of residential energy use data that includes indoor and outdoor temperatures and humidity conditions as well as disaggregated HVAC energy use to quantify the missed opportunities for natural rather than mechanical heating and cooling. We propose a control strategy for change-over mixed mode ventilation that will designated when to open and close windows to optimize performance, and determine the effectiveness of this control strategy for heating and cooling a house with and without additional fan cooling power.

In particular, it is worthy to note that a "smart" building is one that interacts with its occupants and environment in a beneficial way. In recent years a significant number of building-focused technologies have been developed with the goal of using smart technologies to improve the building performance. Smart technologies also typically imply connectivity to the internet or other devices that will ultimately connect them to the internet, through which they can send and receive data and interact with commands sent from the internet. Given the significant improvements in the battery and communication technologies, it is feasible that, moving forward, a windows could be smartly connected to a HEMS (home energy management system), and open and close windows based on the given favorable conditions. Or, similarly it could implement a text-message or other email alert to indicate that it makes sense to open the windows for natural heating, cooling and ventilation.

METHODOLOGY AND RESULTS

In order to evaluate the missed opportunity for natural ventilation in residential building HVAC systems, the following methodology is developed with four steps. First is the data collection. Second is the determination of the ON/OFF status of the HVAC system. Next, the missed opportunities for energy savings in HVAC system is evaluated. The final is the evaluation of mixed-mode ventilation in the HVAC system. The results of each step in this method are also represented in this section.

(a) Data collection. This research used three main types of data - electricity data, indoor thermal data and weather data. The electricity data are collected from several hundred residential buildings in Austin, Texas from 2015 to 2017. These data are collected by the Pecan Street Research Institute, a nonprofit research institute headquartered in Austin, TX. In this research, only the residential buildings that had over 97% of whole-home and HVAC electricity data are studied. Similarly, for indoor thermal data, the indoor temperature data were required to be available for over 97% of the total time of the studied months. These requirements are utilized to ensure the data is sufficient over a continuous period of time. After filtering of the dataset, 28 residential buildings had sufficient electricity data for the combined whole home, HVAC system and indoor temperature, for use in this analysis. The weather data collected includes outdoor temperature and relative humidity. To determine the missed opportunity for natural ventilation in these houses, the most appropriate time in a year for study is the transition seasons, including April-May and October-November, where the outdoor environmental conditions are likely to be within the thermal comfort zone of occupants for a larger percentage of time.

(b) Determine the ON/OFF status of HVAC system. In previous studies, the threshold power (kW) designated as differentiating between the ON and OFF status of an HVAC system was 0.05 kW for the indoor unit (evaporator/fan) (Cetin et al. 2018). However, following this relatively simple proxy for the ON-OFF transition, in this dataset there are still outliers in the data. Therefore, in this research, in addition to a threshold power value, a five minutes minimum is set to require the designation of the HVAC system to be switched. Based on the HVAC unit signals in cooling season (June), the thresholds of HVAC indoor/outdoor units are determined. The final thresholds are the median values in the signal histograms of both indoor/outdoor units (Figure 1). Based on this method, the thresholds for designated the system as being ON or OFF are different for each studied home. With the new thresholds of HVAC indoor/outdoor units, the HVAC system status is corrected. Figure 2a shows the signals of HVAC indoor unit in heating status (ON = 1). With the threshold of 0.131 kW, the indoor unit status is matched with the indoor temperature. Similarly, Figure 2b represents the signals of HVAC outdoor unit in cooling status (ON= -1) in this house. Here, the threshold of HVAC outdoor unit is 0.4995 kW.

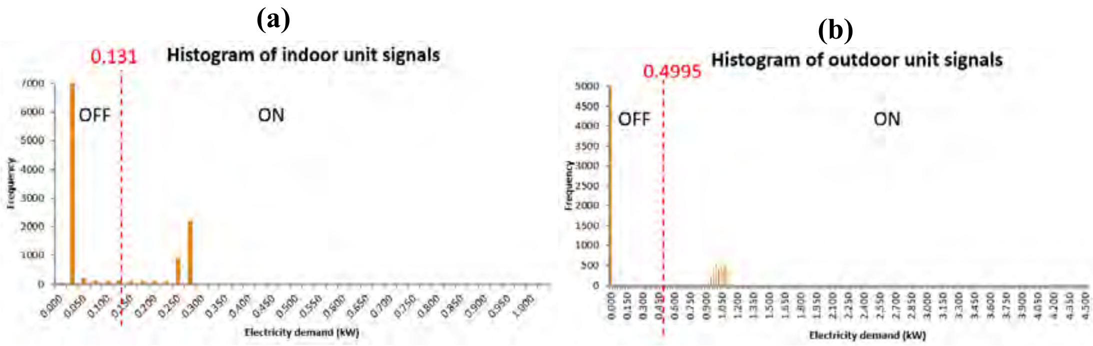

Figure 1. Histograms of electricity demand from indoor/outdoor unit signals for a sample home.

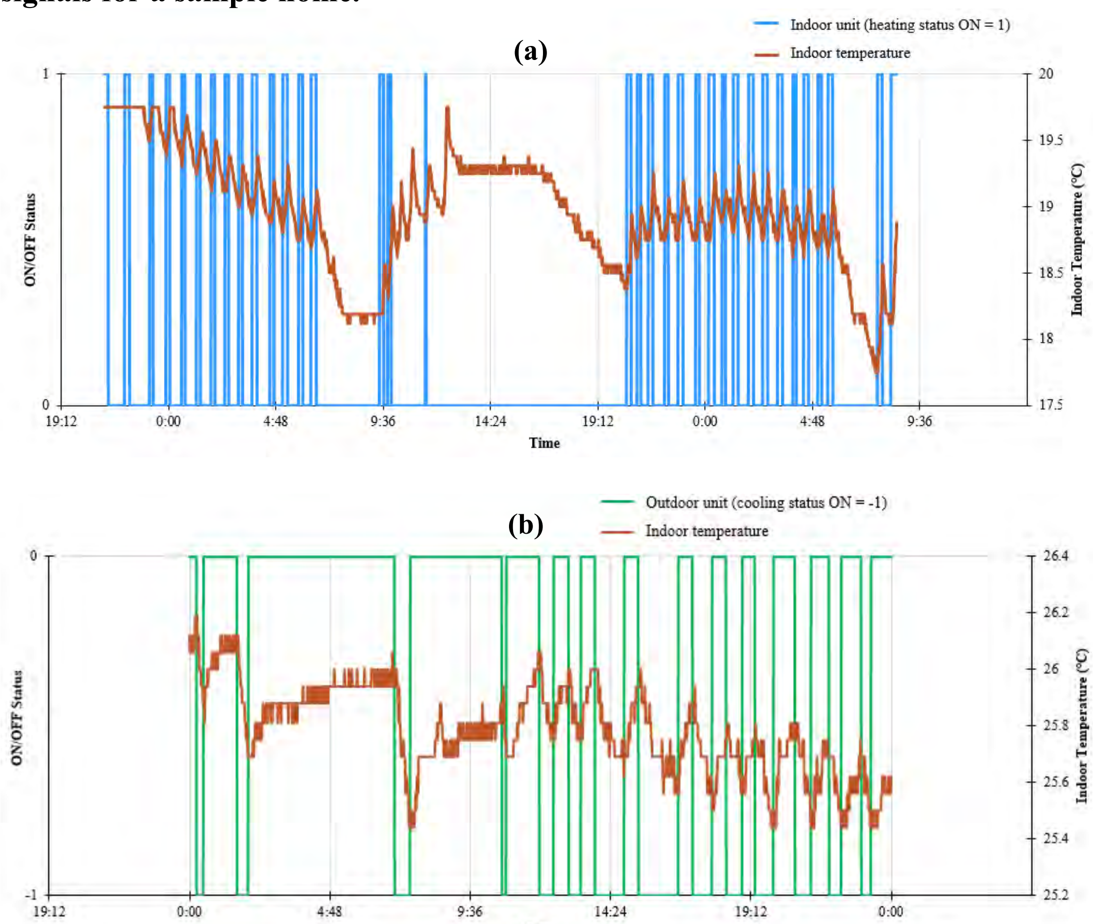

Figure 2. Example of the signal of (a) HVAC indoor unit or (b) HVAC outdoor unit, and indoor temperature for a sample home to confirm the appropriate development of the ON and OFF designations.

(c) Evaluate the missed opportunities for energy savings. In The evaluation of missed opportunities for energy savings of an HVAC system is based on the comparison of indoor and outdoor temperatures. This means that if outdoor temperature is lower than indoor temperature, the doors and/or windows could be opened instead of using the HVAC system to cool the home. Vice versa, if outdoor temperature is higher than indoor temperature, the doors/windows could be opened, instead of using the HVAC system, to heat the home. In both cases, natural conditioning of the indoor spaces of the home can be applied to heat/cool the home, saving the homeowners money on the energy use of their home's HVAC system. Table 1 shows the results from studying 28 houses in transition months (April/May and October/November) from 2015 to 2017. The results indicate that 3% - 35% of the HVAC runtime in the spring transition seasons, and 11% - 35% of runtime in the fall transition seasons could have benefits from mixed mode ventilation, resulting in strong opportunities for HVAC energy savings.

Table 1. Residential building characteristics in studied ASHRAE climate zones

Average (%)	Missed Opportunities	
	Heating mode	Cooling mode
Spring transition months (April/May)	*63.0*	*62.7*
2015	2.7	2.7
2016	51.9	53.8
2017	2.5	2.5
Fall transition months (October/November)	*32.0*	*31.1*
2015	57.8	61.4
2016	21.2	21.1
2017	11.5	9.6
Total Average	*9.5*	*7.9*

(d) Evaluate the mixed-mode ventilation in HVAC system. The ASHRAE 55 [11] designated thermal comfort criteria for both mechanically conditioned spaces, and for naturally conditioned spaces. The allowable indoor operative temperature ranges for naturally conditioned spaces for occupants to remain comfortable are based on the indoor operative temperature and the mean monthly outdoor temperature. There are two ranges of operative temperature limitations, including 90% and 80% acceptability limitations. If the average data is inside these limitations, in general, occupants should feel comfortable/satisfied with the conditions in the indoor environment.

In this research, we consider several different cases of mixed mode ventilation including, including (i) using 70% indoor and 30% of outdoor air, (ii) using 50% indoor and 50% of outdoor air, and (iii) using only outdoor air (100%). Figure 3 shows four cases of ventilation, including the three above-mentioned cases, as well as 100% indoor air, as a basis of comparison. These are analyzed for comparison in spring and fall transition months. These figures only show periods of time in the Spring transition months where we have identified that the outdoor environmental conditions are conducive to the use of mixed-mode ventilation (see Table 1). For comparison, the left side of the figures are for the 100% data of studied time, and the right side are for the periods of times determined to be missed opportunities.

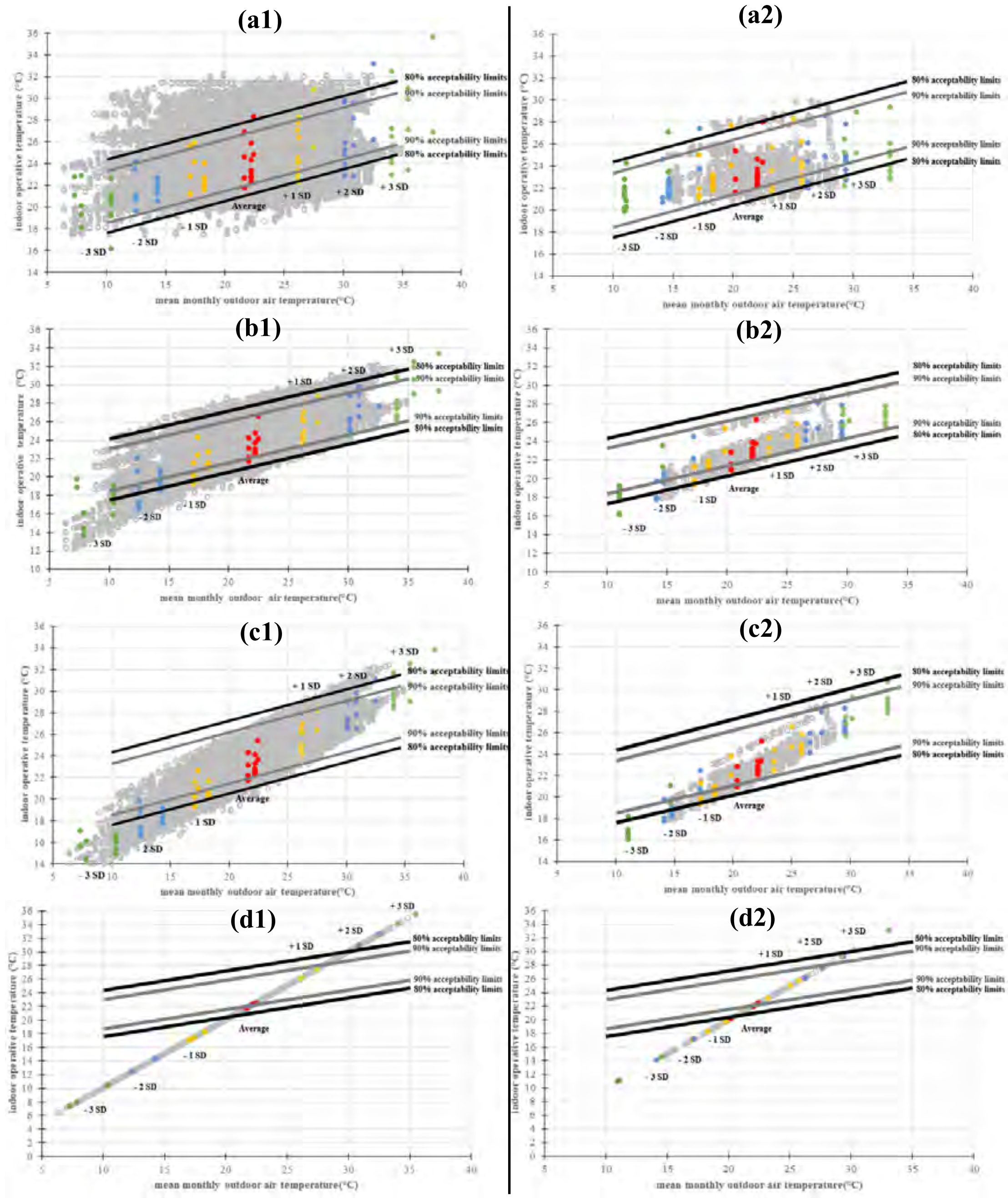

Figure 3. Mixed-mode ventilation in spring transition months (April and May) in different cases: (a) only using indoor air (100%), (b) using 70% indoor and 30% of outdoor air, (c) using 50% indoor and 50% of outdoor air, and (d) using only outdoor conditions (100%); by using (1) all data in studied time and (2) only data determined to be a missed opportunity

In these figures, the red points indicate the average values of indoor operative temperature in transition months in each residential buildings. The ±1, ±2, and ±3 standard deviation from average values of indoor operative temperature in each residential building are also calculated. Overall, the average values are in the 90% acceptability limits in both spring and fall transition months. Most of the ±1 standard deviation values are also inside the 80% acceptability limits, while ±2, and ±3 standard deviation values are outside of limit ranges. Comparing the four cases of indoor operative temperatures, case (a) using 100% indoor air and case (b) using 70% indoor and 30% of outdoor air, have the averages and ±1 standard deviation values insides the acceptability limits. These results from four cases of indoor operative temperatures with 100% data in studied time in transition months are similar to the results from four cases using only data during missed opportunity times. This means the combination of indoor conditions and a certain percentage of natural ventilation results in conditions that are acceptable from a thermal comfort perspective, therefore, the use of natural ventilation in HVAC system could be beneficial in these conditions. Therefore, in these homes, and likely other similar types of homes, there is notable opportunity to utilize mixed-mode ventilation, which could help lead to overall HVAC energy savings.

CONCLUSIONS

The results of this research represent the strong opportunities for HVAC energy savings through using mixed mode ventilation for naturally conditioning residential buildings. This occurs when the outdoor conditions are cooler than the indoor conditions in the cooling season or warmer than indoors in the heating season. The initial findings indicate that 3% - 35% of the HVAC runtime in the spring transition seasons, and 11% - 35% of runtime in the fall transition seasons could benefit from mixed-mode ventilation. Based on these results, the residential buildings in Austin, TX studied in this work, when conditions are conducive to natural ventilation, can operate their HVAC system by introducing approximately 30% outdoor air or potentially 50% of outdoor air the large majority of the time, while continuing to maintain comfortable indoor environmental conditions. The results of this work also provide motivation to further study this opportunity and consider the use of smart technologies to facilitate reduce energy use of residential buildings.

ACKNOWLEDGMENTS

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Proposing A Deployable Post-disaster Modular Temporary Shelter Using Vernacular Materials

P. Farrokhsiar[1], H. Mirhosseini[2], and A. Saeedfar[3]

[1] M.S. Student, Department of Architecture, Stuckeman Center for Design Computing, Penn State University, 121 Stuckeman Family Building, University Park, PA, 16802, puf69@psu.edu.
[2] Ph.D. Student, Department of Architectural Engineering, Penn State University, 227 Engineering Unit A, University Park, PA, 16802, hzm62@psu.edu.
[3] Research Operations Associate, Autodesk Inc., 1 Market St, #200, San Francisco, CA 94105, arian.saeedfar@autodesk.com

ABSTRACT

The rapid pace of climate change and global warming in recent years has led to the extensive growth of natural disasters such as wildfires, floods, hurricanes, and earthquakes, and consequently a need for planning to provide settlements for those suffering from consequences of these disasters. Depending on the duration of use and conditions of the residents, these settlements are categorized into four groups: emergency shelters, temporary shelters, temporary housing, and permanent housing. The focus of this research is to propose a modular quick-erect structure as a temporary shelter to provide accommodations for multiple weeks or months after an earthquake. In the first step, samples of existing temporary shelters are evaluated in terms of structural performance, material accessibility, deployability, transportability, and use of space to establish the best practices for designing an operative temporary shelter. Studies show that many of the existing shelters are difficult and time-consuming to transport and assemble and are usually made of heavy materials. Moreover, many of them are not deployable in a configurable geometrical order which makes their transportation even more difficult, and their storage for future use more problematic. In the second step, the research proposes a lightweight, deployable, low-cost, and modular structure based on the criteria studied in the first step. The proposed geometrically-optimized temporary shelter is capable of being placed, repaired, and stored in a short time period by unskilled individuals. Furthermore, using local materials such as wood, stone, and mud to create the foundation of this structure would make it usable in various locations and circumstances. The proposed structure, which can be expanded by adding more space to its ends, consists of scissor-shaped modules of narrow metal ribbons that are easy to pack and assemble.

Keywords: Temporary shelter, modular structures, deployable structures, post-disaster settlement, lightweight, geometrical optimization

INTRODUCTION

Disasters are threats to the entire world population and require complex strategies for recovery (Frankenberg et al., 2013). The intensity and frequency of natural hazards in the world are increasing which results in tens of thousands of lost lives and the displacement of millions of people. The response to disasters needs to be relevant to the population impacted by that disaster. In terms of hazard management systems, greater resilience is needed by communities to overcome challenges related to environmental hazards. (Djalante et al., 2011; Frankenberg et al., 2013). The 100 Resilient Cities organization, established by the Rockefeller Foundation, defines resiliency as “the capacity of individuals, communities, institutions, business, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience” (Harrison & Williams, 2016). Although many communities are residing in areas that are vulnerable to natural disasters, the risk reduction and readiness to overcome the catastrophic consequences of these diastases is sometimes neglected by many of them. In recent years, researchers and government agencies have been suggesting to move from disaster vulnerability to disaster resilience. Resilience is more focused on engaging the communities to be more proactive in natural hazard reduction (Cutter et al., 2008; Karji et al., 2019).

Natural disasters are often considered as unpredictable events that need emergency responses, while the growing number of natural hazards requires a paradigm shift towards considering them as ongoing threats for which the entire lifecycle is planned before the occurrence. Large investments by lawmakers and urban planning agencies are needed to decrease the impacts of such events in the future and mitigate or minimize the risks communities are facing in terms of readiness and survivability (Harrison & Williams, 2016). Increasing adaptability is one of the solutions that is considered in many cases (Djalante et al., 2011; Sadat-Mohammadi et al., 2018). Increasing resilience includes helping communities to maintain livable conditions post-disaster as well as strengthening adaptation in many aspects before a disaster impacts communities (Mirhosseini et al., 2019). The question that needs to be answered is although we are ready to design and build in “normal conditions”, what needs to be done to function in “limp-along” conditions following a natural disaster (Harrison & Williams, 2016). The use of lightweight temporary structures is proposed by many researchers to provide temporary settlements for those impacted by natural disasters. The objective of this research is to design a shelter for areas in which conditions for the rapid construction of new structures is unfavorable. The final product is a low-cost semi-prefabricated structure with no need for professional labor to assemble, using recyclable vernacular materials that could be accessed around the project site.

POST-DISASTER SHELTERS

Moving or displacing tens of thousands of people affected by a natural disaster only in a few hours in hazardous post-disaster conditions is a complicated process. Seamless coordination among various organizations is needed to successfully complete such tasks. Complex considerations are needed in terms of determining the best evacuee route that needs to be decided in advance or be determined by mathematical models based on the aftermath of the disaster (Li et al., 2012). Quick availability of temporary shelters is very important for those impacted by disasters for a quick recovery and returning to a daily routine (Abdolpour et al., 2017). One successful use case of temporary shelters is a set of shelter hospitals designed in 2012 to rescue citizens in

China in events of a natural disaster. The hospital consisted of four separate units that could be loaded and unloaded by automated devices. After the outbreak of the adenovirus in China in 2013, the shelter hospital model was used as the main method for emergency rescue (Bai et al., 2017).

According to the U.S. Department of Health and Human Services (2019), depending on the duration and living situation of the dwellers, temporary settlements can have many different forms and use cases. There are three stages of post-disaster accommodations in general: emergency shelter, transitional shelter, and permanent housing. This project focuses on the second stage, transitional shelters. Industrial manufacturing and prefabrication of parts can help in designing more efficient shelters that can be deployed faster and easier. Using prefabrication, the construction and assembly process can be faster (Abdolpour et al., 2017). Although various designs of shelters have been proposed by many researchers and designers, there is still a need for more efficient and more cost-effective emergency shelters. Most current designs of emergency shelters are expensive and difficult to assemble or construct in a short period of time after the disaster (Park, 2017). A few cases and proposals for temporary transitional are discussed and studied in this paper.

Deployable structures. In the traditional definitions, deployable structures are considered as a category of structures that can be transformed from a closed configuration to an expanded form. In the modern definition, deployable structures are a category of adaptive structures with the ability to change shape based on the requirements of their surroundings (Del Grosso & Basso, 2012). Deployable structures can either be categorized as "deformable" or "rigid links". The former relies on the intrinsic properties of materials to change the configuration, while the latter depends on the "geometric inter-linking" of elements to change the configuration. Examples of the first category include Compliant Mechanisms, Tensegrity Structures, and Pneumatic Structures. The examples of "rigid-link" structures include Mutually Supported Elements (MSE), rigid foldable origami, morphing truss structures, and scissor mechanisms (Del Grosso & Basso, 2012). The lightness of the building materials is a very important aspect of temporary shelters (Abdolpour et al., 2017; Amini et al., 2017).

Park (2017) suggests a design based on recycled paper tubes with prefabricated joints which introduces an easy approach to build a lightweight shelter for those impacted by a disaster. The challenge for using this design is immediate access to enough resources of material near the disaster site. In other proposals, earth-based deployable structures are used for temporary and emergency situations (Del Grosso & Basso, 2012). Asefi and Sirus (2012) propose a modular retractable tent that could be deployed on the site of the disaster. Henrotay et al. (2006) propose a model that consists of a small variation of compound structural elements that form a variety of shapes and structures based on the situation of site and environment. Quaglia et al. (2014) use origami-inspired design for deployable shelters that could be rapidly assembled and can be used for military purposes. Gunawardena et al. (2014) state that prefabricated modular construction can be used as an effective method for post-disaster permanent housing which decreases the times required for temporary housing. The temporary shelter proposed by

Abdolpour et al. (2017) is composed of a single-story building with a rectangular area and is consisted of the floor, ceiling, and wall modules. The walls are made by fiberglass materials and the joints are prefabricated and can be assembled on-site. While these proposals provide different alternatives for post-disaster temporary shelters, there is a need to explore more cost-effective methods using materials that are accessible in the site of a disaster.

Scissor structures. The Scissor mechanisms have the ability to shape more flexible structures if the transformations happen between more than two shapes (Sterk, 2006). With the use of modified scissor units, the shape of the system can be changed without changing dimensions of the elements involved (Del Grosso & Basso, 2012). Units developed by Akgün et al. (2007) and Akgün et al. (2010) prove the extension and rotation capabilities of scissor structures. In other proposals, scissor mechanisms are used with springs to achieve zero stiffness (Barents et al., 2011; Guest et al., 2011). The design proposed in this paper uses the scissor mechanism to provide transitional shelter that could be assembled with limited to zero access to professional labor.

PROTOTYPE DESCRIPTION

The proposed prototype focuses on providing post-disaster transitional shelter that can get assembled within the first few days of the disaster and be occupied as a dwelling for several months until the dwellers are ready to be moved to a more permanent settlement. Considering the transitional nature of the proposed structure, the following criteria are considered in the design process:

1. The proposed structure design uses simple lightweight parts and joints that occupy minimum space for transportation.
2. The assembly process is easy and understandable by local residents.
3. The quick time of assembly allows for building up many structures in a short period of time.
4. Each individual structure can be customized based on the specific needs of residing families and the number of occupants.

Following the mentioned criteria, a simple spatial geometry is considered in the design of the proposed modular structure. The first prototypes started with a cube that could be expanded on each side and provide more space as needed depending on the number of people residing in the structure (Figure 1). The cubical design was rejected as it needs to be prefabricated as one single unit which makes its transportation very challenging. In the next step, the possibility of simplifying the geometry based on the stability of the structure was considered. The 90-degree corners of a rectangular section (cube) need complex fixed joints in order to be steady enough to tolerate an earthquake. Therefore, by eliminating these joints, the section profile of the structure was transformed in a way to be the closest shape to a circle shape. A circular shape is structurally steadier as it eliminates the need for a roof which causes complexities for designing a self-standing structure. Hence, the walls and roof are integrated into one single element with a circular section which eliminates the need for complex joints (Figure 2). The main geometry of the structure is then shaped by the extrusion of the circular section into a near-cylinder shape. The near-cylinder shapes can be used as modules, putting together any number on which can provide different sizes of settlements. Similar cylindrical shapes can be seen in the tents used by nomads in the Middle East (Andrews, 1997). Another characteristic considered in design was to minimize the space occupied on the ground. This feature, as well as expandability of modules in a linear direction, make it possible to use the structure in steep slopes where finding a flat surface to build the foundation of the structure is difficult.

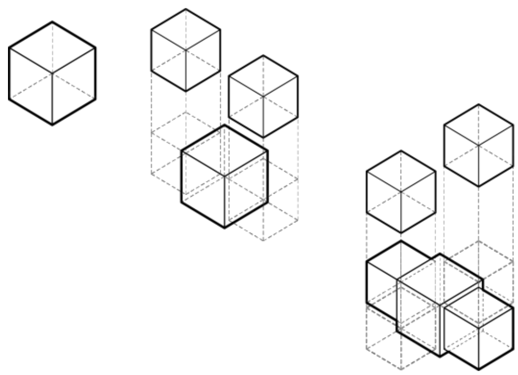

Figure 1. An early prototype of the form and structure using expandable cubes

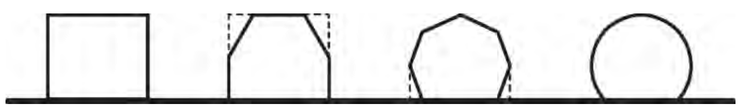

Figure 2. The transformation of the section profile of design from a rectangular to a circular shape

The width of each module is defined by the space needed for a person lying down on the ground while having enough space for another person to walk by (Figure 3). Also, considering the circular shape of the section profile, the module needs to be high enough on the sides for an average-size person to stand on the side (Figure 4). Therefore, in the final design, the length of each edge of the cyclic square of the section profile is 2.4 m (Figure 5).

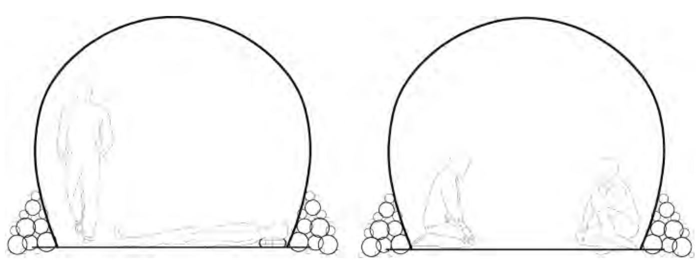

Figure 3. The criteria defined for the minimum width of a module

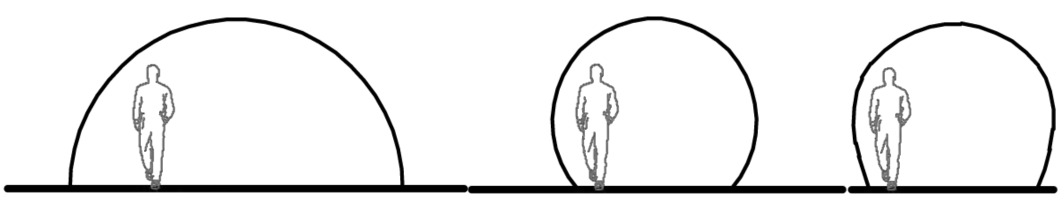

Figure 4. The criteria defined for the minimum height of a module

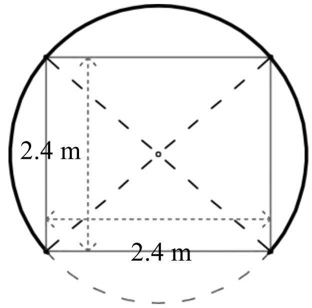

Figure 5. The dimensions of the cyclic square of the section profile

The module shell is formed by scissor structural elements consisting of two metal belts intersecting on both ends and in the middle. The propulsion of each module is controlled by its side elements. The two belts are situated diagonally and intersecting in the middle to harness the driving force on both ends of the unit. Vernacular materials can be used by local residents to cover the two transverse walls. In many parts of the world, using vernacular materials to build surfaces quickly is a common practice. For instance, in the northern parts of Iran, wooden walls called Zygaly, are built flat on the ground and then installed on the wall. Similar practices are common among other communities throughout Asia and Africa (Mirhosseini & Smith, 2017). The entrance door and windows will be placed on these walls and the interior space within the longitudinal section can be used as storage space (Figure 6).

Figure 6. Storage spaces near the transverse walls in the longitudinal section

STRUCTURAL COMPONENTS

The proposed prototype consists of the following structural components and elements (Figure 7):

Steel belt. The final designed module consists of two metal belts with scissor-like joints on both ends and in the middle as prefabricated parts. These parts could easily wrap together and be transported. The metal belts have pre-drilled holes to connect other structural and ornamental pieces.

Pipe. Each module needs an element that keeps the intersecting belts in their intended positions. Metal pipes are placed in between the pairs of belts on both sides.

Gabion. Gabions are used for leveling the ground and prepare the foundation of shelters and preventing the permeation of the surface waters into the shelter. This also helps to stabilize the structure and insulate the shelter from the base.

Metal tubes. To establish the base for attaching the belt structures, two parallel tubes with pre-drilled holes are placed at a distance of 2.4 meters from one another (designed distance for optimum usability of the module) on wooden beams as the foundation of the structure. The main structure is attached to the pipes using screws.

Wooden beams. To maintain a constant distance between the two pipes, wooden beams are placed at intervals of one meter on the ground and pipes are installed on these timbers.

Wooden rods. Several wooden rods are installed on the main structure to make it more integrated. The rods also help the dwellers to hang lightweight objects in the shelter.

Prefabricated joints. Connecting the horizontal rods to the main structure requires an element that has the ability to change angles. Different intersections between the wooden rods and the belts have different angles. The prefabricated connecting pieces that hold the rods horizontally can be adjusted to the desired angle.

Wooden pallet. Flooring, furniture, and walls can be made of low-cost recycled wooden pallets.

Tarpaulin cover. Tarpaulins cover layer is formed primarily to make a habitable house in the shortest time. After assembling a number of units, an insulating layer will be added on the first cover.

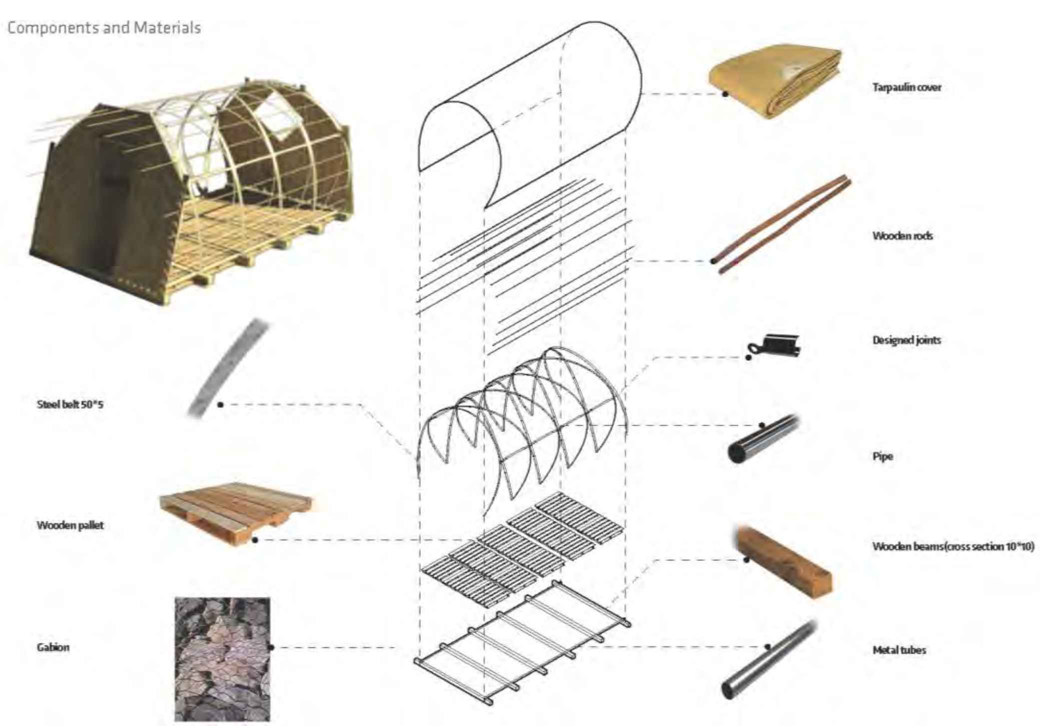

Figure 7. Structural components and materials of the proposed prototype

ASSEMBLY PROCESS

The following steps need to be taken to assemble the proposed prototype:

1. Placing the wooden beams at prespecified intervals after flattening the substrate by Gabion
2. Installing two metal tubes on the beams with an interval distance of 2.4 m after placing an open net underneath.
3. Placing the wooden pallets in between the beams on the ground as the flooring.
4. Filling the empty space between pallets beams and the ground by a layer of mud. This also thermally insulates the floor and reduces the possibility of issues associated with vermin.
5. Opening the modules one by one and placing them in a stable position using pipes will be placed in the middle of each side of the module.
6. Placing the required number of modules side by side and connecting them.
7. Screwing the assembled diagonal belts to the two pipes on the ground.
8. Installing wooden rods horizontally at regular intervals from each other on the structure to strengthen and stabilize it.
9. Covering the structure with a temporary tarpaulin cover and tying it to the metal tubes on the base.
10. Building a stone wall with a height of 40 cm on the sidewalls for structural support at the base and insulation on lower levels.
11. Covering the two transverse walls with surfaces that are made on the ground from vernacular materials and installed on the structure.

CONCLUSION

The number and intensity of natural disasters in the world are increasing every year. In recent years, there has been a large number of research studies on the importance of increasing resilience and adaptability to reduce the post-disaster impacts in hazardous areas. Studies show that vulnerable communities are much more exposed and affected by hazards related to natural disasters. In order to increase the adaptability of communities in facing such events, there is a need to explore opportunities to use the resources on the site of the disaster to build temporary settlements for those impacted by the event. This paper proposes a transitional shelter that can be used as a post-disaster temporary dwelling. By reviewing the scholarly research about important aspects and characteristics of temporary shelters, a prototype is proposed that uses scissor mechanism and leverages lightweight prefabricated elements as well as vernacular materials that could be accessed near the site of the event. The proposed structure requires a limited number of pieces that need to be transported to the site and requires minimum professional labor.

Structural analysis can be performed on the proposed shelter design to evaluate its stability and durability. Additionally, future research is needed to evaluate the performance of the proposed structure in different contexts and under various environmental conditions such as climate and available materials near the site. The use of modified scissor units can also be considered to design a more flexible structure that can be adapted to the spatial constraints of the site.

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Existing residential neighborhoods in Italy: from strategy to project to activate a sustainable mutation process

Alessandro Gaiani, is Assistant Professor in Architectural and Urban composition at Department of Architecture, University of Ferrara. Email: alessandro.gaiani@unife.it

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Abstract

There are numerous residential neighborhoods built in Italy from the 50s until the 21th century that are in precarious conditions, social, spatial and constructive. Its redefinition takes place with a theoretical and methodological approach that includes memory, innovation and sustainability leading the mutation of spaces towards the assumption of new value by using tools of hybridization.

The proposal of the conversion of public residential buildings, and now characterised by a spatial and social alienation, is based on the architectural theory of *circular re-conditioning*: the contamination between place and object capable of reactivating the identity of "discarded" urban elements, where the absence of adequate space and energy-intensive buildings has led to a physical and symbolic obsolescence. The main tasks are the ones that follow:

- A circular strategy based on the re-conditioning of the existing by recognizing a value to the current waste;
- Define new adaptive intervention tools able to change spaces and redefine the boundary between reception and exclusion, and make buildings energy sustainable;
- Equipping buildings with porous spaces to accommodate those in need (for example for homeless but not only)

The methodological process uses the one proposed in 2003 by Haeckel, *Adaptabily loop*, updated on 5 points (one new): the *sense*, which defines a new spatiality for housing, the *interpretation* where the elements of the process take shape, both circular and adaptive, redefining the sense of identity through architecture and a participated communication, the *decision* defines the intervention strategy, **resilience**, the ability of a system to adapt to change following a high impact event; the *act* determines the operative tools, a series of "adaptive grafts"; the *outcome*, a project that combines architecture's own tools with social and and energy savings ones that can revitalize a neighbourhood and make it habitable again.

BACKGROUND

The continuing excessive growth of the capitalist system has led, in the last decade, to an ever-increasing confrontation with the dramatic climate changes and the consequent economic and social crises.

The construction sector accounts for around 40% of the consumption of material resources and available fossil energy. In Italy the residential suburbs, built from the end of the 50s to the present, are the first cause of CO2 emissions, a disorderly and uncontrolled consumption of soil that has led to a series of consequences with which we

must now confront, first of all those of of the environmental sustainability of the system, but also the social sustainability of this set of uncontrolled expansion.
Living then becomes the fundamental element from which to start again with particular reference to the peripheral condition of the many residential districts designed by the Modern.
In Italy, after the Ina-Casa experience ended, in which an attempt was made to mediate between the dictates of the Modern and those of the compact city, typical of the Italian urban experience, new suburban residential districts arose that refer to the lesson imparted by the quantitative development and the serial of the Modern: dormitory quarters, physically separated from the historic city, used only by less affluent classes, an expression of monofunctionality, and fruitional segregation. (Figure 1)

Figure 1. Pilastro residential district in Bologna: first nucleus, 1966. (Acer Bologna photo archive)

The spaces are clearly identified through some predetermined elements: standardized housing defined in each individual environment, buildings mostly for residential use only, linked to the logic of zoning and equipped with very few services; the open space conceived as a 'technical room' intended as an anonymous distance between the buildings, a generic void declined in parking lots or undifferentiated green, linguistic styles that are repeated indifferently in every context, typologies in line or tower, multi-storey, of considerable size.
In 1956, the historian Siegfried Giedion, arguing over Le Corbusiers Marseilles unit in Marseilles, warned against the danger of seeing simply constructed residential architectures built with "*the juxtaposition or stacking of individual living cells*". (Figure 2)

Figure 2. The “Virgolone” from the Pasolini park in the Quartiere Pilastro, Bologna, 1980 (Acer Bologna Projects Archive)

This is the most cumbersome legacy of the Modern Movement to have denied architecture a linguistic capacity based on the semantic value of its elements, in favor of a research that, starting from the function, focused on the syntactic structure of the project, a kind of composition mechanics, which in the logical paradigmatic void of modernity, represents the continuous search for a universal validity method.
These neighborhoods became, between the end of the last century and the beginning of the new one, a place where the social condition: a place of confrontation between different communities and ethnic groups, between inequalities social also expanded by the illegal occupation of empty housing (housing without any internal service and without the main technological networks), a place where the clash took place daily in the spaces of degradation, leading to a functional and technological obsolescence of housing, to a intolerance towards the conditions of living, which started a process that has definitively segregated these districts into "trash” of the city. Within these Quarters the containers of social marginality, to which social isolation is often accompanied, have affected different groups and subjects traditionally excluded from the benefits of development such as unemployed young people, low-income elderly people, single-parent families, parents separated and their children, low-income and temporary employees, foreign immigrants who by ethnicity, religion or language reduce relations with the outside and fail to achieve social integration. The demand for a different dwelling, which in some cases takes on a precarious character precisely in relation to the classes considered weaker, seems to insistently require interventions devoted to a regenerative logic of what exists and to find that "common territory" and that "social agreement” ”that has ensured a "dialoguing "habitation in the past. The effect of the disintegration and decomposition of social ties has had serious consequences: the concept that was at the base of these neighborhoods of a popular nature was that of

mutual support among the inhabitants. The family social structure and the common working status in which the inhabitants found themselves, had ensured a rich fabric of mutual aid and support for the weakest segments: the disintegration of this social "agreement" led the group of unskilled workers to leave from the world of work. (Figure 3)

Figure 3. Corviale residential complex, Rome (Photo G.Chieregato)

We believe, therefore, that in order to respond to the complex conflicts of contemporary living, it is necessary to cross thresholds that until now have not been crossed, get out of the disciplinary areas so far used and enter the fluid world of the hybrid that permeates the complex everyday life for provide more appropriate answers to the solution of peripheral residential neighborhoods within the difficult world of multiabilities that contemporary living requires.
The meaning of the verb to inhabit that we are trying to propose in this paper is very different from modern experiences and begins from the assumption that living is organized around the body of the inhabitant, of his person, united in a Community and crystallized in the structures that contain it. Therefore, living is interpreted as an expansion of the self within the Community, as a production - between the latter and the space - of quality relationships, as a custody in and with it of emotional and emotional relationships. Of a resilient community, meaning at the same time a physical place and a cohesive social context, meaning architecture and the community, as a system that continually redefines itself and sustains and produces itself from its own interior.
The city must offer new forms of accommodation, promote integration, include diversity, combat tensions with gestures of concrete intersocial training.

Starting again from a dwelling where not only the hygienic or functional parameters of the modern are present, or typological cuts between 70s and 80s in which the demand-performance building process based on components and not on systems, has failed to produce living of quality, but a domestic life, in which the relationships between people take on the main importance, a dwelling in which it is possible to co-respond, a dwelling where the different conditions of today's living can be expressed. By now living in any part of the planet, with some exceptions, unlike some years ago, is subjected to a change "*obsessive, compulsive and unstoppable*" [Prigogine 1986, VI], and has as a minimum common denominator a sense of fragility , provisionality and vulnerability that leads to constantly changing one's state, and being in a perpetually "*unfinished and indefinite*" condition [Prigogine 1986, VI].
The periphery lives of distance, of discontinuity, of everything that is fragment, collage, mosaic, is not connected, identity is recognized in the distance. Thus the dichotomy between urban homogeneity and the production of peripheral differences is actually its dramatic strength. The problem of recognizing the suburbs is solved through the acceptance of the discontinuity of space and through the intensity of the architecture. To reconstruct the sense of belonging, the periphery must be expressed through conflictuality, through the language of differences, or as Persico said, through the "[...] *substance of things hoped for* [...]." [Persico 1935]
The redefinition of meaning and sense of this heritage takes place with a new theoretical, methodological and applicative approach, which includes memory, innovation and sustainability, accompanying the mutation of spaces towards the assumption of new value with hybridisation tools.
To work through this vision means to enter into that system of thought in which the concept of "translation" is introduced, understood as a spatial element in which one's own and the stranger cohabit which are therefore not brought back to a single thing or an absolute knowledge, but they are unified on the model of hospitality and coexistence: as George Steiner states, "to understand is to translate". It is that attitude to receive, transmit and assimilate what derives from the context, and to register ourselves in the contemporary world as a complex reality in which both the universalism of the hypermodern society and the defense of the Communities and identities coexist details.
If the Modern had modeled objects that were defined through their masses, the organization of full and empty spaces, the constructive system and functional organization, basing on this compositional grammar the pride of permanence and the challenge to time, today this is the re-appropriation of the pre-existing heritage, the collective memory that places are able to represent, the key to shifting the search for a community's sense of belonging from a crisis level to a responsive one.
"*Beyond a peaceful and sterile coexistence of reified cultures (multiculturalism), we must move on to the cooperation between cultures that are equally critical of their own identity, that is, to enter the stage of translation*" [1].
In other words, we can try to "rewrite" history to the benefit of plural stories, that is, we can work on history through an identity approach in which past histories are "overwritten" with those present, using instrumentation in "agreement"[6] with expressive identity drives.
"If the fundamental artistic question is no longer" what to do again "but" what to do with what we have available "... we must activate processes in which alternative

protocols are developed for representations and narrative structures already existing:" learning to use forms it means first of all knowing how to make them their own and inhabiting them "passing from a culture of consumption to a culture of activity, from a passive attitude to a form of resistance based on the reactivation of denied or marginalized potentials" [2].

The great signs, the great works of architecture, the urban projects aimed at reconfiguring entire cities or parts of them are no longer part of the new vision of the world. A majestic infrastructural signs rather than imposing new districts or renovation projects of entire residential compartments, a strategy must be replaced that foresees much more targeted interventions, whose sum leads to the whole, but that even only a part of it has a defined character and concluded.

Mutation spaces, open systems, interstitial projects, projects in constant progression, solitary insertions capable of rebalancing a system of relationships and reciprocal relationships that are completely inhomonous today, aimed at defining the evolving form of urban environments through punctual non-invasive interventions, pragmatically oriented to construction of rhizomatic networks of new urbanities.

AIMS & OBJECTIVES

In this new dimension that Alain Touraine defines as "post-social", it is necessary to redefine the methods and tools of the project through a new and hybrid approach in which both the global economic actors and the new subjects that are emerging in our society can coexist. Ethical *informal communities* united in individual subjectivities [3], which create flows of opinions able to change our lifestyles with a typically *glocal* [4] approach, thanks to the new tools of technology.

This approach establishes the temporary end of architecture as an autonomous thought. And this is not a novelty in architecture. Aldo Rossi has already confirmed architecture in history and its elements, just as for Robert Venturi architecture is communication and can recover the expression of latent cultural values within a given social group and translate them into symbolism historical, or for Peter Eisenman architecture finds confirmation in a language endowed with a structure and syntax proper to the semiological linguistic theory.

Consequently the architectural thought in this continuous and amplified flow of the "social types" and of their multiple instances, cannot avoid the attempt to understand their needs, nor limit themselves to a realization of only response to quantitative dynamics, but must be able to activate qualitative processes that can respond to the needs of a multiple and mutant contemporaneity: only in this way will it be possible to carry out interventions capable of satisfying the different and heterogeneous needs of society.

The replacement, in contemporary design, of the closed idea of composition (the exact and designed establishing of parts) with that of "system" (an "open" mechanism or ideogram vector, capable of favoring varied combinations and different formal manifestations), is one of the first examples of paradigm shift. [Habraken, The structure of the ordinary].

The architectural system of function, or the post-modern concept of exaltation of the concept / design born from a totally personal approach, is opposed to the systemic organization. The new architecture is defined and made comprehensible through non-Euclidean canons, through a process logic of the organization of relations with the different elements present: information, communication, temporariness, spaces and their conditions, the topographic and morphological type, historical, community values, activities, proximity and reciprocity.

The concept of processualism that can be declined through strategy is assumed as a paradigmatic element for the contemporary architecture project: processualism understood as a plan of actions conceived and designed to achieve a particular objective, identifies the goals and direction of the project that is accomplished through a series of actions /instruments. A strategic approach that allows us to respond over time to the ever-changing and increasingly accelerated programs that the mutation space will undergo over time.

The architectural project is called to contaminate its theories, methods and strategies in a new project method that is a strategic approach inclusive of the changed cultural, social and architectural scenarios closer to the circularity, to the recovery of resources and existing spaces.

Circular system [5] that in architecture declines, unlike the linear one characterized by the continuous consumption of soil and resources, in a vision determined by the containment and arrest of this consumption, in which sustainability is not only understood as a technical element but above all modus operandi, immanent value, to collect and decline the multiple instances, with particular regard to environmental and social ones and in which it is necessary to introduce different methods and tools typical of the architectural project.

It is therefore necessary to include the architectural and social "waste" in the process of mutation in order to carry out a process of overall regeneration of the degraded spaces. (Figure 4)

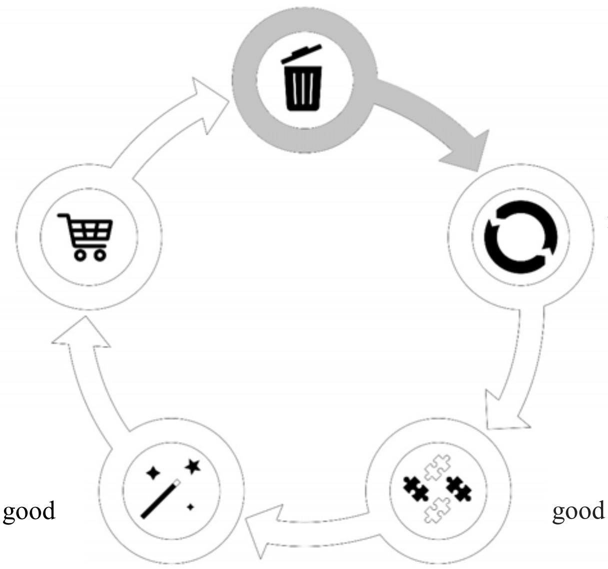

Figure 4. Circular design process

These conditions lead to a set of interventions on the city and its architecture that is no longer unitary, but fragmentary, with the conviction of reinterpreting and creating a new link with the specific context, based on a new agreement between architecture and sociality.

Working on the already built, on the memory of the pre-existing, with the figures of re-conditioning rather than with those of infinite growth, seems the most convincing way for contemporary architectural thought.

In order not to run the risk of operating with considerations that include large-scale problems, it becomes fundamental to define a reflection of necessity that is implicitly identified in the relationship between theoretical thought and action in architecture.

The main objective becomes the definition of a new design method, sustainable and circular, reversible and adaptive, able to involve the different communities and socialities in the project system, as well as the different spatial scales of the built, urban and architectural, through:

- *The use of a circular strategy based on the re-conditioning of the existing recognizing a current value to the current waste;*
- *Involve in the project the opportunities present in the urban fabric, recovering them in a system logic and making them accessible to the community, making them new polarities capable of bringing regenerative phenomena into the internal fabric, using new tools to redefine housing and elements such as compatibility between ethnic groups, waste and consumption;*
- *Redefining the limit by changing it into a margin, so as to take on the role of a meeting interface between the new and different socialities and between the internal / external spaces of the housing generating a new perceptive value and elements of energy containment;*
- *The use of the "technical vacuum" between buildings as an element of "environmental restoration" through urban-farming, densification of trees and needs identified by the community*
- *to expand the public portion of the buildings, "inserting", on the blind sides "parasites" able to allow "disadvantaged" social groups the use of a "temporary" shelter.*

A circular, adaptive process system that defines its operability through the architectural project.

METHODOLOGY

Re-conditioning therefore becomes both a theoretical assumption and the operational purpose of the discussion, but also that "relational" system of connection of the differences is that symbolic element able to highlight and emphasize the sustainable change of linear to circular system. [6].

Theoretical assumption as it defines a new explanation of the relationship between the existing and the new, from the scale of architecture that of the anthropized landscape, passing through the city, through *"an attitude proper to architecture to adaptation, to subversion, to the reinvention, to dialogue with one's own time, and the call to measure on new conditions the search for new attitudes"* [7].

Operational purpose since it is based on the response to the opportunities of mutation of existing architectures and spaces, in which ada ptive intervention tools are defined that are able to change, adapt and rename the existing and change the gap in value.

The intervention on the "discarded" architectures of the city, becomes *a pretext*, in its sense of non- substantial ornamentation (the Latin *pretextum*), an occasion for the

launch of social sharing platforms, premise, *pre-text* of a new social and urban story, able to favor the transfer of interest (transference) from the technological object of the *virtual community* to the place of life of the real community.
Using re-conditioning as an overwriting operation and known practice means starting from the analysis of the typical elements of the new forms, even virtual, of community and sociality and of the physical element, building or space and defining a design system of the discarded spaces of the city.
Operating through a procedural system, understood as a plan of actions designed to achieve a particular objective, identifying the aims and direction of the project that is accomplished through a series of actions / tools, allows us to answer a series of questions on the history of the single building or specific part of the city occupied by the community. Verify if it has a historical testimonial value or belongs to a minor vocabulary, if the collocation in the context, both urban and landscape, suggests possible relationship scenarios, if the insertion of new needs is possible in relation to the existing structure / space, if the mutation operation is sustainable both socially and economically, they become the cornerstones of the process.
Re-conditioning as a new paradigm is rooted in contingencies, and is the occasion for the definition of tools and techniques belonging to one's own cultural system of mutation of the existing which, recognizing a dimension of history in which the relationship space time is not reduced only to the present, it moves between the recognition of necessity and the search for a new definition of expressive tools capable of giving a different answer to the relationship between *"notum"* (in the meaning of finding what we have buried and forgotten or “discarded") and *"novum"* (in the sense of inventing "what is proposed and required) [8], and it is proposed as a new paradigm for the architectural project.
This strategy becomes a tool for mediation and contamination between pre-existence, heritage, identity and new ways of interaction, organization and participation of people, gathered in the Community, in a "shared" space.
New application tools are defined to be able to investigate and work with existing tools. heritage and left in dismantling in our cities, which are the theoretical and disciplinary nucleus of architecture and to allow us to regenerate what is today abandoned or discarded, leading to functional, structural and aesthetic obsolescence.
“[…] *to look at architecture as an achievement on the world of our life that translates and specifies through the project. Architecture asserts itself according to its own expressive means, affirms itself in the culture of its own time: it is an expression of change, but jointly offers itself through the resistance of the place of its establishment and its necessity to relate to the context*” [9].
The design process proposed in 2003 by Stephan H. Haeckel, *Adaptably loop* [10], is the methodological starting point of the procedure. It is based on the multidisciplinary of knowledge and content and on the synergistic interaction between all the components. Based on four points, the *Sense*, the *Interpretation*, the *Decision*, the *Act*, for Haeckel the process allows intersections and interactions between different knowledges. The application of this design process evolves into a personal interpretation of the four points with a fifth one: The *Outcome*. However, the Haeckel process applied to the various complexity of the phenomena typical of the contemporary leads to reconsider the original reading of the contaminations between the many and

infinite stories of the social and architectural elements that define the design. They relate, intersect, hybridize, allowing a continuous "adaptation" to the fast and changing conditions of the project itself.
The *Sense* becomes a field of action to work and try "*to break the vicious circle that links the growth of empathy with the increase of entropy*" [11]. The *Interpretation* outlines the elements of the process. The *Decision* defines the intervention strategy through the elements of the circular and adaptive process. The *Act* determines the operational tools to implement the strategy. The fifth one, the *Outcome*, is the result of the application of the tools. (Figure 5)

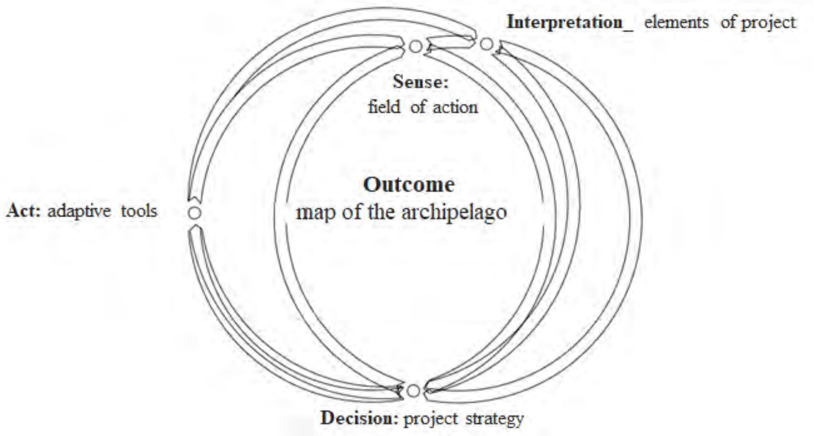

Figure 5. Circular design process

***Sense**: area of intervention*

The planned *re-conditioning* operation does not require a revolution, but rather a reorganisation, limited to repairing the spaces rendered unusable by time and introducing a new design system that uses adaptive tools. It is a whole series of actions that imply an accurate documentation of the architectural and social state of art. Not only as a support element of the architectural concept, but as a true reference tool for the constitution of the architectural project, the economic program, the relationship with the inhabitants and the management of the intervention.
This proposal arises from the need to practice a new vision of the operations of reconversion and mutation. A vision that arise awareness to the re-conditioning not as an outcome, but as a process, constant and continuous, in which the role of the architect changes from being a pure technical of the project to a strategist architect, skilled amanuensis of *urban overwriting*.
A consequent device of integration between what exists and new insertions, implemented with the logic of minimum intervention and translating the circular system into the entire design process and not just as "technological sustainability" or re-assembly (re-cycle) [12] of components used in other contexts or uses. A design strategy based on punctual urban insertions able to revitalize the object itself first and then the whole surrounding area through an osmotic principle. This strategy can be implemented gradually, even temporally, step by step, area by area, through clusters; it can be realized starting from a small space with simple interventions able to gradually transform it and redesign the area.

Interpretation: *Elements of the process*

It is therefore intended to *re-condition* part of the existing, starting the mutation of the neighborhood starting from the mutation of housing through light, temporary insertions able to allow continuous mutations in a continuous process of mutation able to satisfy the continuous and changing needs of family units and redefining the threshold space between inside and outside.
This relationship is the circular reinterpretation of the concept of boundary, no longer a line of physical separation but a band of overlapping cultures, ethnic groups, events, different tourism systems, mobile margins that are always in continuous discussion and mutation. The *margin* is an interface tool that is based on the concept of social and architectural proximity.
The social one is based on a new way of seeing the permanence of people within a group whose intentions are shared, and which include processes of integration. The architectural one is where the internal and external common spaces become an interesting complex of intents in the definition of a barrier. It is intended as a margin, threshold, which acquires thickness, and which is modulated to meet the different needs of use.
The *margin* is an element that refers to a variety of situations adjacent to something that is physically recognizable. Areas of proximity, hybrid interfaces, in which the social and intergenerational encounter takes place. It is a tool that captures the elements of permanence and memory to be privileged and actualizes new ones through which the project will develop.
No more boundaries, i.e. lines that mark a separation between different entities, or limit, which reinforces the concept of separation. A porous space between the elements of the "*relationship*": that conception of proximity between people and things that can generate and generate an identifying space between the different entities that make up the scene. The *margin* as an interface then becomes the instrument with which to communicate and the space where the different social and architectural realities that make up the scene meet.
Decision: *project's strategy*
The main concept behind this method is the architectural and social **resilience**. **Resilience** is the ability of a system to restore conditions following a high impact event by adapting to change. This capacity is expressed through an innovative method underlying the circular project system.
In this way, referring to those scientific investigations that reveal how natural structures "evolve in the context", as complex adaptive forms, it was decided to change and intervene on existing buildings and not to perform a demolition or a replacement operation.
Likewise, as natural systems present a diversity and redundancy, have an interconnected structure and have the ability to "self-adapt" the distribution of structures is on scales so the project system has tried to resign the same characteristics in the field.
It is proposed to shift the emphasis from the pure building, object of design, to an element of transit for a social change: the intervention becomes an opportunity to start sharing platforms, the premise of a new social and urban story through the introduction of a new urban alphabet, new tools, minimal interventions.
Act: *Adaptive tools for urban overwriting*

The adaptive tools used have been applied to the architectural scale and define a new urban alphabet of minimal interventions: a reconfiguration with light elements, temporary housing, to equip them with all those services that contemporaneity requires. The pre-existing heritage, the field of identity, becomes the field of action of the social and architectural project; their relationships, the selection that will be made on the existing elements will trace new hierarchies and allow the introduction of new tools for sustainable mutation.
The tools, precisely because they are child of a strategy and not of a language, will have the characteristic of being "adaptive" with respect to the project, that is, able to satisfy the possible reconfigurations over time. (Figure 6)

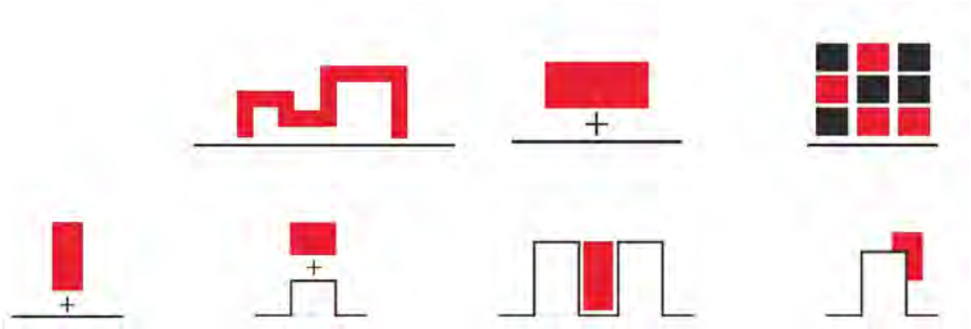

Figure 6. Urban alphabet of minimal interventions

So we work through a series of juxtaposed figures, hybridized together to interpret the previous layers and introduce new ones
The strategy therefore uses adaptive tools that include interventions on different scales and on different spaces:

- **Grafting** [13], In their original configuration, the lodgings were organized in all the buildings and on all the floors according to an identical basic structure. Room elements, usually of a square shape, are connected directly in simple or in double row, separated by a central wall.
  With the use of new tools and the inclusion of new elements, we preferred to create spaces without a precise destination, adaptable to different needs in space and time that do not define a function a priori but are subject to the hybridization of living and working in the contemporary. Temporality is the central element.
  In this way it has been possible to create a mix of housing divided in all different layouts into the same building organism, usable by a various type of users.
  The new simplex and duplex accommodations were then designed interconnecting rooms and were articulated using light elements positioned by the user according to their life styles to detail the spaces without a defined use.
  That includes the kitchen block, only two different types of bathroom, a single type of staircase for the duplex, only two groups of cabinets made with light "temporary" and "reversible" wooden parts. (Figure 7)

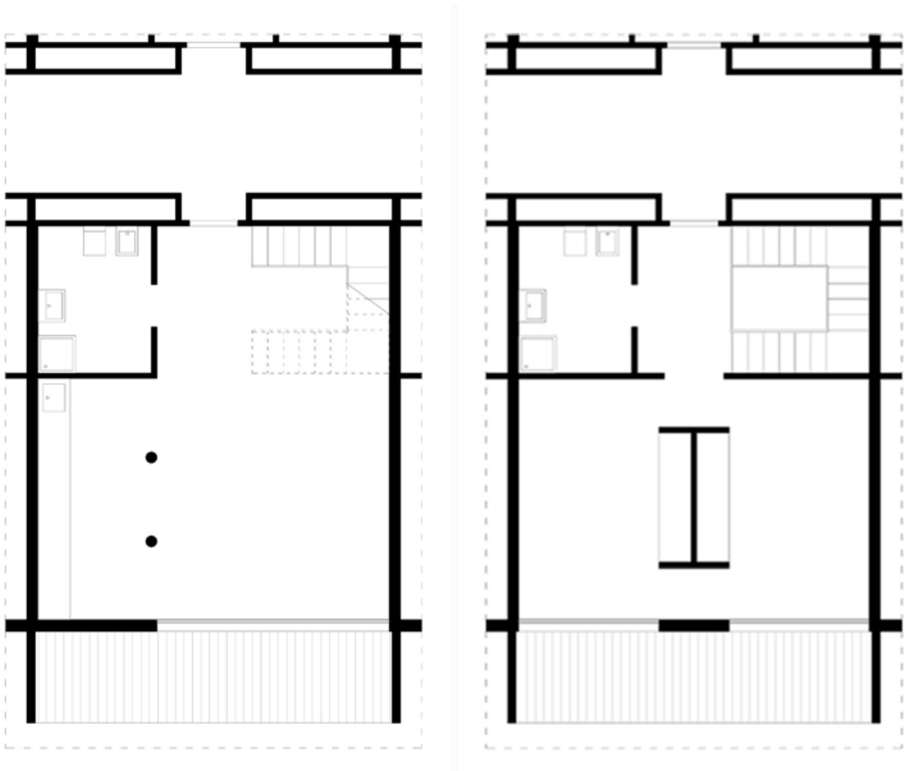

Figure 7. new housing configuration with both the new "boxes" and the "parasite" inserted

- At the same time, it will also operate on the main facades, making the external walls completely windowed where a "parasite" will be "inserted". The idea of the residential building is hybridized, eliminating repetitiveness and enhancing self-adaptation. In this way, rather than creating collective interpretations of individual life models, we have tried to achieve prototypes that represent individual interpretations of the possible collective models. This interaction was made possible through a communication with the inhabitants mediated by the social facilitators, who have rather openly suggested the pressing need for a new and mutable organization of living space;
- **Parasite** [14], operating on the faces of buildings by inserting a new element with its own structure that allows a different perception of the external space. To this new internal configuration we can think of adding a new mediation space between the interior and exterior of the buildings, building a new space on the long facades of the buildings, opening, where possible, the existing external walls, composed of an autonomous frame, able to define new “covered or uncovered” spaces, which allow a greater surface area of the lodging, to relate to the external space, but also to interface as an element of bio-climatic management bringing warmth during the winter months and mitigating the sun during those summer. This parasite, with a mixed wood-cement structure, will have glass walls and will serve, as well as an element of "relationship" also as an element of energy management in the different months of the year. On the blind sides a similar autonomous structure in steel or wood / cement can be inserted, able to accommodate small cells for temporary housing or for homeless. (Figure 8).

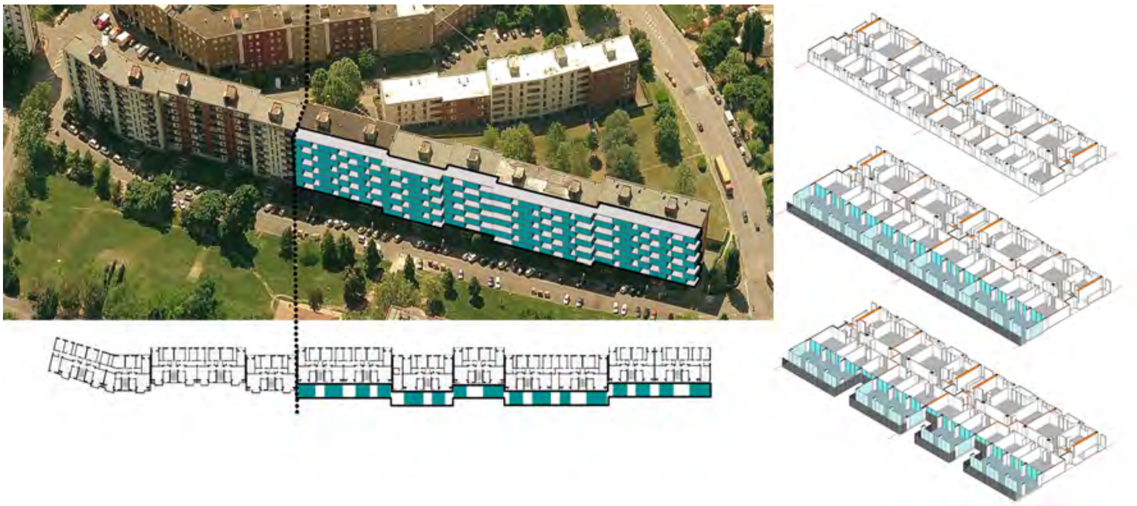

Figure 8. New configuration of building Pilastro Quartier in Bologna. New external parasite for to have a new margin. Right up existing above possible configuration of new margin.

- **In-between**, of the open space between buildings, which should no longer be understood as "generally green" but as a space where the community finds itself and dedicates itself to its own pastimes, to its sustenance through urban gardens, to the place where to insert plants to improve air quality: it must be "densified" by the community.
- **Level 0,** housing must be converted into hybrid spaces for the community. These spaces will have to find conditions of necessity with respect to the requests of the Community and will have to be translated into services for the same: such as, for example, small kindergartens where single mothers can keep children for those who work, small bicycle repair shops and local refills electric.

The design tools derive, in part from an interpretation of the typological classification system as an evolutionary and dynamic principle applied to spaces and situations not yet codified. Partly from adaptive logics to the use of a circular structure that changes and configures according to the conditions of the context.

Outcome: *map of the neighborhood Archipelago*

The result of this design method is to propose a regenerative intervention approach, able to promote the renovation of the existing and a quick configuration in continuous change, attentive to the city development. That makes the project adaptive to the flow of time, in harmony with the real, cultural and immaterial changes of the context. Working *in and with time*.

An operation managed with this methodological design approach will lead to the *real-time* reactivation of the social and building connection within the Residential Quarters, allowing over time that continuous overwriting of the space and therefore of the relationships between the people who would re-establish the waste today existing speed between the urban development of the city and the community. Working with the present Community, prefigures a continuous monitoring and interdisciplinary management system of the results able to guide future choices within the design process. As temporary and light, the use of adaptive tools will allow a stable reconfiguration in infinite possible solutions, in relation to the continuous and dynamic changes of those who live in the districts.

In this way a series of specific interventions will be set up which will form a *neighborhood archipelago* [15]. It determines a map no longer **outcome** of planned transformations, but fragmentary and solitary insertions deriving from the relationship between the strategic project and the progressive check-change following the needs expressed by the local community of the inhabitants.

The final result is therefore the great variety of possibilities to change the internal organization and the size of the housing since the households, mostly immigrant households, from a recent survey, are numerically larger. Working with and for the communities of residents allows users to become co-producers of the mutation and therefore share the project choices understanding and translating the needs.

The introduction of a new threshold space between inside and outside allows the user to relate to the common space and to have a platform space to be used: as an internal space it allows to have a closed, semi-closed or open space to be used according to the needs of the family; with regard to the external space it becomes the space in which the "technical void" of the modern is attacked, giving it a space of relationship between the different families and the outside. This type of intervention, at low cost, also allows to mitigate the temperature inside the house both during the winter months, when this space becomes an accumulation of energy, and during the summer months when it is a space of shadow and therefore mitigation and ventilation.

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Net-Zero Energy Housing Prototype for Low-Income Families

G. Ozcan-Deniz [1,*], R. Fryer [2] and
A. de Castro Amorim Ferreira [3]

[1] Associate Prof., Construction Management, Thomas Jefferson University, Jefferson-East Falls Campus, Philadelphia, PA, 19144. +1 (215) 951-2914, Gulbin.Deniz@jefferson.edu.
[2] Associate Prof., Sustainable Design, Thomas Jefferson University, Jefferson-East Falls Campus, Philadelphia, PA, 19144. +1 (215) 951-5634, Robert.Fryer@jefferson.edu.
[3] MS Sustainable Design Student, Sustainable Design, Thomas Jefferson University, Jefferson-East Falls Campus, Philadelphia, PA, 19144. amorimferreira1606@students.philau.edu.
* Correspondence: Gulbin.Deniz@jefferson.edu ; Tel.: +1 (215) 951-2914.

ABSTRACT

Sustainability approaches in the U.S. and around the world have motivated builders to offer net-zero energy capable houses. Yet, green homes are still considered expensive alternatives to conventional designs. With the improvement of green technology, costs associated with materials, technology, labor and whole building approaches can be decreased to achieve high levels of energy efficiency even in low-income neighborhoods. A prototype for net-zero energy is needed to keep the residential housing industry sustainable and repetitive. This paper proposes an affordable and energy-efficient design for a low-income rowhouse in Philadelphia, which has the highest poverty rate in the U.S. The key features of the prototype are the combination of an efficient building design with onsite power generation, water conservation and rainwater harvesting features. With this unique design, residents will have the opportunity to contribute to a healthier neighborhood economy by investing their savings locally, without jeopardizing the comfort and functionality of a typical housing unit. The results showed that the proposed prototype has a payback of approximately just over 16 years. Although this seems considerably long, the life-long affordability and sustainability will continue with the ongoing operating expenses that will be significantly less than a conventional residential rowhouse. This design prototype and approach to achieving net-zero energy in low-income neighborhoods can be replicated in other locations. Considering the added benefits (energy and water) that will continue after the payback period, the design can be a pioneer for low-income neighborhoods, although there is a limit to how small the rowhouse can be and still achieve a reasonable payback period.

Keywords: Net-zero energy housing; low-income and affordable housing; whole building performance; life cycle assessment.

INTRODUCTION

The United Nations (UN) has estimated that 60% of the world's population will be living in cities in 2030 (UN 2008). Considering the residences only in the U.S. are responsible for 20% of total U.S. energy consumption for heating, cooling, and lighting each year (U.S-HHS 2019), it is a necessity to focus on energy-efficient housing in metropolitan cities. "Green Building" emerged during the 1970s in response to increased fuel costs and environmental threats. Concerns over these issues lead environmentalists and architects to launch the green building movement (NaturalStoneInstitute 2019). Yet, a critical shortage in affordable and energy-efficient housing remains, especially among the most populous U.S. cities. In highly populated U.S. cities, like Philadelphia, affordable housing demand exceeds supply, which leads to rising prices in the housing market. Sustainable and affordable housing options would be a solution to the energy, emissions and affordability issues, while meeting quality, durability and sustainability targets for low-income homeowners (NREL 2012).

In Philadelphia's early Colonial period, residents began building row houses, which became the typical residential building type, designed by both anonymous Colonial craftsmen as well as by "the city's most distinguished architects" (Schade 2008). Rather quickly, these row houses became the typical residential building type due to being space-effective and cost-effective. Considering the need and benefits of sustainable and affordable housing, a prototype low-income green housing design in Philadelphia is proposed in this paper. The proposed net-zero affordable prototype is composed of two floors above ground, an accessible rooftop, and a basement to accommodate three people, which is the average number of people per household in this region of Philadelphia. The prototype design aims to be replicated as an investment in the future, where people live in a sustainable and efficient home with net-zero energy and zero emissions. The methodology consists of developing guiding principles and green goals to guide and measure the proposed low-income green housing design. Design development is performed with certain restrictions in terms of location, use, sustainability goals and cost to achieve both sustainability and affordability in such an urban location.

BACKGROUND

A Net-Zero Energy Building, or Zero-Energy Building (ZEB) is defined as a unit producing its own energy and therefore not requiring additional energy from the grid. A ZEB produces enough energy to supply its annual energy consumption necessities producing it from renewable energy sources available onsite. The production of energy onsite allows for a reduction in the usage of energy generated from non-renewable sources in the building sector (U.S. Department of Energy 2015). Affordable energy-efficient houses come into the picture, where green building benefits and affordable housing goals intersects in literature. Green housing provides opportunities to achieve ZEB, as energy efficient products and properly insulated homes decrease utility costs (Boehland 2005). However, having higher first costs compared to conventional affordable housing remains a concern. Higher initial capital costs can demotivate developers to invest in green construction (Bradshaw 2005).

In order to combine the opportunities of energy efficiency and address the disadvantage of first costs, affordable green housing is highlighted as a low initial investment that provides opportunities during the lifetime of buildings. Although the majority of home owners states energy-efficiency as the most valuable green building property (BD+C 2006), there are additional positive impacts of green housing such as providing clean air to improve health and occupant comfort and decreasing asthma and similar conditions (FHLBA 2005). These benefits are more apparent for low-income and minority residents, who live in neighborhoods with higher rates of asthma and environmental health hazards (Pacheco et al. 2014).

According to HUD, from 2013 to 2015, the number of low-income renters in the U.S. grew from 7.72 to 8.3 million households. One of the reasons for this is the "shift from homeownership to renting across the nation" (Romero 2017, para. 5-7). Additionally, HUD reported that nationally 43% of higher income renters are occupying housing meant for low-income renters. Philadelphia's renting market is following the same trend, compounded by the fact that not enough new housing is being built to keep up with demand. Between 2000 and 2014 the number of affordable housing units in the city decreased by 20% (Romero 2017, para. 8), and Philadelphia would need 38,000 more residences (Romero 2017, para. 10) to satisfy the city's affordable housing demand.

Similar to other large cities, low-income housing is decreasing in Philadelphia. The city's low-income population is unable to afford higher rents and has fewer opportunities to find housing. Therefore, Philadelphia is trying to increase the number of affordable, green residential units. According to a recent study, the city is expected to add 18,863 residential units from 2015 until the end of 2019 (Romero 2017). Housing-related expenses are constantly increasing, and these expenses are taking up more and more of renters' take-home pay. One way to limit and even decrease housing-relating expenses is by constructing green buildings that generate their own energy. This study and the proposed design are created to address the need of energy-efficient affordable housing in cities, while focusing on the emerging recognition of their impact on healthy communities.

THE PROPOSED LOW-INCOME HOUSING DESIGN

The construction of an affordable and sustainable house in one of the poorest neighborhoods of Philadelphia will help to address poverty, one of the biggest social, economic, and cultural issues of the city. The *New York Times* created interactive maps based on Census Bureau data showing levels of poverty across cities in the United States (TheNewYorkTimes 2014). Philadelphia has very high poverty rates throughout the city. Kensington is one of Philadelphia's poorest neighborhoods with 68.6% of the population living below the poverty line. North Kensington is selected as the site location of the prototype rowhouse (Figure 1), and the design seeks to integrate the site context and the existing and historic residential architecture of Philadelphia within its proposed solution.

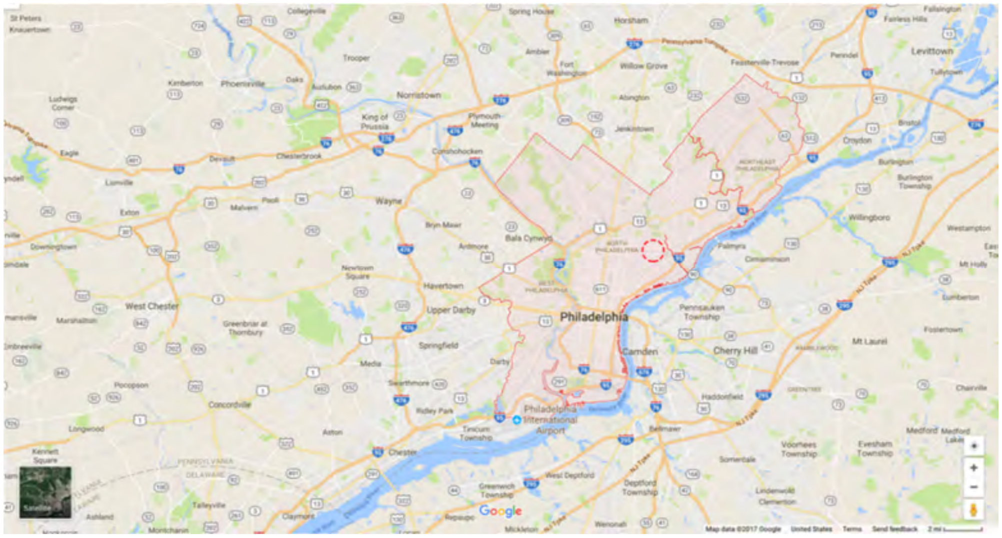

Figure 1. Location of the Site on the Philadelphia Metro Area Map

The site is located on Gransback Street. To the east, there is a large public park where a public library is located, and an elementary school is located just north of the street, as Figure 2 shows. The site is close to public transportation such as a subway and bus stops (marked with blue circles), has several mini markets (denoted with orange circles), and schools, Libraries and Churches (marked with green circles) in the surrounding area. Gransback Street follows the axis north south and is comprised of a neighborhood of two-story buildings.

Figure 2. Location of the Site on North Philadelphia Area

Site Inventory and Analysis

The site, as Figure 3 illustrates, is a rectangular plot approximately following the east-west axis. The site dimensions are 45 feet by 15 feet. The graphical site analysis, in Figure 4, shows the levels of noise and the wind direction in the summer, predominantly from the southwest to northeast, and during winter, which are predominantly from the northwest to southeast. The figure also illustrates the solar path.

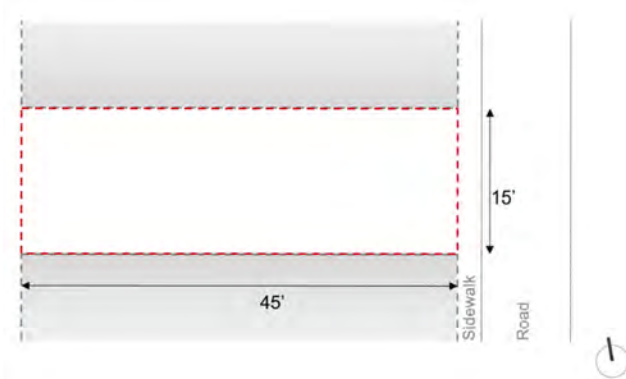

Figure 3. Site Plan

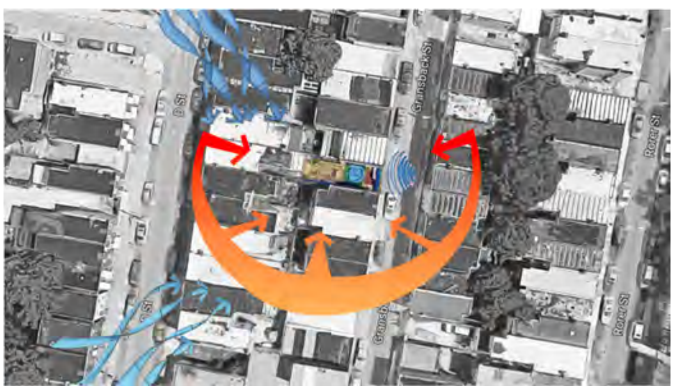

Figure 4. Site Analysis

Guiding Principles and Main Goals

Based on the site analysis, guiding principles for the design of the prototype rowhouse are set as follows:

- Have a healthy interior environment with minimal monthly cost in utilities, saving water and energy and using recycled and recyclable materials for construction
- Design with the climate to save and conserve natural resources like water and electricity
- Contribute to creating a pleasant view of the street and help to provide a better and healthy environment for the residents

- Improve affordable construction quality building in the neighborhood
- Incentivize the community to save money on utility bills and help improve neighborhood economy
- Create a prototypical housing unit that can be replicated in other places to stimulate social and economic development

These guiding principles establish touchstones that will be followed during the project development. They are used to guide design decisions and will ensure that the final project matches with some ideas set prior to the project such as research and identified problems.

Benchmarks are established to be used as reference points that will help to reach a positive final result. Benchmarks are usually existing standards to which the project could aim to match or can provide reference for how well the project performs. The United Nations set seventeen (17) Sustainable Development Goals to “end poverty, protect the planet, and ensure prosperity for all” during the next fifteen years (UN 2015). Eleven (11) of the Sustainable Development Goals are adopted in this study to serve as Benchmarks for the proposed project:

1. No Poverty
3. Good Health and Well-being
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation and Infrastructure
10. Reduced Inequalities
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
15. Life on Land

Other considered Benchmarks for this project are:

- Energy Use Intensity (EUI) of 19.72 kBtu/sf/y
- Renewable energy sources
- Be energetically off grid
- Passive House standard

The EUI benchmark of 19.72 kBtu/sf/y is from the Mission Zero House, a Living Building Challenge house is located in Ann Arbor, Michigan, USA. This house is a single-family home located in a cold climate. It has a building footprint of 870 sf, 2 floors, and a total area of 1,500 sf. This house uses only 8,939 kWh/y in electricity annually and generates more than the energy it needs, actually giving back to the grid about 295 kWh/y (Liljequist 2016).

In order to achieve the best possible results, the project set out a series of goals. In Table 1, the goals for achieving a Net Zero Affordable Housing in Philadelphia are proposed:

Table 1. Goals

Experience Create a house where people would like to live in	**Facts/Performance** Be net zero energy Use 100% of harvested rainwater Produce 100% of energy on site
Culture Improve residents' and neighborhood quality of life	**Systems** Have a water treatment system Generate energy through photovoltaic panels

The Prototype Design

With the goals in mind, this rowhouse will have two floors above ground, an accessible rooftop, and a basement. The Basement occupies the entire footprint of the building and contains all of the mechanical equipment. The first floor has a front porch followed by the main entrance, and an open floor plan with the living room and kitchen. On this floor, there is a courtyard in the back. The backyard exterior space is a common quality of Philadelphia's row houses. The front porch will provide a cultural asset "offering an enjoyable as well as safety-enhancing vantage during nice weather" (Schade 2008) and support neighborhood community social interaction development. The second floor has two bedrooms facing the front and the back of the house, and a bathroom in between them. Finally, the house has an accessible rooftop. The use of each space and areas are presented in Table 2.

Table 2. Use of Spaces and Areas

Location	Space	Area (SF)
Basement	Study Room	146
	Bathroom 1	42
	Mechanical Room	144
First Floor	Front porch	75
	Living Room	162.5
	Kitchen	208
	Backyard	150
Second Floor	Bedroom 1	131
	Bedroom 2	82.5
	Bathroom 2	42
Rooftop	Accessible Roof	357
Total		1,530

This row house project will adopt the same envelope exterior materials, using the same commonly used brick on the façade in order to integrate as much as possible with the existing architecture. An example exterior elevation of the prototype building and the Site Plan is presented in Figure 5.

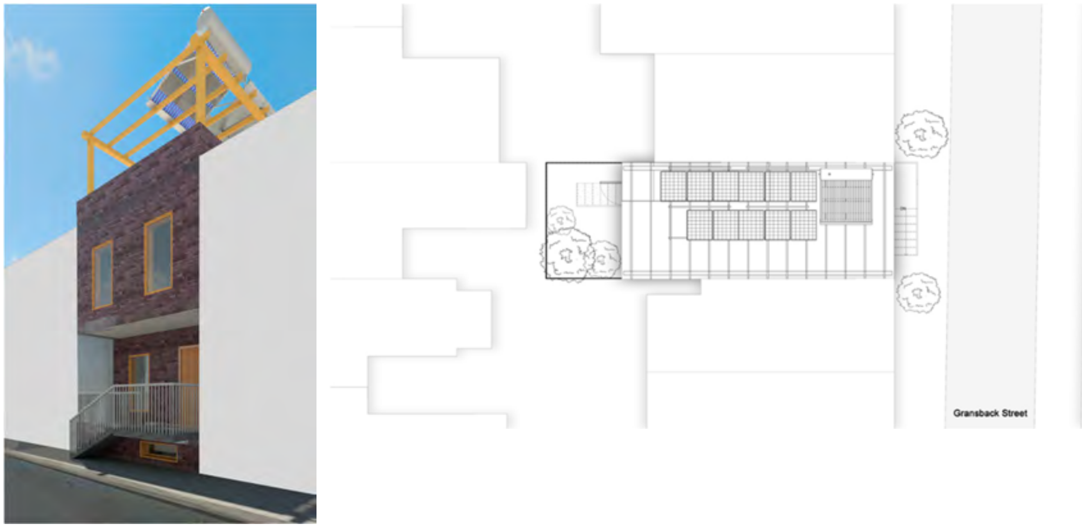

Figure 5. a) Exterior East Façade Perspective b) The Site Plan

ANALYSIS AND RESULTS

The process starts with a baseline model and develops until it reaches a high-performance building. This process will develop a building that is code compliant and study the effect each performance improvement has on energy usage. The baseline and high-performance building models are generated with assemblies available at Athena Sustainable Materials Institute (Athena Sustainable Materials Institute 2019). Athena Sustainable Materials Institute is an online tool that provides Life Cycle Assessment (LCA) software for each building assembly according to the materials used in each one. This software analyzes the environmental impacts of materials using these categories:

1. Fossil Fuel Consumption – The estimated amount of fossil fuel energy used in the extraction, processing, transportation, construction, and disposal of each material. Measured in megajoules (MJ).
2. Global Warming Potential – the estimated amount of greenhouse gases created. Measured in moles of hydron (H+) equivalents.
3. Acidification Potential – the estimated amount of acid-forming chemicals created. Measured in moles of hydron (H+) equivalents.
4. Human Health Criteria – the estimated amount of airborne particles that can lead to asthma, bronchitis, acute pulmonary disease, etc. Measured in mass of 10 micron particulate matter.
5. Aquatic Eutrophication Potential – the estimated amount of water-nutrifying substances that can lead to the proliferation of photosynthetic aquatic species. Measured in mass units of Nitrogen equivalents.

6. Ozone Depletion Potential – the estimated amount of ozone-depleting substances (CFCs, HFCs, and halons) created. Measured in mass units of CFC-11 equivalents.
7. Smog Potential – the estimated amount of chemicals that could produce photochemical smog and ground-level ozone when exposed to sunlight. Measured in mass units of ozone equivalents.

The baseline model building assemblies are chosen for being the most environmentally friendly, or with the least LCA impact, using assemblies available at Athena Sustainable Materials Institute. The description of each assembly type is shown in Table 3. The assemblies in the baseline model are further analyzed with several iterations of a series of improvements in the building envelope and some interior elements and systems, to reach the most feasible and energy-efficient option for the high-performance building model.

Table 3. Baseline Model Assemblies

Assembly type	Materials
Foundation wall	8" Cast-in-Place Vapor Barrier
Foundation slab	4" Poured Concrete slab
Footing	Poured Concrete footing
Intermediate floor	Wood Joist w/ OSB Decking (uninsulated) Vapor Barrier
Exterior wall	Clay Brick Cladding w/ 1" Air Space R13 Cavity Insulation Weather Resistant Barrier ½ Gypsum Board + 2 Coats Latex Paint
Windows	Aluminum – Operable Low-E, Argon Filled
Interior walls	Wood Stud 2x4 16" o.c. ½" Gypsum Board 2 Coats latex Paint
Roofs	Wood Joist w/ OSB Decking Asphalt Shingles, Fiberglass Felt based, 20 year R38 Cavity Insulation ½" Gypsum Board + 2 Coats Latex Paint

The 3D model of this rowhouse is completed using Revit software. Green Building Studio is a Revit plugin that runs "building performance simulations to optimize energy efficiency and work toward carbon neutrality" (Autodesk Green Building Studio 2013). Green Building Studio runs energy analysis "under ANSI/ ASHRAE Standard 140, Standard Method of Test for the Evaluation of building Energy Analysis Computer Programs and Certified by the U.S. Department of Energy" for all assemblies including Heating, Ventilation, and Air Conditioning (HVAC) units.

Table 4 has detailed information on all the data collected throughout the energy analysis, from the baseline model until the model that has a better energy performance. For a high-performance building, the assemblies are different from those of the baseline building. These assemblies, in Table 5, were chosen for being the most energy efficient, which could increase the overall thermal performance of the building.

Table 4. Detailed Summary of EUI Results for All Models

Model	EUI	Fuel		Electricity			Fuel (%)			Electricity (%)					
		kBtu/sf/y	%	kBtu/sf/y	kWh/sf/y	%	Space Heating	Hot Water	Misc. Equip	Pumps & Aux & Fans	Space Cooling	Misc. Equip	Lights	Heat Pumps	Space Heating
Baseline	63	34	54	29	8	46	90	10		61	11	11	17		
Interior Walls	63	34	54	29	8	46	90	10		61	11	11	17		
Basement Slab	61	32	52	29	9	48	89	11		61	11	11	17		
Basement Walls	58	28	49	30	9	51	87	13		60	12	11	17		
Exterior Walls	52	22	43	30	9	57	84	16		60	12	11	17		
Roof	51	22	43	29	9	57	84	16		60	12	11	17		
Window size decrease	53	21	39	32	10	61	83	17		60	15	10	15		
Window size increase	51	22	43	29	9	57	84	16		60	12	11	17		
HVAC 1	38	4	10	34	10	90		98	2	43	10	10	15	4	18
HVAC 2	35	3	9	32	9	91		98	2	44	9	10	15	5	17

Table 5. High-Performance Model Assemblies

Assembly type	Materials
Foundation wall	8" Cast-in-Place R10 Polyisocyanurate Foam Continuous Insulation Vapor Barrier
Foundation slab	4" Poured Concrete slab
Footing	Poured Concrete footing
Intermediate floor	Wood Joist w/ OSB Decking R19 Cavity insulation Vapor Barrier
Exterior wall	Clay Brick Cladding w/ 1" Air Space 3 ½" Structural Insulated Panels (R19) (SIP) Weather Resistant Barrier ½ Gypsum Board + 2 Coats Latex Paint
Windows	Vinyl clad wood Filled Low-E, Argon Filled
Interior walls	Wood Stud 1 5/8 x 3 5/8 24" o.c. ½" Gypsum Board 2 Coats latex Paint

Roofs	Wood Joist w/ OSB Decking Asphalt Shingles, Fiberglass Felt based, 20 year R38 Cavity Insulation ½" Gypsum Board + 2 Coats Latex Paint

The LCA Analysis is performed with The Athena EcoCalculator for Residential Assemblies for both the baseline and high-performance models. Some assemblies increase their environmental impact, in the high-performance model such as how the change in foundations increase the ozone depletion potential (Figure 6), while other assemblies, like windows, decrease the negative impact on the global warming potential even more. It is an unexpected result to have higher levels of ozone depletion potential in the high-performance model.

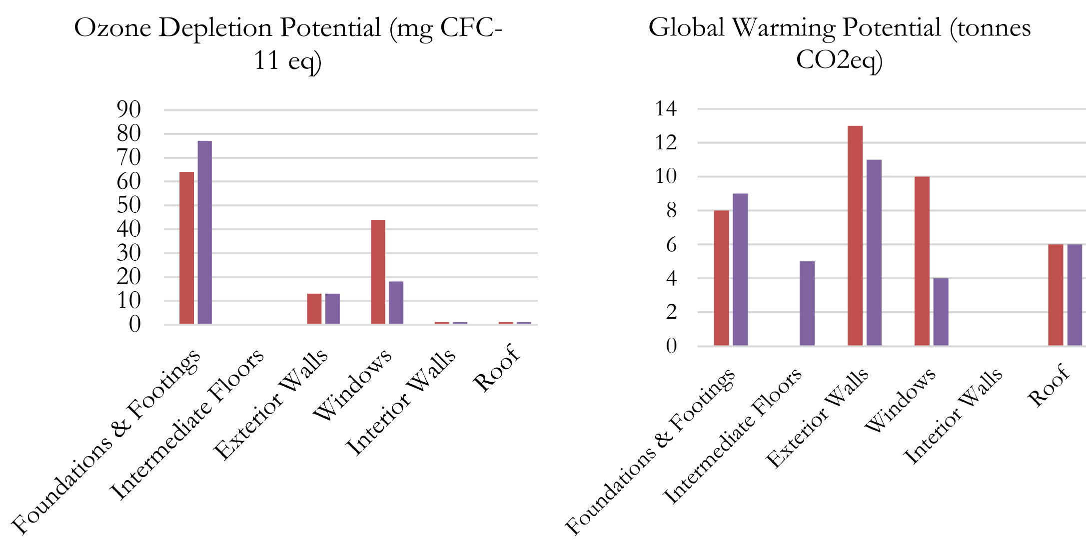

Figure 6. LCA Comparison between Baseline and High-Performance Models

A water consumption analysis was performed for both baseline and high-performance models. The water consumption of the efficient fixtures is compared with the baseline water consumption and the total water saved is about 10,828 gallons a year, which corresponds to 25.53% water saved. Additionally, the proposed house design will harvest rainwater to be used in the toilet, the lavatory faucet, the shower, and the washing machine, all of which are fixtures that do not need to have potable water.

The next analysis is on renewable energy sources. Solar panels increase savings on utilities bill, and at the same time generate their own clean energy. In Philadelphia, a household can save monthly $81/month using energy generated from photovoltaic panels (SolarNation 2019). According to Solar Nation, the price of solar panels is decreasing each year (since 1998, PVs' price has dropped 70%), making solar a more affordable choice.

The National Renewable Energy Laboratory (NREL) Photovoltaic (PV) Calculator is used to calculate the energy produced using of photovoltaic panels installed on the pergola is. According to NREL PV Calculator, the area available to install the panel would generate about 8,001 kWh/year (NREL, PVWatts Calculator 2019). The array of panels is fixed, facing south, and tilted about 20°. The area available to install the array, without the area of the heat water system flat plate collector, is about 465 SF, which gives a total of 17.20 kWh/sf/y of electricity produced. According to Table 6, the energy need is 9 kWh/sf/y, meaning a 91% surplus of energy is potentially being produced.

Table 6. Part of Detailed Summary of EUI Results for All Models

Model		Fuel		Electricity			Fuel (%)			Electricity (%)					
	EUI	kBtu/sf/y	%	kBtu/sf/y	kWh/sf/y	%	Space Heating	Hot Water	Misc. Equip	Pumps & Aux & Fans	Space Cooling	Misc. Equip	Lights	Heat Pumps	Space Heating
HVAC 2	35	3	9	32	9	91		98	2	44	9	10	15	5	17

To know if the proposed residential unit is actually considered affordable or not, a cost estimate was conducted. To make this cost estimate, the publications Assemblies Cost Data (RS Means 2013) and Green Building Cost Data (RSMeans 2012) were used. The total cost of this building is $203,779.30, or $133.19/sf. The green building cost estimate includes greener materials and assemblies when compared to the baseline building. The total cost of the proposed green building is $231,658.54, or $151.41/sf, which is a 14% increase.

For the Life Cycle Cost (LCC) analysis, the number of years that will be needed to pay the total cost difference from the baseline building was evaluated. Despite the green building being more expensive, the green building has features that will decrease the operational cost. One of those is the electricity demand. The amount of energy needed to be bought from public supply is lower than in the baseline building. With the first cost analysis, the difference between the cost of the baseline building and the green building was calculated as $27,876.60 ($231,658.54 - $203,779.30) and the difference in energy needed in both buildings was calculated as -8.21 kWh/sf/y (63 kBtu/sf/y – 35 kBtu/sf/y = 18.46 kWh/sf/y – 10.25 kWh/sf/y). According to Table 7, the estimate for payback is close to 17.20 years when the electricity rate is $0.1290. When the electricity rate becomes 0.1 cents more expensive, the payback is 17.07 years (0.13 years less than the previous one). However, the payback may still be shortened further.

Table 7. Payback Estimate

8.21	kWh/sf/y
0.68	kWh/sf/month
1,046.78	kWh/month

Electricity rate	$ 0.1290 2017 average USA	Distribution + Use $ 0.1300 2017 PECO
$ Utilities/month	$ 135.03	$ 136.08
Months	206.44	204.85
Payback years	17.20 years	17.07 years

Besides the estimated payback of the total cost, some of the sources (e.g., NREL) used to calculate the PV array to provide a cost estimate for each of those systems. Due to the excessive surplus of electricity generated by the PV panels, and in order to diminish the payback period, a reduction in the number of PV panels is planned to reduce PV panels from 20 to 11. To be able to analyze the savings achieved with the reduced number of PV Panels, a new estimated payback is calculated. Table 8 compares the number of payback years when the green building needs only 11 panels. The conclusion is that it is possible to decrease almost 1 year of payback just by adjusting the PV array size with the house electric needs.

Table 8. New Payback Estimate

8.21	kWh/sf/y	
0.68	kWh/sf/month	
1,046.78	kWh/month	
Electricity rate	$ 0.1290 2017 average USA	Distribution + Use $ 0.1300 2017 PECO
$ Utilities/month	$ 135.03	$ 136.08
Months	195.26	193.76
PAYBACK YEARS	16.27 years	16.15 years

CONCLUSIONS

This study proposed an affordable and energy-efficient design for a low-income rowhouse in Philadelphia, which has the highest poverty rate in the U.S. The key features of the prototype are the combination of an efficient building design with onsite power generation, water conservation and rainwater harvesting features. With this unique design, residents will have the opportunity to contribute to a healthier neighborhood economy by investing their savings locally, without jeopardizing the comfort and functionality of a typical housing unit. A set of guiding principles were defined to improve the health and well-being of the neighborhood, while designing a resource and energy-efficient building for low-income families. To fulfill the design goals in four quadrants, the following items are achieved:

- The house is creating a pleasant view of the street and helping to provide a better and healthy environment for the residents.
- The design encourages a heathy interior environment with a minimal monthly cost in utilities, saving water and energy and using recycled and recyclable materials for construction.

- The proposed design provides an affordable building in the neighborhood and saves money on utility bills. If replicated, this prototypical housing unit may stimulate local social and economic development.
- The house has a closed loop water system with rainwater harvesting and treated water, and is off grid generating its own electricity.

A series of tools were used to estimate the electricity generated on site and consumed in the building during the development of this design. These tools were used to generate building assemblies and perform the LCA and LCC analysis. Additional energy analysis is performed with the help of a 3D Revit model and Green Building Studio software from Autodesk. High-performance building assemblies were selected, and the baseline building was revised to reflect these. These assemblies were chosen for being the most energy efficient, which increased the overall thermal performance of the building.

The proposed high-performance prototype has a payback of just over 16 years. This design prototype and approach to achieving net-zero energy in low-income neighborhoods can be replicated in other locations. Considering the added benefits (energy and water) that will continue after the payback period, the design can be a pioneer for low-income neighborhoods, although there is a limit to how small the rowhouse can be and still achieve a reasonable payback period.

Limitations of the study include a lack of interoperability between the software applications used. Creation of assemblies, 3D modeling, LCA analysis, and energy analysis were performed in different software applications with manual transfer of data in between. It would be helpful to have a united software platform to ease information and data share between various software applications. Another case that can be pointed is the lack of choice in the available systems options in the 3D modeling software. Specially, when it comes to the use of Revit, the available options for HVAC systems, as well as more information about them need to be specified by the user for each case. The requirement of manual inclusion of information can reduce the variety in possible outcomes, especially when it comes to apply system-specific properties into real-life projects.

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Deep Renovation of the European building stock adopting Plug-and-Play solutions

E. Piaia[1], B. Turillazzi[2], R. Di Giulio[3], G. Bizzari[4], L. Ferrari[5], S. Brunoro[6]

[1] Professor, Department of Architecture, University of Ferrara, Via della Ghiara 36, Ferrara, Italy, 44121, +39.0532.293685, emanuele.piaia@unife.it
[2] Professor, Department of Architecture, University of Bologna, Via del Risorgimento 2, Bologna, Italy, 44121, +39.051.2093155, beatrice.turillazzi@unibo.it
[3] Professor, Department of Architecture, University of Ferrara, Via della Ghiara 36, Ferrara, Italy, 44121, +39.0532.293627, roberto.digiulio@unife.it
[4] President, Becquerel Electric, Via Emilia San Pietro 1, Reggio Emilia, Italy, 42121, +39.0522.706103, g.bizzarri@becquerel.it
[5] Engineer, Becquerel Electric S.p.a., Via Emilia San Pietro 1, Reggio Emilia, Italy, 42121, +39.0522.706103, l.ferrari@becquerel.it
[6] Professor, Department of Architecture, University of Ferrara, Via della Ghiara 36, Ferrara, Italy, 44121, +39.0532.293633, silvia.brunoro@unife.it

ABSTRACT

The European (EU) Energy Roadmap 2050 impose to reduce greenhouse gas emission to 80-95% below 1990 levels by 2050. Moreover the – EU Climate & Energy package introduced 3 main targets to achieve for year 2020: 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables, 20% improvement in energy efficiency. In this scenario, the building sector has been identified as one of the key sectors in consideration to the fact that buildings count for 40% of the EU's energy consumption, 36% of its CO2 emissions and 55% of its electricity consumption. In particular, 90% of the existing building stock in Europe was built before 1990 and exist an urgent need for a significant improvement of energy efficiency through "deep renovation". So, the main today priorities of the European Commission are to swiftly improve energy efficiency and decarbonization of the building sector. Deep renovation is the term coined by the Energy Efficiency Directive of the European Community (2012/27/EU) for defining economically advantageous building renovation interventions that make it possible to reduce the energy consumption of a building by at least 60% compared to the condition prior to the refurbishment.

The paper introduces the innovative methodology and techniques for the "deep renovation" of the European building stock promoted by the P2ENDURE research project funded by the European Union's Horizon 2020 research and innovation program grant number 723391. The project goal is to apply and monitor, on specific demo-cases, cost-effectiveness and energy efficiency renovating strategies proposing Plug-and-Play solutions. The prefab PnP technologies proposed regards building and Heating Ventilation Air Condition components and are supported by Building Information Modelling (BIM) to overcome the main barriers of deep renovation inside the building process. The paper presents: the P2ENDURE concepts; the PnP solutions used for the deep renovation; the main tools adopted inside the 4M process in order to assess the building condition before, during and after the renovation; the demonstration cases and finally the methodology to assess the energy saving target.

INTRODUCTION

The 28th of November 2018 the European Commission (EC) presented its strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050 (The Energy Roadmap 2050). The commitment is to reduce greenhouse gas emission to 80-95% below 1990 levels by 2050. One of the priorities to meet long-term climate and energy targets is to swiftly improve energy efficiency and decarbonization of the existing buildings stock.

This challenge follows the previous 2020 – European (EU) Climate & Energy package which is a set of binding legislation to ensure the EU meets its climate and energy targets for year 2020. The package has been sets three key targets: i) 20% cut in greenhouse gas emissions (from 1990 levels); ii) 20% of EU energy from renewables; iii) 20% improvement in energy efficiency. In this scenario, the building sector has been identified as one of the key sectors to achieve the "20/20/20 targets" of the EU and to meet "The Energy Roadmap 2050" in consideration to the fact that buildings count for 40% of the EU's energy consumption, 36% of its CO_2 emissions and 55% of its electricity consumption. Moreover, 90% of the existing building stock in Europe was built before 1990 and exist an urgent need for a significant improvement of energy efficiency through "deep renovation".

In order to meet these goals, the EU has adopted in the last years specific energy saving policies and directives. In the 2002 the EU issued the Directive 2002/91/EC on the energy performance of buildings. In comparison to the previous policies, this Directive introduced additional important topics such as: the need to adopt a calculation methodology on the building energy performance; the definition of minimum energy requirements; the adoption of specific energy performance measures for new and existing buildings. Recently, two other important Directives have completed the reference framework at European level. The Directive 2010/31/EU on the energy performance of buildings (EPBD) and the Directive 2012/27/EU on energy efficiency, which currently constitute the main European regulations on the subject (EU 2010, 2012). Among the most novel elements presented by the new Directives there are two important notions. The first concerns the concept of "nearly Zero Energy Buildings" (nZEBs), which emphasizes the need to reduce energy demand to minimum standards and use renewable energy to meet the remaining demand. The second is the introduction of the "Deep renovation" concept which means the important restructuring of the existing building stock as an energy saving strategy. However, the directive does not suggest any specific definition and transfers the task of defining a specification to the Member States. In this contribution an important restructuring is intended as a redevelopment capable of leading to an effective and high reduction of energy consumption, in relation to the pre-intervention status, for a minimum level of 60%. The deep renovation also implies a contextual improvement of the building comfort, healthiness, safety and usability.

Despite in the last years several building technologies has characterized and improved the sector of the building retrofit, the building deep renovation process is characterized by complementary barriers: economic (high costs, minimum public contributions and return on investment only in the long term), procedural (fragmentation of the production chain); regulations (differences between national and European requirements and guidelines) and technical (high complexity and extreme typological variety) (*Artola, 2016*).

H2020 P2ENDURE project (Plug-and-Play product and process innovation for Energy-efficient building deep renovation), presented in this paper, demonstrate that is possible to overcome these barriers adopting Plug-and-Play (PnP) solutions for deep renovation. PnP solutions are industrialized prefab architectural and MEP-HVAC components which simplifies on-site assembly, reducing construction time and costs.

The P2ENDURE research project started in September 2016 and will finish in August 2020. The project, financed by the European Commission with 4 millions of Euro (EU Programme H2020-EE-2016-PP_Grant Agreement n°723391) involve a multidisciplinary consortium composed by16 partners coordinated by the Dutch company Demo Consultants B.V.

P2ENDURE CONCEPT

A large number of innovative technologies and tools for deep renovation have become available in the last decade. In this field, P2Endure is working to resolve the main barrier for wide-scale implementation of innovative solutions concerning the absence of solid empirical evidence that such innovative solutions deliver the expected performance, both energetically and financially. The project provides evidence-based innovative solutions for deep renovation that are applicable and replicable for the widest range of building typologies.

P2Endure takes on a progressive principle:

- to build further on credible state-of-the-art solutions of 3D scanning and printing technologies in combination with prefab renovation systems;
- to develop modular processes for deep renovation through BIM-based design, engineering, production and installation for speeding up the implementation of the state-of-the-art solutions;
- to optimize and integrate the state-of-the-art solutions grounded in practical evidence of their performance through real deep renovation cases;
- to perform real deep renovation projects at a higher complexity level and with a larger performance impact than typical residential buildings through transformation of obsolete public and historic buildings.

This challenge is pursued by achieving five main aims:

1. to optimize, integrate and validate state-of-the-art prototypes and commercially available packages of PnP prefab solutions for deep renovation;
2. to demonstrate and promote innovative on-site processes for fast deep renovation projects with low disturbance for the residents, and significantly improved Indoor Environment Quality (IEQ) after completion;
3. to measure, monitor and validate P2Endure product and process innovations based on live demonstration projects of deep renovation, virtual simulation and prototyping;
4. to provide solid empirical evidence of the performance and quality of P2Endure solutions while ensuring their scalability and replicability at district, city, region, country and EU level,
5. to ensure the market uptake and upscaling of P2Endure innovations during and immediately after the project by directly involving ‘launch customers’, value-chain and distribution network partners, and other stakeholders at local, regional,

and EU level.

The innovative solutions for deep renovation are based on PnP prefabricated systems, combined with innovative technologies for the control and implementation of the intervention, such as 3D printing, advanced diagnostic techniques and Building Information Modeling (BIM). The integration of these solutions takes place by adopting a methodology, called 4M process, consisting of 4 main steps:

1. *"Mapping*". This step is dedicated to perform a condition assessment of the existing building, to measure the energy consumption as well as the IEQ before the renovation. This step includes the use of 3D laser and thermal scanning and other tools (e.g. comfort eye) to facilitate and improve the analysis. The purpose of the mapping is to develop a detailed technical plan and economic feasibility report for deep renovation, as a starting point for the renovation design.
2. "Modelling". This step is dedicated to create (if not exist) the As-Built BIM input for BIM-based renovation designing and Building Energy Modelling (BEM) for simulating the performance of viable renovation measures.
3. "Making". This step takes place both off-site and on-site. BIM is used for product engineering and in support of off-site prefabrication. In certain cases, BIM is used for on-site 3D printing with collaborative robotics. This step will result in improved, tested and implemented innovative PnP to be installed ensuring the P2ENDURE goal of 60% in energy improvement, 15% improvement in first cost, and an overall time reduction needed for completing a deep renovation.
4. "Monitoring". It is the final step dedicate to measure the building performance. This step is continuing throughout the entire life cycle of the building measuring the status of the energy and IEQ performance with sensors and control instruments whose data, connected to the BIM model, are compared and verified with those simulated in the design phase.

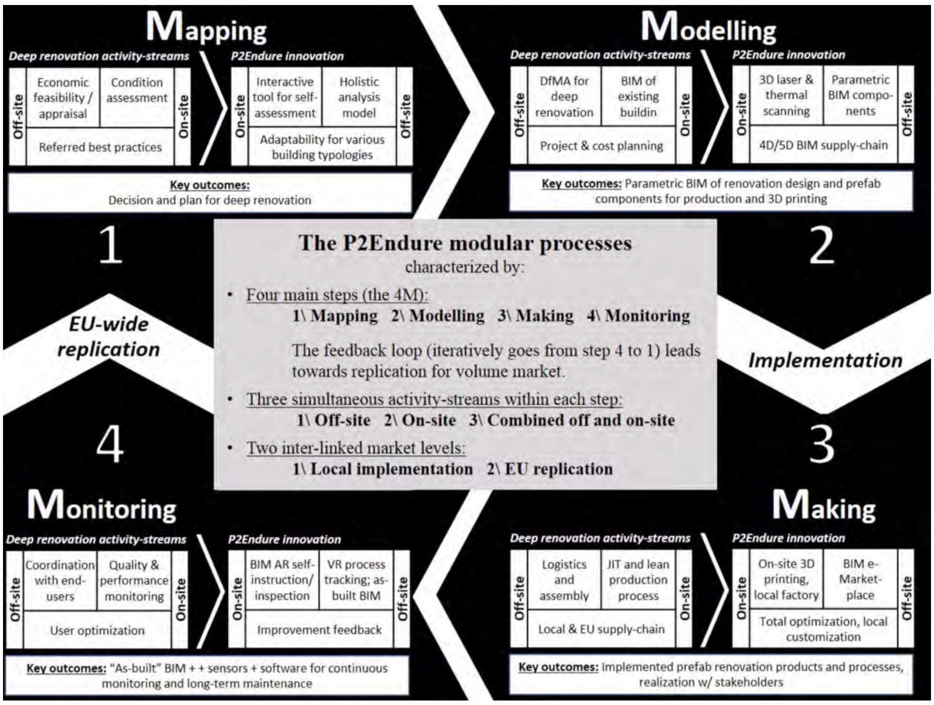

Figure 1. Scheme and flow of the 4M process adopted by the P2ENDURE

The 4M process is designed to allow for staged renovations. Through the iterative nature of the 4M process – the last stage monitoring directly provides the input for the first stage mapping – renovation activities can be spread out over a longer period (10-15 years) and a continuous energetic performance can be guaranteed.

P2ENDURE PLUG & PLAY SOLUTIONS AND TOOLS

Main scope of the introduced "Deep renovation" is to drastically reduce the building energy consumption. As presented, P2ENDURE follows this scope demonstrating that is possible to improve the building performance adopting PnP solutions and using specific tools inside the introduced 4M Process. The research consortium has analyzed advanced technologies allowing energy efficient deep retrofits (PnP prefab components), tools for the building assessment and/or real-time monitoring.
5 PnP prefab components have been selected in order to set-up specific intervention on the "building envelope":

1) *"FC multifunctional panel"*. FC multifunctional panel was developed by Fermacell. It is a versatile prefabricated facade panel composed from a wooden or steel substructure that will allow integrating of water ducts and pipes, air supply or/and even ventilation channels, heating and cooling functions. Within the P2Endure project Fermacell developed a construction kit "versatile PnP facade for renovation" that will be a solution for deep renovation of existing buildings.
2) *"EASEE multifunctional panel"*. The EASEE prefab panels are composed of two layers of textile reinforced concrete (1,2cm each) and insulation core between them made of expanded polystyrene (10,0cm). The total thickness of the panels is 12,4cm. The thickness of the insulation may be increased if needed. The width of the panel is in the range of 0,5m - 1,5m and the height 1,5m – 3,0m. The weight of the panel is around 54 kg/m^2. The anchorage system allows achieving flexibility and capability to adapt to different architectonic configurations and building typologies. When applied, these panels increase the thermal properties of the envelope after retrofitting (U<0.23 W/m^{2}K for retrofitted wall), reduced installation time by 50% in comparison with traditional retrofitting, high aesthetic properties that allows application of the solution to buildings under cultural heritage protection.

Figure 2. Example of PnP building component: multifunctional façade panel constructed by Fermacell

3) *"Smart windows"*. Windows designed by Bergamo Tecnologie, that can be rotated by 180° to reduce the thermal radiation from the outside during summer season and reduce the thermal dispersion from the interior in the winter, thanks to the double positioning of the low-E glass. The smart window provides natural ventilation, rotating and locking mechanisms which enhance anti-burglary features, as well as integration with domotics solutions. It satisfies the needs for high energy-efficiency, better indoor climate, and top-class security features. The reversible window technology is enabled by innovative hydraulic gaskets and burglar-proof electro-magnetic locking mechanisms fully integrated in the frame.
4) *"Rooftop retrofitting"*. Adding new dwellings on existing roofs increases the sustainability and lifetime of the buildings, at the same time reduces the energy consumption. This has successfully been demonstrated in several pilot projects within the EU-IEE (Intelligent Energy Europe Programme) project SuRE-FIT (Sustainable Roof Extension Retrofit for High-Rise Social Housing in Europe). The pilot additional new roof-top dwellings partially cover the expenses for the refurbishment of the existing apartments. It has been proven as a well-performing deep renovation solution that results in energy neutral dwellings. Flexible roof-top extension retrofit has been proven as a viable solution, both technologically and financially and combining social, ecologic and economic advantages.
5) *"Folding balcony"*. Bloomframe, designed by Hofman Dujardin Architects, is an innovative window that transfers into a balcony at the touch of a button. The advantages of the concept are especially clear in transformation projects were housing is realized and a regular balcony is not possible or not allowed while residents in congested urban areas demand private outside space to enjoy the weather. The cost of the bloomframe folding balcony as demonstrated will trend to the cost of a large window frame of the same quality and performance and a traditional balcony of the same size. The energy performance of a bloomframe folding balcony (high insulation rate and high solar factor) for deep renovation will help to realize zero energy target for the building, which puts the Return on Investment (RoI) realized at zero.

4 PnP prefab components have been selected in order to set-up specific intervention on the "MEP-HVAC":

1) *"Compact energy store"*. Thermal technologies do not have such general interconnectivity and therefore rely on sizing typically meeting 90% of summer demands in moderate climates. This existing approach provides little benefit in winter. Therefore, an obvious approach is that of thermal energy storage that overcomes issues of heat loss, substantially increasing the overall use of Renewable Energy Sources (RES) in buildings throughout the seasons. The innovative P2ENDURE product derived from the MERITS project is a compact seasonal storage system based on novel high-density materials that can supply required heating, cooling and Domestic Heat Water (DHW) with up to 100% RES.
2) *"Prefab HVAC systems"*. P2ENDURE will implement a complete PnP MEP/HVAC (Mechanical, Electrical, and Plumbing/ Heating, Ventilation and Air Conditioning) engine for deep renovation. This solution includes air-heat pump, storage capacity for DHW, mechanical ventilation system, expansion barrel, and control systems. It has an extra option of split-engine (two cores), i.e. one for

energy conversion and storage the other for ventilation and heating/cooling. The mounting time on-site is significantly reduced by the application of smart connectors. This innovative solution has significant advantages: 1) the total cost of retrofitting is reduced by 40% due to efficient manufacturing and efficient use of labour; 2) quick assembly time of just 0,5 day to place engine, connect pipes/ducts, and then operate with predictable performance; 3) weight of the modules reduced by 35% compared to traditional components, due to redesign and combination of functions.

3) *"Smart connectors"*. P2ENDURE will apply smart connectors for mechanical, hydraulic, electrical, air and ICT joints in order to reduce the danger of cracking.
4) *"The RenoZEB Units"*. It consists of prefabricated units aimed at simplifying the renovation process in terms of performance, time, and costs. The unit is a prefabricated component composed by a steel frame which contains several types of layers. Eight typologies of units have been developed to fulfill different building requirements. The units are created and installed following a modular approach to improve the production line, the design, and the installation process. The deep know-how and experience in the fields of building facades and aluminum allow the company to manage each step of the design process (design, production, and installation). The product modularity simplifies both the design of the whole façade and the installation of the units. In fact, the different types of units can be arranged according to the existing façade layout. The units have been developed to improve the thermal performance of the building.

5 Tools have been selected in order to characterize the innovative P2ENDURE 4M process:

1) *"Comfort Eye"*. It is a low-cost sensing device which allows real-time monitoring of indoor thermal comfort. It is based on a microcontroller and a set of sensors and embedded algorithms to derive Predicted Mean Vote index (PMV) for multiple subjects in different positions of the room. The advantages of Comfort Eye are non-invasive multipoint measurement, interoperability and ease of integration and installation. The technician installs the scanning system on the ceiling of the room and connects it to the control unit. The system scans continuously all the surfaces to measure their average temperatures and sends the results back to the control unit.
2) *"Energy grid and RES production"*. P2ENDURE targets maximum flexibility in power generation (heat and electricity), distribution and usage. P2ENDURE will propose innovative solutions for RES and energy grid through the following three-step approach: to pursue the best utilization of suitable portions of the building-envelope to lodge the RES production; to promote the best utilisation of PnP compact energy storage systems at building level; to promote the development and deployment of combined heat and power (CHP) plants, associated to centralized storage systems.
3) *"Thermal and acoustic scanning technologies"*. In P2ENDURE, the quality controls for prefab panels will be adopted to provide data for the ICT Platform. The main purpose is to eliminate or reduce the quality gap between the design and construction phase through self-inspection and self-instruction techniques connected with an enhanced Augmented Reality (AR) and a detailed BIM. The

following functionalities using advanced low-cost sensors geo-referencing of the 3D data will be deployed at live demonstration projects in P2ENDURE for: thermal bridges detection; thermal transmittance degree; structural integrity diagnosis; acoustic leakages detection; 3D geometric scanning and reconstruction; continuous update of the BIM can be performed in order to have a complete and detailed time history of the performance evolution of the building and of each building components.

4) *"3D scanning (geomatics) – laser and photogrammetry"*. Applications of 3D laser scanning technologies range from the building scale to environment assessment, up to infrastructures, for refurbishment/renovation projects, to manage the construction site or to condition assessment. Different devices can be used depending on needs and application (exterior/envelope, interior morphologies, accurate inspection aimed at energy refurbishment, etc.).
5) "*3D printing and robotics"*. P2ENDURE further develops and implements robotic technologies for on-site 3D printing for façade retrofitting. This solution works with various sorts of materials, yet a mix of thermosilit and limestone is currently preferred to create effective layers of insulation. 3D printing is primarily used to create plastering with special limestone material on concrete walls, ventilation ducts, or water pipes. It gives a 3D design exterior finishing in combination with painting. 3D printing is also used to create a façade layer with any kind of materials suited for the new or retrofitted building structure. In combination with robotic technologies, mounting of windows or other PnP prefab components can also be done very effectively and efficiently on-site. The robots are controlled by an on-site scanning and coordination system. 3D BIM model is used to pre-programme the robots and on-site processes. By using robots, the number of construction workers on-site can be kept up to 2 or 3 persons.

DEMONSTRATION CASES

P2Endure mainly aims to provide scalable, adaptable and ready-to-implement innovative PnP prefab solutions for deep renovation of building envelopes and technical systems. The innovative solutions are complemented with a proof-of-performance, which is based on pilot implementation and monitoring in several live demonstration projects representing deep renovation characteristics in all main EU geo-clusters.

The following paragraphs introduce an overview of the main P2ENDURE demonstration cases, and the PnP solutions adopted for the Deep Renovation:

1) *"Menden (Germany) demonstration case"*. It is an office building erected between 1910 and 1930. It is part of an industrial area containing mostly storehouses and manufacturing companies. The building is attached to the neighbour buildings that are aligned on the street side. The office is a 1 floor building with basement and has a footprint of 187 m² and a gross volume of 744 m³. The deep renovation solutions proposed: adding prefabricated facade elements, additional thermal roof insulation, thermal insulation of the basement ceiling, installation of new windows with triple glazing and installation of a new gas boiler.
2) *"Korsløkken (Denmark) demonstration case"*. The building no.34.3 at Korsløkken is a typical Danish 2 floor residential building from the 1970's. The building is

part of one of the biggest residential housings in Odense city. The overall objective in this building is a total renovation interior and exterior. Furthermore, they would like to have some 3D design and promotion of the whole residential park Korsløkken. The target is to make a 3D design facade faster and with less manpower onsite.

3) *"Ancona (Italy) demonstration case"*. This case study is a multi-apartment block, located in Ancona and built in 1980. The building is composed of 100 dwellings, 6 floors and total gross area of 1720 m^2. The objective is to demonstrate the energy savings from advanced retrofit solutions (e.g. insulation materials, renewables and MEP, comfort monitoring and improvement).
4) *"Florence (Italy) demonstration case"*. This historical residential building in Florence is part of the expansion and rehabilitation area implemented in the period from 1864 to 1871. Considering the location and architecture typology the building was born with a multifunctional used: commercial / craft on the ground floor, and residential use on the upper floors. The objective is to demonstrate the energy savings from advanced retrofit solutions as: adding insulation materials on the roof, new MEP-HVAC systems, replacement of high-performance windows.
5) *"Genova (Italy) demonstration case"*. The nursery school called NEMO is located on the second floor of a two-level building, built in 1930s with concrete structure and non-structural brick walls. The building is listed under the Italian Legislative Decree 42/2004, which poses cultural heritage constraints on its conservation. The goal of this project is the reduction of heating consumption through replacement of high-performance windows.
6) *"Reggio Emilia (Italy) demonstration case"*. The historical hotel was built in the Middle Age and refurbished in the early 1900 by one of the most important architects of the period, Guido Tirelli, under the influence of art deco and liberty. Unfortunately, the building has been abandoned for many years. It had been extended, and it was definitively closed in 1999 in consideration of structural and functional requirements problems. Today 300 m^2 net floor area of the pavilion is subject to a deep renovation to get an energy efficient building, preserving its historical elements. Building morphology: the historical part of the building is made from brick walls, not insulated floors and wooden pitched roof. The south facade is mostly covered by large windows with scarce thermal performances. The restoration project will improve the energy performances and will explore prefab products. Application of P2Endure prefab solutions on: building envelope (smart efficient windows) and technical systems.
7) *"Breda (Netherlands) demonstration case"*. Renovation of row homes for a social housing company to the level of NOM. Area Kruiskamp is in the city of Den Bosch, Netherlands. The homes to be renovated were built in 1967. Demonstration of applicability of NOM concept, stemming from the Dutch Government program' Energiesprong' carried within the regional program SB NOM.
8) *"Enschede (Netherlands) demonstration case"*. This demonstrator is the deep retrofit, redesign and transformation of an abandoned university building, originally built in 1965, into a student hostel and hotel building. The goals are to improve the energy efficiency of the building from energy label G to B (target A) and extend the lifespan of the building. The field demonstration activities will

focus on the testing and inspection of new facade panels and parts of the new MEP system.

9) *"Tilburg (Netherlands) demonstration cases".* Lidwina monastery is a historical building (1935) used as a temporary guest accommodation. The 5400 m^2 building accommodates approximately 60 (potential) rooms. Most parts of the building are well maintained but never been replaced. The objective is to fully renovate the monastery to a new level of comfort, improving energy performance substantially, increasing flexibility of rental situation and modernizing the monastery. The plan is to add to every room a new bathroom, new ventilation and installation concept, insulate windows and façade and reduce sound comfort of the rooms.

Figure 3. Enschede (NL) demonstration cases. Transformation of university building to student hostel in Enschede, the Netherlands

10) *"Gdynia (Poland) demonstration case".* Demonstration building is a two-story kindergarten building, attended by about 130 children. It was constructed in year 1965 and it has the function of kindergarten from the beginning. Building volume is 2712 m^3 and built up area is 464 m^2. The main goal of the demonstration is to minimize the energy consumption especially for heating needs through the retrofitting of the envelope (add insulation layer), implementing new windows and improve aesthetic appearance of envelope. The building is connected to district city network.

11) *"Warsaw (Poland) demonstration case".* The building was built in 1983. It is in the southern part of the city, in Ursynów District, and is one of 55 municipal

nurseries in Warsaw. It is a place for temporary care to 108 children aged 1-3. The main goal of the demonstration is support Warsaw's climate targets – energy efficiency, CO_2 reduction thanks to the opportunity to test innovative solutions.

At the end third year of the project several demonstration cases are finalizing the construction site activities moving from the "Making" step to the "Monitoring" step.

In consideration of the completed tasks, in the following paragraph is introduced the adopted methodology to assess the energy saving target with the PnP solutions proposed. Per each demonstration case is presented the actual measured energy performance.

METHODOLOGY TO ASSESS THE ENERGY SAVING TARGET

The targeted reduction of net primary energy use is calculated in accordance with European Directive 2010/31/EU on the energy performance of buildings, which encourage the adoption of a methodology for calculating the energy performance of buildings.

In this field, the total primary energy demand is then the sum of the primary energy associated with many possible end-uses: heating, electricity, hot water, cooling and ventilation. The numerical indicator of primary energy use is kWh/m^2 per year, *id est* the overall primary energy demand, in kWh/year, associated to the fulfilment of the various end uses of interest, divided by the net floor area of the relative demo case (m^2).

The value, assumed as the reference in the calculation of the saving, is, indeed, the one associated to the specific primary energy demand in the pre-renovation scenario. For each of the presented demonstration cases, the reference primary energy demand is hence determined is based on the characteristic of the existing building before the retrofit:

When direct recordings were not available (vacant buildings), an indirect procedure has been adopted to compute the pre- renovation primary energy:

- Electricity needs, the related primary energy is calculated using standard national coefficients (i.e. the average efficiency associated to the transformation of primary energy into electricity, considering the available plants that operate in the country: thermo-electric plants fed by oil, carbon, etc., PV plants, wind farms, etc.);
- Thermal needs for heating, calculated from energy bills and/or through site specific calculation (normally considering a quasi-steady state heat exchange between the building envelope during the cold season), also considering the energy vectors involved in the transformation processes (e.g., hot water, air, etc.);
- Hot water demand is computed considering the average usage of hot water for the specific facility and the efficiency of the technology adapted to its production;
- Thermal needs for cooling, it is usually extrapolated from the electricity consumption, isolating the needs that can be referred to the cooling consumptions.

It is clear that the reliability and precision of the calculation are strictly related to the available information and the knowledge of the building, of its activity and, in general, of its energy behaviour:

- 1st level: a general knowledge of the energy needs is available from the energy bills (it has been recommended to consider at least two years of data, in order to avoid seasonal variation and or demand anomalies); once the electricity consumptions are known, it is possible to calculate the primary energy, associated to the electricity demand, applying the National Primary Energy Factors. Historic energy use from bills is, therefore, the first reference used in the analysis of the energy use breakdown. When these documents were not available, the requirements have been reconstructed using similar data taken from scientific literature and/or reports of comparable buildings in the same country/geo-cluster. Thermal energy demand and hot water needs can be calculated similarly using energy bills through a similar procedure, however considering the efficiency of the thermal plant installed in the building, instead of national factors. Again, some exception could be considered as it happens in case the dwelling is fed by a district heating network.

- 2nd level: a deeper knowledge of the building is provided by an energy audit: a systematic procedure with the purpose of obtaining adequate knowledge of existing energy consumption profile of a building or group of buildings (Directive 2012/27/EU. The energy audit is the outcome of a deep analysis of the building, its activity and historical energy consumptions; it is provided by a specialist considering the local norms and it can include a site inspection (if needed).
- 3rd level: the creation of a detailed energy model of the building permits a complete awareness of the building and its energy behaviour though the running of energy simulation and analyses.

In general, primary energy consumption is strictly related to the activities and the occupancy of the building. Therefore, the acknowledgement of some usage information, such as the usage time pattern, or the temperature set-point of the plant is pivotal and might help in finding reliable result, both in the pre and post renovation scenarios.

Since the complexity of the last variables in the energy balance equations, the availability of an energy model of the building highly facilitates the validation of the various selected opportunities to get the energy savings, also helping in the standardization of the results for future comparison.

In P2ENDURE the calculation of Primary Energy Consumption has been performed through two different methodologies.

1) “Manual calculation”: many different tools are available on the market for the energy use assessment; each of them required at least a detailed knowledge of historic energy bills and specifications of the installed systems: electricity, natural gas, hot-water plants, and/or others; finally, it is necessary to have a deep knowledge of current lighting and HVAC plants;
2) “Digital model of the building”: this methodology is based on BIM to BEM concept where is necessary the availability of a model of the building, created in a digital environment, where one can simulate the energy behaviour of the subject applying meteorological data, and simulating the operation of the installed on the MEP, in accordance to their given efficiencies. Tools and software yield energy demand through their calculation engines, using heat transfer algorithms, giving very precise results. Different freeware and not freeware software are available on the market and the required input may be substantially different.

These procedures have been adopted to define per each demonstration cases the "energy consumption" before the renovation. At the same time, this result defines the minimum level of energy performance to achieved after the deep renovation (60% less than the pre-intervention status).

PRE RENOVATION																
Country, Partner, Demo case			Energy Assessment - Primary energy consumption			Geometric data and modelling		Energy and Indoor environmental data								energy consumption
			reference of baseline			BIM-to-BEM		transmittance		indoor usage		systems				
			bills	energy audit	energy model	Completed	Validated	envelope	interior	indoor operating temperature	time pattern	HVAC	lighting	power	other	kWh/m2y
DE	3L	Menden	Y	Y	N	N	N	Y	-	Y	Y	Y	Y	Y	-	255
DK	INV	Korsløkken	N	Y	N	Y	Y	N	N	Y	N	N	Y	Y	-	64
IT	UNIVPM	Ancona	Y	Y	Y	Y	N	Y	Y	N	N	Y	Y	N	-	85.8
IT	SGR	Firenze	N	Y	N	Y	Y	Y	N	Y	N	N	N	N	-	366.3
IT	RINA	Genoa	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	161
NL	HIA	Breda	N	Y	N											501
NL	CAM	Enschede	Y	Y	N											300
NL	PAN	Tilburg	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	N	-	428
PL	FAS	Gdynia	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	-	120.5
PL	WAW	Nursery	Y	Y												137.3

Figure 4. Energy assessment of the main demonstration cases before the deep renovation

CONCLUSION

The demonstration cases being implemented aim to show that through the components offered by P2ENDURE such as the adoption of the integration of innovative technologies for the control of the intervention through the 4M process, it is possible to achieve a 60% energy saving compared to in the pre-intervention state, a 15% reduction in costs and 50% of the time required to carry out the intervention compared to the standards, guaranteeing comfort for the occupants (both in terms of quality of the internal environment and reduced disturbance due to the restructuring operations). The project is closing the third year of research and by still following the 4M scanning method of the phases, it is possible to trace both the already obtained and potential results, and the difficulties emerging (Sebastian, 2018) as introduced in the following paragraphs.

The most interesting results of the first step, Mapping, of the adopted 4M process regard the registered procedure that assists the 3D scan and the subsequent BIM modelling, and the BIM Parametric Modeller application which, by importing the model and breaking it down, acts as a guide with regard to the type and number of interventions to be performed. The limit is the lack of a totally automated method of transforming the 3D point cloud survey into a BIM model. The Modelling phase has produced calculation procedures of the energetic behaviour resulting in a BEM that are also importable in the BIM Parametric Modeller application, even though some interoperability defects still emerge. The first results of the Making phase include the solutions themselves during the assembly in the demonstration cases. The P2Endure consortium has analyses and selected advanced PnP technologies allowing energy efficient advanced deep retrofits on demonstration cases. The main focus was the selection, consolidation, optimisation and integration of innovative PnP prefab components that are necessary to achieve the targeted quality and performance in terms

of energy, cost and time-saving as well as improved IEQ and reduced disturbance during on-site processes. All solutions were presented to the building owners or their representatives. The proposed solutions were confronted with the needs of the end-users where was emerged the request of hard evidence about cost and energy effectiveness of the proposed solutions. The Monitoring phase will begin with completed interventions, also assisted by the devices (e.g. Comfort Eye) already installed and the data of which on the quality of the internal environment, detected before and after the intervention, will certify the outcome of the operation.
The P2ENDURE project is working on building renovation interventions managed in a public-private partnership system, the research is experimenting with innovative methodologies, procedures and technologies within a context in which innovation often has to break down innumerable barriers. Also considering obstacles concerning different existing situations in the EU countries.
The tested 4M modular process adopting series of practical ICT tools is demonstrating its functionality facilitating and optimizing the deep renovation process on each demonstration cases and solving the introduced barriers. The experimentation of the tools and technologies developed in the P2ENDURE project is still ongoing. Despite this is possible summarize that the various ICT tools integrate in the 4M process has contribute to:

- established a solid baseline before renovation;
- facilitated the renovation design process by configuring the suitable PnP / prefab solutions for deep renovation;
- provided BIM-based input for energy calculation / energy simulation of the possible deep renovation designs;
- supported the decision-making at deep renovation, i.e. to decide on the most optimal renovation design, as well as after renovation.

Moreover, the results achieved so far have highlighted its potential, not only in terms of optimization and refinement of the functions emerged in the research project, but also of their significant development, prefiguring its high aptitude for replicability in the various countries of the European Union.

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Low-Income Housing Tax Credit Program: A solution to the Crisis of Affordable Housing and Modular Construction?

Arezou Sadoughi[1]
Mian Farrukh Raza[2]

[1]School of Construction and Design. The University of Southern Mississippi. 118 College Drive. Hattiesburg. MS. C:3528880334, Email: ar.sadoughi@gmail.com
[2]School of Social Science and Global Studies.The University of Southern Mississippi. 118 College Drive. Hattiesburg. MS. P:6012664306, Email: mian.reza@usm.edu

ABSTRACT

The shortage of affordable housing units has severely affected every state across the nation. In the west, a scarcity of construction workers exacerbates the problem. Modular construction has been widely studied as a means of providing faster and more cost-effective building construction to address the crisis of affordable housing. Developing and enforcing affordable housing policies could encourage modular design and techniques.

The Low Income Housing Tax Credit Program is a primary subsidized federal program to develop multi-family rental housing for low-income populations. This program mandates or incentivizes design and construction criteria, which are embodied in the Qualified Allocation Plan (QAP). They have been responsible for the development of more than two million affordable homes for low-income families, seniors, and special needs populations since 1986, and have contributed to the creation of more than 100,000 affordable apartments a year (Nedwick, & Burnett, 2014). The most successful in the delivery of standardized rentals, LIHTC has become the largest subsidy for place-based, affordable housing in the United States. Also, recent studies reported the program's effectiveness on the improvement of design and construction criteria, in terms of green and health-related provisions. The inclusion of health provisions, for example, has increased by 13% since 2013. This program has a similar capacity to develop or enforce policies toward the mass production of modular affordable housing units. Although this program could potentially encourage investments in affordable modular housing, it has some resolvable deficiencies against modular construction. This paper aims to elaborate on both the potentials and weaknesses of the program. In the end, some recommendations will also provide guidance to overcome the deficiencies.

A CRISIS: SHORTAGE OF AFFORDABLE HOUSING UNITS

The United States (U.S.) has a shortage of more than 7.2 million affordable rental units. Only 35 out of every 100 extremely low-income households can get affordable rental homes (NLIHC, 2018). Among them, 84 percent are seniors, persons with disabilities, or are in the labor force. Many others are enrolled in school or are single adults caring for a young child or a person with a disability. Figure 1 shows the shortage of available affordable housing units by state. California, Oregon, Nevada, Washington, New Hampshire, Florida, Washington, and Wisconsin have more than a 69% percent shortage of available units for extremely low-income households (NLIHC, 2018).

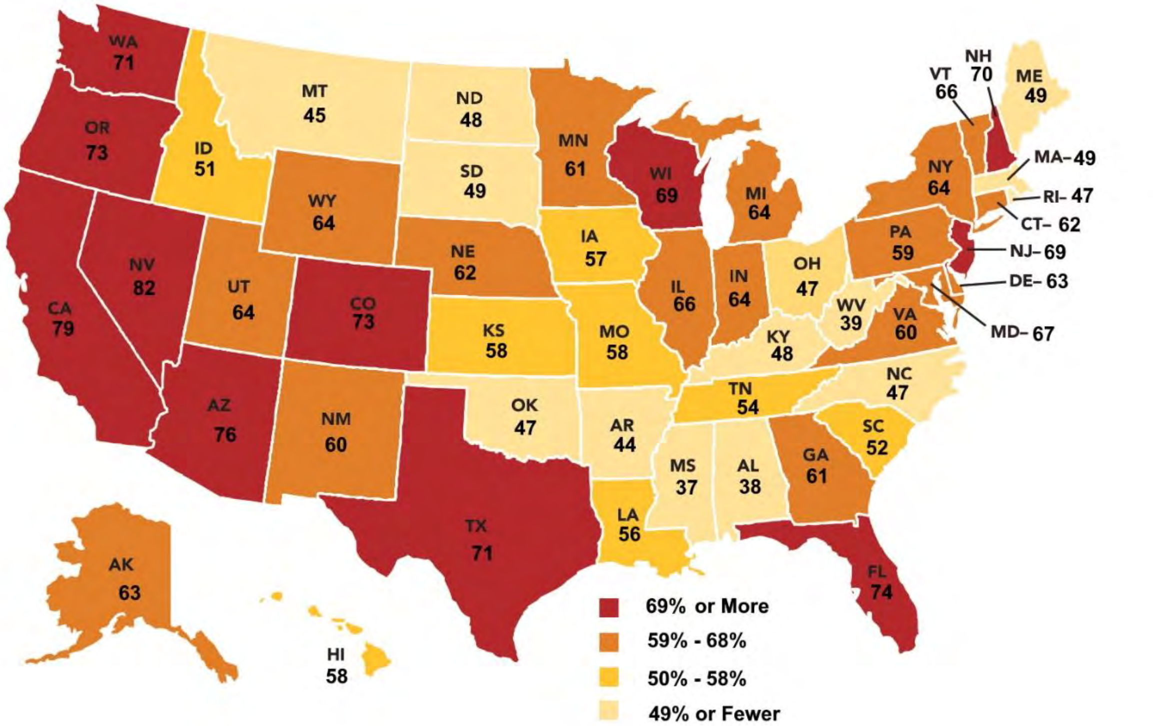

Figure 1: shortage of affordable rental units available for extremely low-income households by state (By percentage (Data extracted from NLIHC, 2018 retrieved from https://nlihc.org/housing-needs-by-state)

LOW-INCOME HOUSING TAX CREDIT PROGRAM (LIHTC) PROGRAM

In the United States, each state has its own housing finance agency that governs programs to develop multi-family rental housing for low-income populations. One of the federal programs these state agencies administer is the Low-Income Housing-Tax-Credit Program (Nedwick, & Burnett, 2014). This program, set forth in part by policies embedded in the Qualified Allocation Plan (QAP), varies from state to state and can mandate or incentivize developers to create healthy housing options, among other housing characteristics (e.g., households, locations, financing mechanisms). QAP can reference other state policy documents, such as "Design, Construction, and Sustainability Standards," that developers must adhere to as well.

The Low-Income-Housing-Tax-Credit program is one of the most important and successful U.S, federal housing programs ever created. Responsible for the development of more than two million affordable homes for low-income families, seniors, and special needs populations since its enactment in 1986 (CSH, 2015), it has contributed to the creation of more than 100,000 affordable apartments a year (Nedwick, & Burnett, 2014). The most successful in the delivery of standardized rentals, LIHTC has become the largest subsidy for place-based, affordable housing in the United States. LIHTC has also provided funding for about one-third of all new units in multifamily housing built since 1980 (Ellen et al., 2015). The Low-Income-Housing-Tax-Credit-Program is a form of private/government funded housing (Collinson et al., 2015) administrated jointly by the U.S. Department of Treasury and state housing agencies (Nedwick, & Burnett, 2014). State housing agencies (HFA), which have control over siting, design, and tenant selection (Collinson et al., 2015), operate LIHTC. This financial mechanism is a response to demands for creating better quality and affordable housing. It was also a response to not having the government directly pay for the construction of homes (as in public housing). Much of the low-income population resides in substandard housing and LIHTC has been a successful program to meet the population's demand for better quality, affordable housing.

This paper mainly discusses the importance of this program in addressing the crisis of affordable housing by increasing the number of modular-built homes. There is no evidence of any LIHTC advocacy for modular construction in their policies, yet at the same time, the program doesn't put up any barriers. This paper elaborates on the capacities of this program in favor of the growth of modular construction and against the shortage of available affordable housing. When it comes to modular affordable housing, it is a win-win strategy. Affordable housing developers are able to increase the number of units by faster construction of modular homes. Meantime, the modular industry has the opportunity to move toward mass production by governmental jurisdictions through the LIHTC program. Pros and Cons are discussed below.

PROS. LIHTC REGULATORY SYSTEM EFFECTIVENESS IN MODULAR AFFORDABLE HOUSING GROWTH

The LIHTC program goals are to make quality cost-effective affordable housing available for the low-income population. The LIHTC program has been an effective way to incorporate green and healthy building criteria in affordable housing. For example, the energy efficiency criteria in the QAPs have increased by nearly 40% since 2013 (Global Green, 2017), and the number of healthy building criteria had an increase of more than 13% from 2013 to 2016 and 18% from 2013 to 2017. Another study on changes in the location criteria of LIHTC projects from 2002 to 2010 also showed that QAP policies matter. This study by Housing and Urban Development (HUD) found that there are statistically significant relationships between changes in QAPs and the locations of tax credit allocations (Ellen, et al., 2015). These studies provide evidence of the potential growth of the LITHC program for developing quality affordable housing for the low-income population.

The cost-effectiveness of housing development is a key term in the growth of affordable housing. Modular construction provides ways to reduce costs. The LIHTC program has a similar potential to prompt growth that will increase the incorporation of modular construction techniques in affordable housing developments. By including modular construction techniques within their design and construction criteria, HFAs can incentivize the developers and investors to build modular homes.

The HFAs annually review the QAPs and their affiliated documents including building design and construction criteria. They also collect comments from advocates through a public hearing. Annually scheduled QAP reviews give advocates, such as developers, opportunities to influence state QAP criteria priorities. "Advocates can use the public hearing and comment requirements to convince their housing finance agency to better target tax credits to properties that house people with extremely low incomes, locate projects in priority areas, and preserve the existing stock of affordable housing." (NLIHC, 2018). The HFAs can potentially address the issue of modular affordable units within their policy requirements or their scoring system to attract more investment in modular design and construction.

The LIHTC program requires long-term compliance for at least 10 years which makes this program a good fit for the development of modular construction. Developers who have a long-run business payback plan are more interested in this program. It is a similar scenario for modular construction. The companies and manufacturers who had financial success in modular construction produced off-site systems for 15 years or more (Smith and Rupnik, 2018). Developers and companies could participate in the public hearing and submit their comments to the HFAs. HFAs consider the advocates' comments in their annual review and would modify the priorities criteria according to the local advocates. The question here is to determine the key points of success in this scenario. A large-scale study to survey or interview state HFAs could scrutinize the key points, pros, cons, barriers, and possibilities for inclusion of modular techniques in the state QAPs and their affiliated documents.

Modular Construction for Affordable Housing Modular construction has shown a batch of promises to address the shortage of affordable housing. The primary goal of affordable housing programs is to provide quality cost-effective living units for those who need them. Modular construction reduces the construction schedule by up to 45 percent, and labor productivity by greater than 30 percent. It has also shown evidence of both soft and hard cost reduction, by 10 to 20 percent (Thomson, 2019). A report on multi-family modular construction in the Washington, DC area showed that with almost the same construction labor cost as conventional construction, the length of time for modular construction is 33% less than the conventional (Brown, 2016). The cost-effectiveness of modular construction compared to conventional construction is aligned with the primary goal of the LIHTC program to provide quality affordable housing.

CONS; REGULATORY SYSTEM, A BARRIER TO MODULAR AFFORDABLE HOUSING GROWTH

Dealing with the number of codes, regulations and standard reviews has always been a time-consuming part of the process of building construction. Building inspection of the modules adds to the inefficient coordination of the design team with the project manager and the developers, who must learn local requirements established by city reviewers and other local agencies, which cause delays in the construction process. The difference between inspections of site-built homes and modular homes is that modular homes are inspected twice; once by state regulators or independent third-party inspection companies during the manufacturing process and again after delivery to the site when the home is installed on its foundation (Kibert et al., 2016). Thirty-six states have an accredited, third party agency responsible for the approval of quality assurance programs of modular manufacturers. In other states, the local authority having jurisdiction enforces code regulations. Unlike conventional site-built projects, navigating requirements for multi-jurisdictional codes are complicated and time-consuming, especially for project teams with limited experience (Cameron, et al., 2007).

The modular buildings should meet the regulations of the place where it will be constructed, regardless of where the modules are prefabricated (Kibert et al., 2016). Modular affordable housing projects have to deal with the associated regulations for multi-family affordable housing such as LIHTC criteria in addition to design and construction permits and inspections. HFAs reviewers have their own review process in addition to that of the city reviewers. The HFAs have not shown any preference in their selection criteria to prioritize modular projects or to expedite the revision process.

Solution #1: The regulatory systems of other countries have adopted the modular construction industry as a solution for housing affordability. For example, in the United Kingdom, modular techniques have become a governmental strategy that has attracted significant investment in modular construction as "one of the largest in the world. Lloyds Bank's latest housing report claimed that six percent of British investment firms are investing in modular housing." (Smith and Rupnik, 2018). In the United States also, some metropolitan areas, such as New York, San Francisco, and Philadelphia, have shown interest in the advancement of modular construction (Smith and Rupnik, 2018). These cities see modular as a solution to affordable housing.
A research study in 2018 indicated that working with partner organizations could improve the modular construction industry. This study referred to partnerships as one of four main recommendations from the Modular Building Institute to foster modular construction. One tactic is to become partners with municipalities, states, or governmental or local agencies who have spoken well of modular construction (Smith and Rupnik, 2018). Although this study did not explicitly address the LIHTC program, it stated jurisdiction support is a solution to the crisis of affordable housing and the advancement of modular construction.

State agencies and cities control the regional regulatory systems and by that, they can significantly influence the growth of modular affordable housing. New York City's partnership with a modular factory is an example of how cities can facilitate modular construction. The affordable apartment homes development project, owned by New York City, announced a decision to build in east Brooklyn. The project, which will be located on a city-owned lot at 581 Grant Avenue, will have 167 apartments that will be available to low-income and formerly homeless New Yorkers. This project was a city-owned development; however, it has lessons for future LIHTC projects.

In California, a new factory was established to provide a modular solution to the affordable housing crisis in the Bay Area (Smith and Rupnik, 2018). California also passed a law that permits manufactured homes built in accordance with local codes to be placed on any residential lot (HUD, 2007). This kind of policy shift can to some extent ease restrictions in modular and panelized housing and increase the supply of affordable units for homebuyers. This type of legislation, however, may not be enough; there are a number of local and regional policies that lengthen the permitting and review process. Similar efforts need to be made for affordable rental housing.

Solution #2: Early coordination of the design team with the affordable housing partner agencies, and developers could reduce the waiting time for the project to get all necessary documents approved. Figure 2 is an interagency coordination model among the design team and partner agencies involved in the development of affordable units to expedite the project review in New York City (PDC, 2018). Housing Preservation and Development (HPD) governs the New York City affordable housing preservation program. It starts its review process when the design is in the conceptual stage. The interdivisional meetings accelerate the lengthy review process.

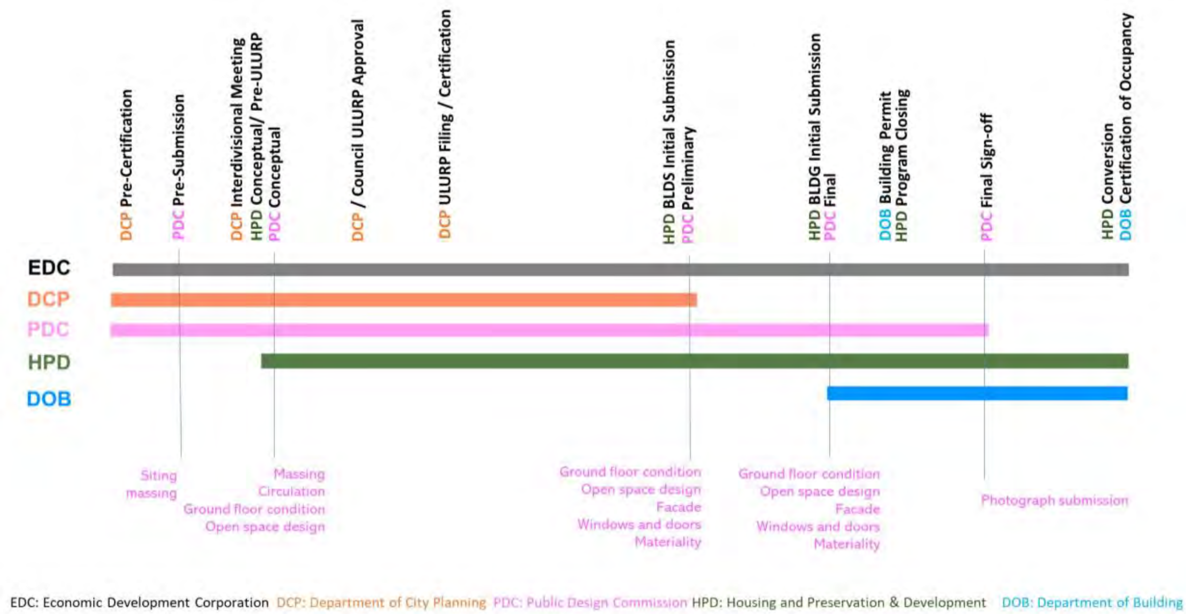

Figure 2: NYC Interagency Affordable Housing Review (Source: NYPDC, 2018) Adopted from (Public Design Commission PDC affordable Housing Process Chart) https://www1.nyc.gov/assets/designcommission/downloads/pdf/5-8-2018_PDC_Affordable_Housing_Process_Chart.pdf

CONCLUSION AND AREAS FOR FUTURE RESEARCH

The LIHTC program has capacities to increase the growth of modular construction and address the shortage of affordable housing. State housing finance agencies could potentially incentivize modular construction, which is a solution to the affordable housing crisis in the United States. The updates and annual reviews on state QAPs and the affiliated design and construction criteria have shown a significant impact on the growth of energy efficiency and health protection in affordable units, which can provide the same capacities to merge the modular construction practice within affordable housing program.

There are some justification barriers. Municipalities, developers, HFAs, and modular homes manufacturers could become partner agencies. Their partnership eases the early coordination toward having fewer restrictions due to local regulations. They would also attract more investments on modular affordable housing; investments not only in terms of community development but also on automation and prototyping modular units in factories. More research is needed to evaluate how these growth strategies could be successful and to identify ways to merge the scientific endeavors to fulfill two interconnected research gaps: addressing the shortage of affordable housing, and the advancement of modular construction.

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New "Q" Method of Punched Masonry Shear Wall Rigidity Determinations

K. Zandparsa

Professor, CE Department, California State University, 1250 Bellflower Boulevard, Long Beach, California, 90840, (562) 985-5118. k.zparsa@csulb.edu.

ABSTRACT

The most important parameter of a shear wall is rigidity that describes its resistance. Lateral loads will be distributed between the shear walls based on their rigidity. Shear wall rigidity comes from flexural and shear stiffness of the wall and adding openings to the wall will make the determinations even more complex. There are different methods for punched shear wall rigidity calculations and among them there are 3 methods A, B, and C in the masonry text books with different accuracy. Based on my experiences on perforated shear walls, rigidity results from different methods are varies, and it is not clear which one is more reliable. To calculate more accurate rigidity for shear walls with openings, a new method "Q" based on spring model concepts of shear wall is developed. By comparing the results from different methods for solid shear walls (without opening) it was clear that "Q" method results were more accurate than the other methods.

In this paper besides considering methods A, B, C, and introducing the "Q" method, different examples for masonry shear walls without opening and with openings (single punched, and multiple punched) for fixed-fixed supports are presented, and the results are compared.

INTRODUCTION

Earthquake lateral force distribution between shear walls in a building structure would be based on the shear walls' rigidity. Determining shear wall rigidity without opening with fixed-fixed or fixed-free connections (top and bottom of the wall) would be based on the flexural and shear rigidity of the wall. Opening in shear walls is very common. Openings might be windows, doors or combination of both. To determine the wall rigidity with opening, different methods were created. Among those there are three methods that are used for masonry shear walls. Those methods are called "A", "B", and "C". The accuracy of these methods is different upon the shear wall openings dimensions and configurations, and the walls lateral load results would be different for each method. The differences might confuse the designer and make it harder to accept the results. A new method based on flexural and shear rigidity modification has been created to be able to determine more reliable rigidity for shear walls with openings for any opening configurations.

SHEARWALL RIGIDITY CALCULATIONS

Solid shear walls

Solid shear wall (without opening) with fixed-fixed and fixed-free supports are shown in Figure 1.

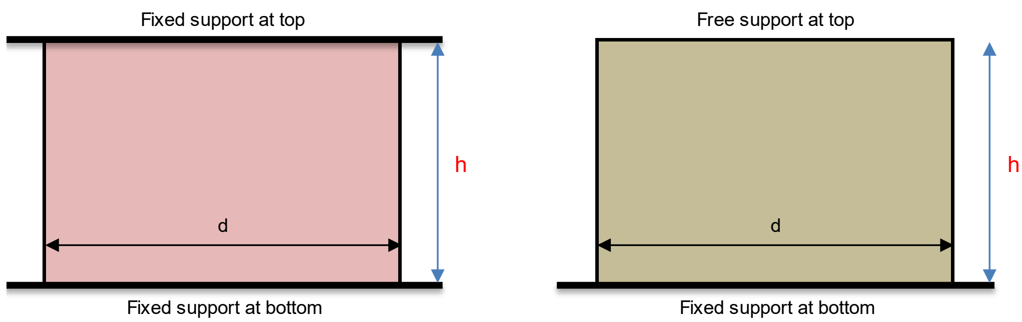


Figure 1. Shear wall with fixed-fixed and fixed-free supports

Shear wall rigidity (without opening) will be obtained based on flexural and shear stiffness of the wall and can be determined by Equations 1 and 2 for fixed-fixed and fixed-free supports, respectively.

$$Ri = \frac{Em.t}{[\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)]} \tag{1}$$

$$Ri = \frac{Em.t}{[4\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)]} \tag{2}$$

where:
Em = Masonry modulus of elasticity
t = Shear wall thickness
h = Height of the wall at each story
d = Width of the wall at each story

Shear walls with opening (punched)

In this case, shear wall can be divided to different segments, and hi and di for each segment as shown in Figure 2 will be used in methods A, B, C, and Q.

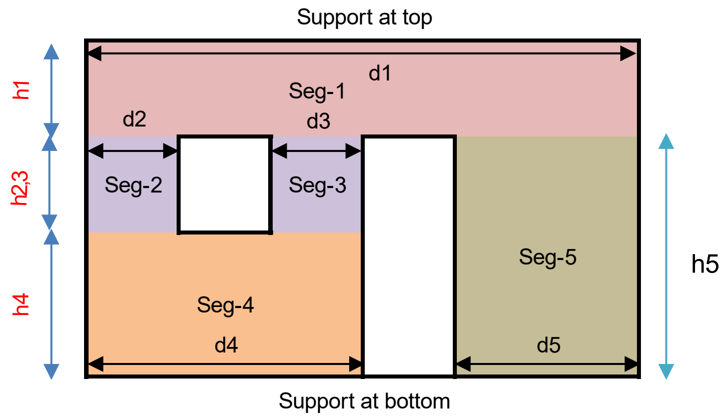


Figure 2. Punched shear wall with fixed-fixed or fixed-free supports

The first step to calculate a punched shear wall rigidity is finding the stiffness of each segment based on fixed-fixed or fixed-free support conditions that will be calculated by Equations 3 and 4 for fixed-fixed and fixed-free supports respectively.

$$Ri = \frac{Em.t}{[\left(\frac{hi}{di}\right)^3 + 3\left(\frac{hi}{di}\right)]} \quad (3)$$

$$Ri = \frac{Em.t}{[4\left(\frac{hi}{di}\right)^3 + 3\left(\frac{hi}{di}\right)]} \quad (4)$$

hi = Segment height
di = Segment width

In this paper rigidity of perforated shear wall with fixed-fixed supports at top and bottom of the wall will be presented.

Methods "A", "B", and "C"

For describing these three methods, shear wall in Figure 3 will be considered.

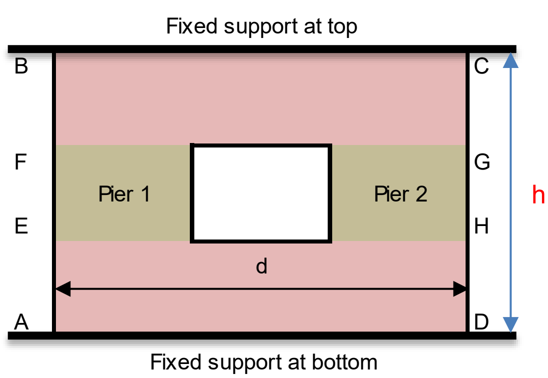


Figure 3. Fixed-fixed Shear wall with opening

Method A

Method "A" has a simplified approach and very easy to use but does not have accurate results. This method assumes that just the piers at either sides of openings contribute to the rigidity of a wall and solid portions of wall above and below the opening will be ignored.

By using Figure 3 as an example for method "A", the shear wall rigidity will be calculated based on rigidity of two piers 1 & 2.

$$R = R1 + R2 \tag{5}$$

Method B

Step by step shear wall rigidity calculations for method "B" may be obtained as follows.

1- Calculate deflection of the solid wall ABCD (without considering openings).

$$\Delta(solid\ wall) = \frac{1}{R(solid\ ABCD\ wall)} \tag{6}$$

2- Calculate the strip EFGH solid strip (without considering openings) deflection.

$$\Delta(solid\ EFGH\ strip) = \frac{1}{R(solid\ EFGH\ strip)} \tag{7}$$

3- Calculate deflection of the piers 1, and 2.

$$R(piers\ 1+2) = R1 + R2 \tag{8}$$

$$\Delta(piers\ 1+2) = \frac{1}{R(piers\ 1+2)} \tag{9}$$

4- Calculate deflection and stiffness of the punched shear wall.

$$\Delta(punched\ wall) = \Delta(solid\ wall) - \Delta(strip\ EFGH) + \Delta(Piers\ 1+2) \tag{10}$$

$$R(punched\ wall) = \frac{1}{\Delta(punched\ wall)} \tag{11}$$

Method C

Method "C" is based on a system of springs in parallel, series or in combination of both. Spring system for Figure 3 perforated shear wall is shown in Figure 4.

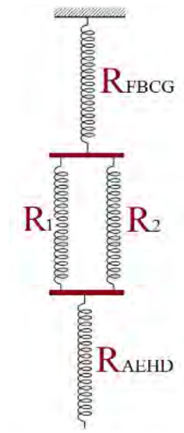


Figure 4. Spring system modeling for method C

The relative stiffness of the punched shear wall in this method can be determined by Equation 12.

$$Rpunched\ wall = \frac{1}{[(\boldsymbol{R}\text{FBCG})^{-1}+(R1+R2)^{-1}+(\boldsymbol{R}AEHD)^{-1}]} \tag{12}$$

NEW METHOD "Q"

Method "Q" is based on spring model along with flexural stiffness modification of each segment. For describing this method, a solid shear wall (without opening) will be considered with vertical and/or horizontal segments as shown in Figure 5.

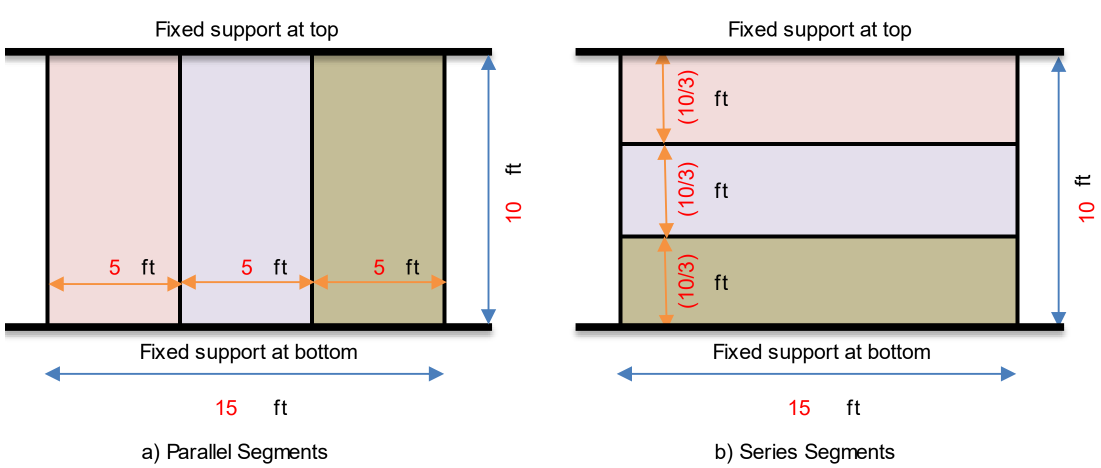
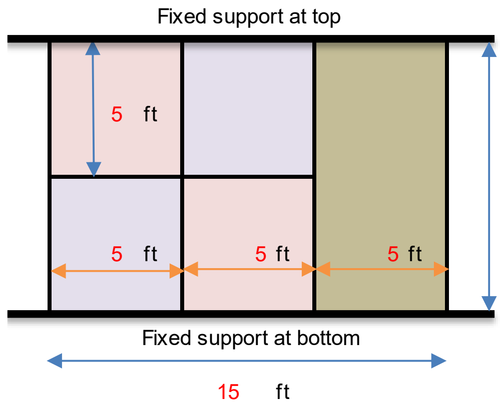
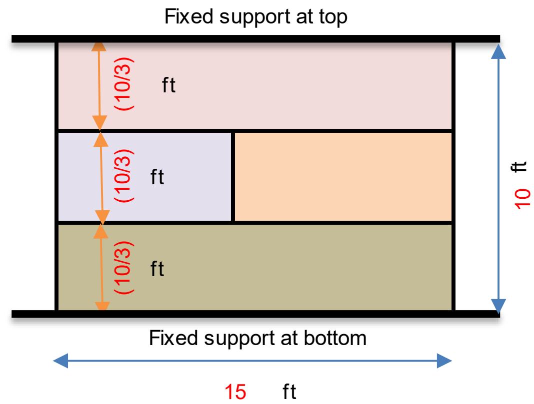


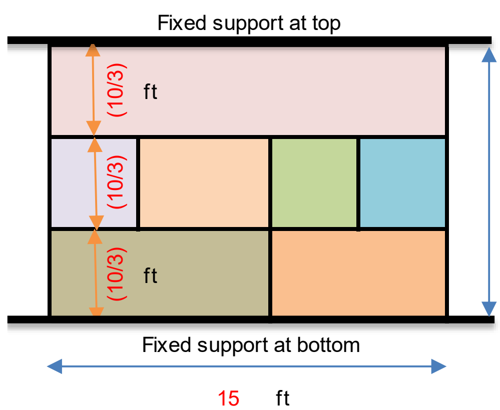
Figure 5. Solid shear wall with different segment configuration (fixed-fixed supports)



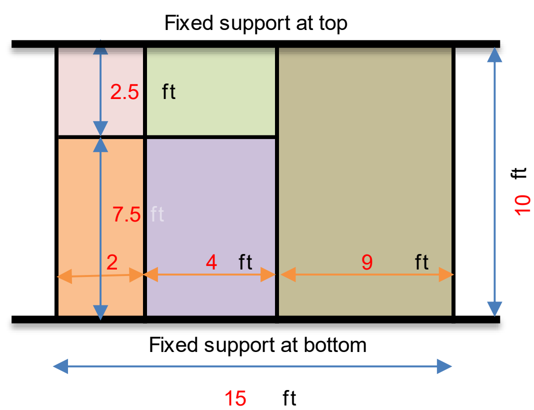
c) Series and Parallel Segments



d) Series and parallel Segments



e) Seriesand parallel Segments



f) Series and Parallel Segments

Figure 5. Continued

Each segment width and height ratio "ni" will be calculated per Equations 13 and 14.

$$nip = d/di \tag{13}$$
$$nis = h/hi \tag{14}$$

Where:
nip = Width ratio for parallel segments
nis = Height ratio for series segments

Modification for parallel segments

With using Equation 3 for calculating each segment stiffness and rewriting that for parallel segments with equal height "h" Equation 15 will be obtained.

$$Ri = \frac{Em.t}{[\left(\frac{h}{di}\right)^3 + 3\left(\frac{h}{di}\right)]} \tag{15}$$

Consider shear wall with "n" equal parallel segments' as shown in Figure 5(a). In this case, the stiffness of each vertical strip will be determined by Equation 16.

$$Ri = \frac{Em.t}{[n^3\left(\frac{h}{d}\right)^3 + 3n(\frac{h}{d})]} \tag{16}$$

Equal width is used for simplification only, and the result for unequal segments' width would be the same.

Rigidity for the whole wall based on the parallel springs would be:

$$Rt = nRi = \frac{Em.t}{[n^2\left(\frac{h}{d}\right)^3 + 3(\frac{h}{d})]} \tag{17}$$

The Rt (rigidity of the whole wall) with fixed-fixed supports must be equal to Equation 1, but they are not the same.
So, with dividing the flexural stiffness part of the Equation 17 by n^2, the wall rigidity Rt would be the same as the whole solid wall rigidity (Equation 1).

Modification for series segments

In this case, the rigidity of each horizontal strip with equal width "d" and different height equal "hi" will be determined by Equation 18.

$$Ri = \frac{Em.t}{[\left(\frac{hi}{d}\right)^3 + 3\left(\frac{hi}{d}\right)]} \tag{18}$$

Considering shear wall with "n" equal horizontal segments as shown in Figure 5(b), Equation 18 can be rewritten as Equation 19.

$$Ri = \frac{Em.t}{[\left(\frac{1}{n}\right)^3\left(\frac{h}{d}\right)^3 + 3\left(\frac{1}{n}\right)(\frac{h}{d})]} \tag{19}$$

Equal height is used for simplification only, and the result for unequal segments' height would be the same.

Rigidity for the whole wall based on the series springs would be:

$$Rt = 1/(\sum_1^n \frac{1}{\text{Ri}}) = 1/(n/Ri) = \frac{Em.t}{[\left(\frac{1}{n}\right)^2\left(\frac{h}{d}\right)^3 + 3(\frac{h}{d})]} \tag{20}$$

With multiplying the flexural stiffness part of the Equation 20 by n^2, the rigidity would be the same as the whole solid wall rigidity (Equation 1).

Modification for parallel and series segment combinations

For any combinations of parallel and series segments of a shear wall Figure 5 (c, d, e) by dividing or multiplying the flexural stiffness part of the segment rigidity by n^2, respectively, the rigidity will be modified and by using the parallel and series combination of springs, the whole wall rigidity can be calculated.

RESULTS

To be able to compare the results of different methods, two examples are presented. First example is considering solid shear walls without opening with vertical and horizontal segments (Figure 5a,b) that are solved based on three methods “B”, “C”, and “Q”. Table 1 shows the walls’ rigidity results for the three mentioned methods.
In this example the masonry wall “Em” and thickness “t” are considered unit. The whole one segment (“h”, and “d”) wall rigidity based on Equation 1 is determined 0.44 k/in. Method “A” for shear wall without opening is useless and because of that it is not considered in this example.

Table 1. Masonry shear wall without opening

Method	Stiffness (K/in)					
	Figure 5(a)	Figure 5(b)	Figure 5(c)	Figure 5(d)	Figure 5(e)	Figure 5(f)
A	NA	NA	NA	NA	NA	NA
B	021	0.44	0.21	0.43	0.37	0.26
C	0.21	0.49	0.32	0.48	0.45	0.30
Q	0.44	0.44	0.44	0.44	0.44	0.44

Second example is based on Figure 2, considering punched shear wall with vertical, and horizontal segments with different dimensions for four cases as shown in Table 2.

Table 2. Masonry shear wall Figure 2 dimensions

Case	Dimensions (ft)								
	h1	h2,3	h4	h5	d1	d2	d3	d4	d5
1	2	5	3	-	15	2	8	15	-
2	2	5	3	-	15	5	5	15	-
3	2	-	8	8	15	-	-	5	5
4	2	5	3	8	15	2	3	10	2

All four cases are solved based on four methods “A”, “B”, “C”, and “Q”, and Table 3 shows the walls’ rigidity results for all four methods.

In this example the masonry wall “Em” and thickness “t” are considered unit. The whole solid wall (“h”, “d”) rigidity based on Equation 1 is determined 0.44 k/in.

Table 3. Punched Masonry shear wall stiffness

Method	Stiffness (K/in)			
	Case 1	Case 2	Case 3	Case 4
A	0.52	0.5	0.22	0.15
B	0.25	0.26	0.20	0.12
C	0.26	0.28	0.25	0.13
Q	0.33	0.34	0.31	0.26

CONCLUSIONS

Based on the examples 1 and 2 results, the following conclusions have been made:

1- Method "A" is easy to use, but it is not accurate.
2- Results from methods "B" and "C" are almost similar.
3- Results from methods "B" and "C" might be 15 to 20 percent off from more reliable modelling of perforated shear walls.
4- Application of method "C" is easier than method "B".
5- Application of Method "Q" is as easy as method "C".
6- Results from method "Q" are almost the same as reliable modelling of the wall.
7- Using combination of methods for finding shear wall rigidity is not acceptable.

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