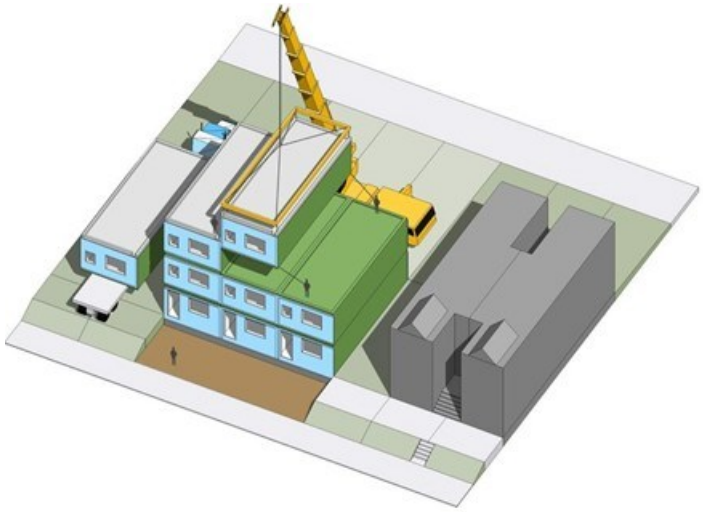
2026 Residential Building Design & Construction Conference



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March 18-19

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2026 (8th) **Residential Building Design & Construction Conference** Proceedings

March 18-19, 2026

Edited by
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Mindy Boffemmyer

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

PennState
College of Engineering

PENNSYLVANIA HOUSING RESEARCH CENTER

Conference Organization

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Preface

The Residential Building Design and Construction (RBDC) Conference series has been created to provide a forum for exchange of new ideas and recent developments toward advancing the state of the art in home building industry. Among some of the most pressing issues facing this industry is to address improving the quality and affordability of homes while accommodating advanced design and construction criteria, such as energy efficiency, sustainability, serviceability, aesthetics, utility, low carbon footprint, and hazard resistance, among others. The conference provides a great opportunity for technology transfer related to building materials and systems, innovative designs, changes in standards and codes, advanced technologies and systems for buildings. The efforts by the contributors to the conference in making the presentations at the conference and publication of papers in this volume of the proceedings will help designers and home builders toward advancing the state-of-the-art in home building. The Pennsylvania Housing Research Center (PHRC) at The Pennsylvania State University is pleased to offer such knowledge sharing and dissemination of the results of recent advancements in the residential construction field. The PHRC will happily and proudly continue to organize the RBDC Conference series in order to support knowledge and technology transfer to the housing and residential construction industry.

It is a great pleasure to share with you the proceedings of the 2026 RBDC Conference, which was held on March 18-19, 2026. As in the past RBDC conferences, the 8th conference was successful to attract researchers, design professionals, manufacturers, builders, code officials, and students engaged in research. Their presence at the conference and also the contributions by the authors who just submitted papers for the proceedings have resulted in a successful program that will help advancements in research and practice in this field.

With 141 participants at the 2026 RBDC Conference, overall, the conference included 54 papers, 60 presentations, and five posters on various issues related to residential buildings. While most of the presentations and papers had focused on single-family homes, the conference also had some presenters and authors whose work reflected advancements related to multi-family dwellings, mid-rise and high-rise structures, and modular construction. Most of the presentation and paper topics fall under the categories that were listed in the conference call:

- Additive Manufacturing and 3D Printing of Homes
- Aging-in-Place and Senior Living Housing
- Alternative Renewable Energy Generating Systems
- Bio-based Materials for Residential Construction
- Building Integrated Photovoltaic and Various Applications of PV Systems for Homes
- Building Performance Assessment, 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 Systems
- Innovations in Residential Architecture
- Innovations in Panelized, Modular and Manufactured Housing
- Innovative and Emerging Housing Construction Methods and Systems
- Learning from the Performance of Residential Buildings under Natural Disasters
- Low-Income and Affordable Housing
- Mechanical Electrical & Plumbing (MEP) Systems
- Passive House Design Approach
- Resilient New Design and Retrofit of Existing Buildings
- Smart Home Technologies and Home Electrification
- Sustainable Housing Construction Materials and Methods
- Temporary Housing for Disaster Situations

Two keynote speakers were invited for the conference:

Sarah Billington, UPS Foundation Professor in Civil and Environmental Engineering and senior fellow at the Woods Institute for the Environment at Stanford University, presented her talk, “From Concept to Community: Design Strategies for Sustainable Affordable Housing,” on Wednesday.

Georg Reichard, chair of the School of Building Construction in the College of Design at Georgia Institute of Technology, delivered his presentation, “The 7 Habits of Successful Builders of High-Performance Homes,” on Thursday.

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 also gratefully acknowledged.

Proceedings Editors:

Ali M. Memari
and Mindy Boffemmyer

June 2026

Wednesday, March 18 Schedule

7:00 AM - 3:00 PM — **Registration Open** — Registration Desk I

8:15 AM — **Opening Remarks:** Dr. Ali Memari & Chris Hine — Deans Hall

8:30 AM — **Keynote:** Sarah Billington, "From Concept to Community: Design Strategies for Sustainable Affordable Housing" — Deans Hall

10:00 AM — **Break with Snacks** — 2nd Floor Break Area
Chat with Exhibitor Plus Sponsors — 1st Floor Break Area

10:30 AM

Panelized, Modular, and Offsite Construction
Room 218

Resilience and Affordability: A Data-Driven Evaluation of Industrialized Construction's Economic Viability
Ankur Dobriyal and Rob Howard

Documenting Constructability and Quantifying Sustainability for a Concept Home That Integrates Consumer-Driven Design and Modular Construction as a Scalable Solution to "Missing Middle Housing" in Urban Settings
Isabella Cicco, Amy Brooks, Dennis Steigerwalt, and Melissa Bilec

Earthquake Resistant Evaluation and Design
Room 204

Advancing Use of Cold-formed Steel Framing Systems for Mid-Rise Residential Construction in Seismic Zones via Full-Scale Shake Table Testing
Tara Hutchinson, Mohammed Eladly, Ruipu Ji, Daniel Rivera, Fidence Cyizere Rukundo, Amanpreet Singh, Shokrullah Sorosh, Jiachen (Charlie) Zhang, Xianzhao Zhang, Lynn Padgett, Harry Jones, Jesse Karns, and Benjamin Schafer

Investigating Construction Methods in a Landmark Ten-Story Cold-Formed Steel Residential Building Shake Table Test Program
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Pre-Test High-Fidelity Numerical Modeling of a Ten-Story Cold-Formed Steel Framed Building under Seismic Loading
Mohammed Eladly, Zhidong Zhang, Jiachen (Charlie) Zhang, Amanpreet Singh, Matthew Speicher, Tara Hutchinson,and Benjamin Schafer

12:00 PM — **Lunch** — The Gardens

1:00 PM

Building Science
Room 205

Additive Manufacturing for Roof Structures: Improving Geometric Accuracy, Design Flexibility, and Strength
Gaurav Manish Lunawat, Shadi Nazarian, and Negar Ashrafi

Use of Local Sheep's Wool for Building Insulation: Effect of Micron Count on Insulation Value
Daniel Hindman and Tom Hammett

Going Beyond the Hype: Lessons Learned from Forensic Analysis of Proprietary Cladding Material Failures
Samantha Leonard and David Schnerch

Mechanical, Electrical, and Plumbing
Room 218

Pipes and Ducts in the Urban Jungle: Where on Earth Is That Smell Coming from?
Sean O'Brien and Daniel Zambito

Residential Heat Pumps: An Update
Dean Wirtanen and Kevin Wilkinson

Hurricane and Wind Hazard for Homes
Room 204

Model-to-Data Validation of Flood Damage Models for Buildings in Coastal Regions: A Case Study of Hurricane Ian (2022)
Josette Audi, Mehrshad Amini, Daniel Cox, and Andre Barbosa

An Exploration of The Building Code Process and Their Relationship to Building Resilience in the Bahamas
Ben Bigelow, David Swaby, and Somik Ghosh

Cost-Effective Wind-Resistant Gable Roof Retrofits in Kentucky and Tennessee: A BIM-Driven Approach to Residential Hazard Mitigation
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Chat with Exhibitor Plus Sponsors — 1st Floor Break Area

3:00 PM

Affordability, Health, and Social Aspects of Housing
Room 204

The Impact and Adoption Patterns of WELL Building Standard Certification for Multifamily Residences: A Global Analysis of Health and Wellness-Focused Residential Market
Suchismita Bhattacharjee and Mojgan Moradi

Casino Proximity and Housing Prices: an Empirical Analysis of Housing Markets in Small Oklahoma Cities
Kaitlan Pollock, Ben Bigelow, and Somik Ghosh

Housing Styles | Architecture
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The Tuscanization of South Africa's Residential Landscape
Gerald Steyn

The Forgotten Middle Child of the Industry: Low-Rise Residential Multifamily Buildings–Built Like a House, Expected to Perform Like a Tower
Sean O'Brien and Ali Yalaz

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7:00 AM - 12:00 PM **Registration Open** — Registration Desk I

8:15 AM **Opening Remarks:** Dr. Ali Memari & Chris Hine — Deans Hall

8:30 AM **Keynote: Georg Reichard**, "The 7 Habits of Successful Builders of High-Performance Homes" — Deans Hall

10:00 AM **Break with Snacks** — 2nd Floor Break Area
Chat with Exhibitor Plus Sponsors — 1st Floor Break Area

10:30 AM

Residential Construction Education
Room 218

From GreenBuild to Garner Street: A Decade of Student Engagement with the State College Community Land Trust (SCCLT) and Advancing Affordable High-Performance Housing
Setareh Farashzadeh, Yasaman Ghaffarian, and Lisa Domenica Iulo

Impact of Organizational Structure on Architectural Production and Its Implications on Academic Education (Design-Build: "Undercover Architect")
Christian Volkmann

Affordability, Health, & Social Aspects of Housing
Room 204

Achieving Affordable Housing and High Indoor Environmental Quality: Solving the Housing Crisis
Abbey Fradette and Suchismita Bhattacharjee

The Impact of Residential Healthcare Facility Proximity on Single-Family Sale Prices
Rafael Hernandez

Technologies for Sustainability | Renewable Energy
Room 205

Resilient by Design: Powering the Renewable Energy Future through Microgrid Housing Innovation for Prairie View and Gulf Coast Communities
Anthony Hill, Jessica April Ward, Penrose Cofie, Joseph Dowell, John Fuller, and Ervin Emanuel

Method to Estimate EUI & PV Production Area to Meet Net Zero Benchmark at the Beginning of a Building Project
Dorothy Gerring

Improving Building Envelopes to Enhance Hybrid Renewable Energy Systems for Remote Communities
Megan Bush, Sepideh Korsavi, Lisa Domenica Iulo, and Rahman Azari

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1:00 PM

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Sam Rashkin

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Elizabeth Farrell Garcia, Mackenzie Stagg, and Timothy Tamulonis

Innovative and Sustainable Construction Technologies | Issues, Materials, and Methods
Room 205

Pneumatically Driven Wooden Nails in Light-Framed Construction and Determination of Appropriate End Grain Adjustment Factor
Elise Harrison and Kevin Rens

Indoor Environmental Quality of Homes: A Comparison of ICF and Traditional Construction
Somik Ghosh, Suchismita Bhattacharjee, and Ben Bigelow

Residential Construction Solutions Using MassBu Panel Systems
Daniel Hindman and Jonas Hauptman

2:30 PM **Break with Snacks** — 2nd Floor Break Area
Chat with Exhibitor Plus Sponsors — 1st Floor Break Area

3:00 PM

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Jud Taylor and Caroline Byrne

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3D Concrete Printing

3D Printable Concrete Incorporating Recycled Cork Aggregate: Advancing Eco-friendly and Climate-Resilient Construction

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ABSTRACT

This study investigates the viability of integrating recycled wine cork aggregates into 3D-printable lightweight concrete to advance CO_2 sequestration and climate-resilient construction. River sand was systematically replaced with cork at 25%, 50%, 75%, and 100% by volume, with performance evaluated across fresh, mechanical, thermal, durability and sustainability metrics. Recycled cork incorporation reduces concrete density (899–1835 kg/m³), enabling lightweight classification (>25% replacement), while enhancing pumpability through reduced dynamic yield stress and plastic viscosity. However, the reduction in static yield stress and its structural rate were reduced (887.31 to 335.25 Pa/min). Improved flowability (180–205 mm spreading diameter) and extended open time, facilitated by cork's moisture retention, support scalable 3D printing. Microstructurally, cork's honeycomb-like porosity increases capillary pores (≥100 nm, up to 51.1% porosity), lowering thermal conductivity (0.408 W/m·K at 100% replacement) and enhancing heat capacity (1.09 J/g·°C). However, interfacial transition zone (ITZ) weaknesses and anisotropic mechanical performance arise, reducing compressive strength by up to 91% at full replacement. In the case study of a townhouse in Alaska, stratified material designs (C-25% exterior walls, C-75% interior walls) comply with Alaska Building Code 2021 and reduce building energy consumption by 21.2% through thermal buffering. Lifecycle assessments demonstrate cork-concrete's carbon-negative potential: under economic allocation, 100% replacement achieves 2,132.9 kg-CO_2eq sequestration per functional unit, while mass-balance allocation yields 289.8 kg-CO_2eq. Building-scale analysis shows 80% embodied CO_2 reduction (25,878.03 to 5,213.85 kg) and net sequestration (70,440.84 kg) under economic frameworks. Despite trade-offs in mechanical strength, cork-concrete aligns with circular economy principles, offering a dual role as a structural-insulative material and carbon sink.

Additive Manufacturing for Roof Structures: Improving Geometric Accuracy, Design Flexibility, and Strength

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ABSTRACT

Conventional roof construction methods, such as cast-in-place and precast concrete, are constrained by costly form work, labor demands, and limited design flexibility. This study investigates 3D concrete printing (3DCP) as a mold-free alternative for prefabricated roof modules, focusing on geometric accuracy, fabrication efficiency, and design adaptability. A sawtooth roof geometry was selected for its environmental performance and fabrication complexity (Figure 1). Using a robotic extrusion system and fiber-reinforced one-part micro-concrete, the research compared printed modules against traditional casting in terms of dimensional tolerance, fabrication time, and material waste. Results indicate that 3DCP achieved tighter tolerances (±2–3 mm vs. ±8–15 mm for casting), reduced fabrication time by over 90%, and reduced reliance on temporary formwork. However, quantitative waste assessment was beyond the scope of this study. Additionally, 3DCP enabled seamless geometric variations without new molds, enhancing design flexibility. These findings position 3DCP as a sustainable and efficient alternative for prefabricated roof systems, capable of achieving construction-scale dimensional fidelity while reducing mold fabrication time. Mechanical load testing was not performed and is reserved for future investigation.

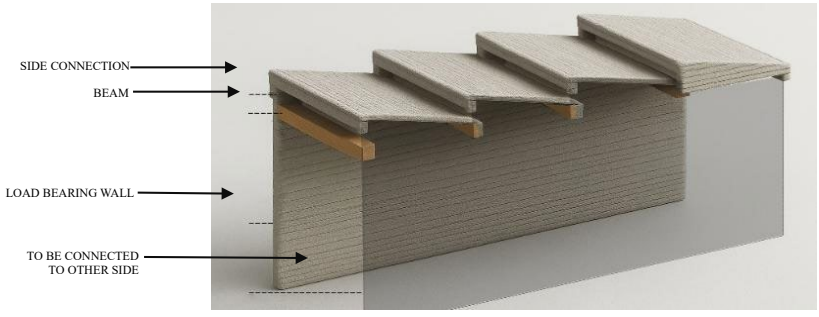


Figure 1. Geometrical design and attachment of the roof module.

INTRODUCTION

Geometric accuracy is a critical benchmark in prefabricated construction, directly influencing assembly efficiency, structural performance, and design fidelity (Ashrafi et al.). Traditional roof fabrication methods, such as cast-in-place and precast concrete, often rely on costly complex molds that limit adaptability, while growing demand for complex data-driven architectural forms calls for more flexible solutions. Additive Manufacturing Technologies (AMTs), particularly 3D concrete printing (3DCP), enable direct digital-to-physical fabrication without formwork, reducing labor and cost. This study assesses 3DCP's ability to improve geometric accuracy, design flexibility, and sustainability in roof modules compared to traditional casting, using performance and accuracy metrics to highlight its potential as a scalable prefabrication method. Structural load testing and long-term durability assessment were beyond the scope of this investigation.

BACKGROUND

Additive manufacturing in construction has progressed from Urschel's Wall Building Machine (1939) to today's robotic extrusion systems, capable of full-scale structures (Montjoy, 2023). Contour Crafting, introduced by Behrokh Khoshnevis in the 1990s, demonstrated how robotic extrusion could produce complex geometries with less waste and labor (Porada, 2013). 3DCP eliminates formwork, reduces labor, and ensures precise digital-to-physical fabrication (Buswell et al. 2018; Ngo et al., 2018). However, challenges remain in material consistency and reinforcement integration. Casting, though dependable and economical for standardized designs, often suffers from mold deformation, curing stresses, and limited adaptability (Lee and Lee, 2018). In contrast, 3DCP offers sustainable, precise prefabrication aligned with digital workflows. Most research has focused on vertical elements, leaving roof systems—with complex spans, openings, and angles—largely underexplored. This study compares 3D-printed sawtooth roof modules with traditional casting.

METHODOLOGY

Design Concept and Case Study

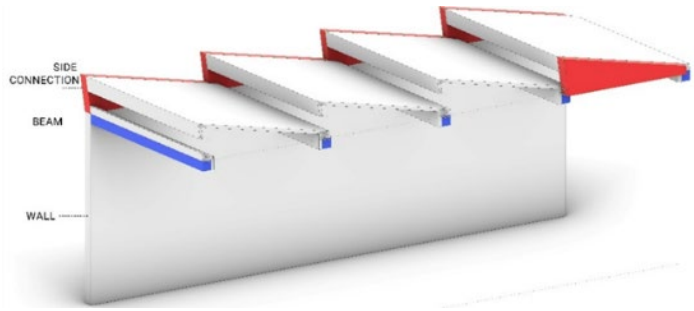


Figure 2. Roof geometry with red being the side panel and blue the wall beams which transfer load.

The study investigates angular sawtooth planes with a wide front ventilation slit tapering to a narrow back (Figure 2). This configuration is parametrically designed to optimize natural airflow and improve thermal performance through passive cooling. Maintaining precise geometry is crucial for consistent ventilation and aesthetics.

3D Printing Setup

Fabrication was performed using a Yaskawa Motoman GP70L robotic arm paired with an M-Tech mixer pump. The printable material, *Sikacrete®-733 W 3D*, provided thixotropic behavior, shape retention, and compressive strength of 50 MPa at 28 days. Reinforcement was embedded between printed layers to enhance interlayer continuity and maintain geometric stability across modules; mechanical performance was not experimentally validated in this study.

Material Development

Sikacrete®-733 W 3D is a fiber-reinforced micro-concrete with stable extrusion, thixotropy for shape retention, and open time for interlayer bonding—well-suited for modular roofs. It reaches ~10 MPa compressive strength at one day, 47 MPa at seven days, and 50 MPa at 28 days, with eight MPa flexural strength and 30 GPa modulus at 28 days. Printable layers range from 6–20 mm. A dry-to-water ratio of 3:1 by weight was adopted during casting trials, corresponding to a water-to-binder ratio (w/b) of approximately 0.33. All mix ratios are reported in mass-based units. The mix supports targeted reinforcement, dimensional accuracy, smooth finishes, minimal shrinkage, reduced CO_2 footprint, and stability for inclined or tapered surfaces.

Printing workflow and Reinforcement Integration

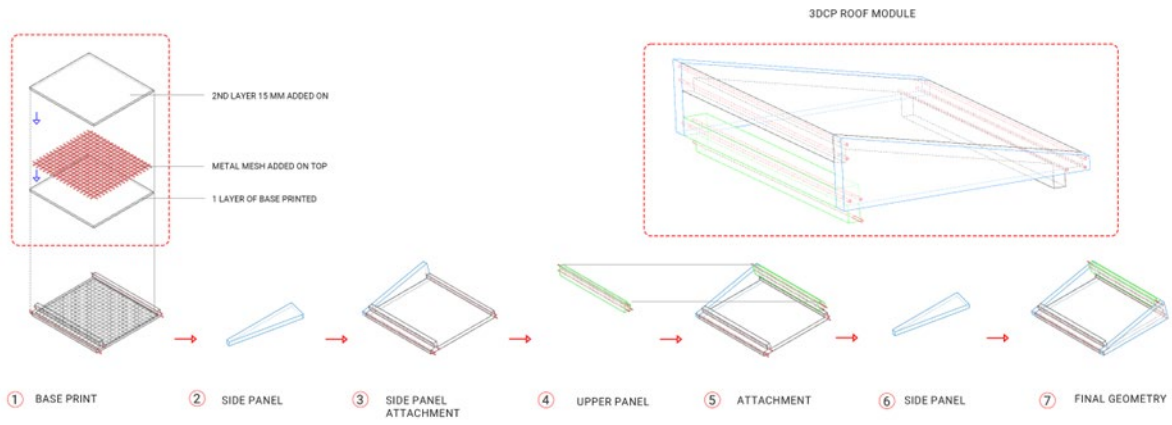


Figure 3. 3DPC printing process.

The sawtooth roof prototype (Figure 3) was fabricated using 3DCP with emphasis on reinforcement integration, modular efficiency, and geometric fidelity. The roof was divided into three interlocking modules: a flat roof base panel with embedded galvanized stucco mesh and steel rebars intended to enhance reinforcement continuity across layers; a flat side panel printed

without reinforcement to serve as an alignment and assembly surface; and an L-shaped connection leg with extended rebars to securely join the base and side panels. This modular approach enabled precise assembly of complex roof geometry while designed to maintain geometric alignment across modules.

Comparative Casting

To benchmark 3DCP against traditional casting, casting tests were conducted using *Sikacrete®-733 W 3D* to compare workability, time, cost, material usage, and waste for producing the same modular roof geometry.

Time Log

The casting process required multiple stages, including mold design, fabrication, assembly, and concrete pouring. The estimated time for each task is summarized below:

Table 1. Time Log Casting.

Task Description	Estimated Time	Notes
Modeling of Mold Geometry	5–6 hours	Created in Rhino/SketchUp
CNC File Preparation	1–2 hours	CAM setup and nesting for MDF
CNC Milling of Mold Pieces	2–3 hours (machine time)	Single run on full-size CNC router
Mold Assembly and Sealing (3-person team)	~24 person-hours total	8 hours with 3 people
Concrete Mixing and Curing	~12–14 hours	Includes prep and monitoring
Demolding, Clean-Up, Finishing	~4–5 hours	Final smoothing and inspection

The full casting process took 50-55 hours—nearly half for mold assembly—while 3D concrete printing completed the same modules in about five hours.

Material Cost

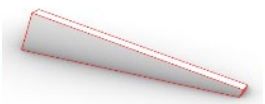
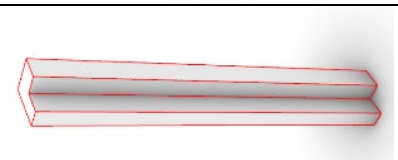
Table 2. Material Cost Casting.

Item	Quantity	Unit Cost	Total Cost	Notes
MDF Sheets (4' x 8' x 3/4")	3 sheets	$55.00	$165.00	CNC-compatible
Silicone Sealant	2 tubes	$12.00	$24.00	For joint sealing
Waterproofing Spray	2 cans	$7.00	$14.00	To protect mold surface
Screws, Fasteners, Wood Glue	Assorted	~$15.00	$15.00	General assembly supplies
Sandpaper, Brushes, Gloves	Assorted	~$10.00	$10.00	For prep and cleanup
Buckets, Mixing Tools (reusable)	2–3 sets	-	-	Previously available or shared lab use
Galvanized Stucco Netting	1 piece (4 ft x 27 in)	$14.98	$14.98	Stucco Netting from Lowe's
Steel Rebar (#3, 3/8-in x 4-ft)	6 bars	$4.16	$24.96	Reinforcement for the module
Marshalltown RM770 Mixer Bit	1 unit	$16.88	$16.88	Ribbon mixer arm for even concrete mixing

The materials and equipment used for casting were primarily standard lab tools, along with purchased mold and reinforcement supplies.

Molds

Table 3. Geometry Part and Molds Volume.

Part	Image (Geometry)	Image (Mold)	Volume (in³)
Roof Flat Part			5040
Side Panel			722.11
Sawtooth Connection			795.53

Evaluation Metrics

Geometric documentation was performed using the Polycam application on a LiDAR-enabled Apple iPhone. The captured data were processed within the application to generate a triangulated surface mesh and subsequently exported in .ply format for further evaluation. The mobile LiDAR system provides practical close-range accuracy of approximately ±3-5 mm (Raj et al., 2020). Challenges arose from sagging, uneven deposition, and misalignments in printing, as well as mold deformation, leakage, and extensive formwork in casting. The flat roof base panel measured approximately 1220 mm × 610 mm × 75 mm. To address these issues, hybrid additive-subtractive approaches, such as post-process CNC milling, were identified as effective strategies to restore tolerances and improve surface quality.

RESULTS: 3DCP ROOF MODULE FABRICATION

Geometric Accuracy

Geometric accuracy was a primary criterion for evaluating the performance of 3D-printed modules compared to cast components, as even small deviations can affect load distribution, joint alignment, and ventilation efficiency in prefabricated roof systems. For the three modules tested—flat, angular, and ventilation-integrated—the 3D-printed elements maintained average deviations of approximately ±2-3 mm for the flat panel, ±3-4 mm for the angular roof geometry, and ±3 mm for the ventilation openings. In contrast, cast modules exhibited larger deviations, with averages of ±8-10 mm for the flat panel, ±10-12 mm for the angular geometry, and ±10–15 mm at the ventilation openings. Improved 3D printing accuracy was achieved through optimized toolpath planning—continuous layer trajectories, fewer sub-path transitions, and a suitably sized nozzle, ensuring consistent extrusion and reduced sagging on inclined surfaces. The observed ±2-3 mm tolerances fall within common prefabrication tolerance ranges (±5-10 mm), indicating

suitability for construction-scale applications (Raj et al., 2020). These refinements enabled tighter dimensional control in complex geometries, demonstrating 3DCP's potential to deliver roof modules with greater precision and repeatability than conventional casting.

Fabrication Efficiency

3D Printing Concrete

The following table summarizes the key outcomes for each roof module, approximate printing time, and representative images.

Table 4. 3D Printing Parameters Table.

Part Name	Speed (mm/s)	Printing Time (Approx.)	Image
Flat Roof Base Panel	45	23.19 min.	
Side Panel Module	35	4.36 min	
L-Shaped Connection Leg	45	16.25	

CASTING TEST

Phase One Casting:

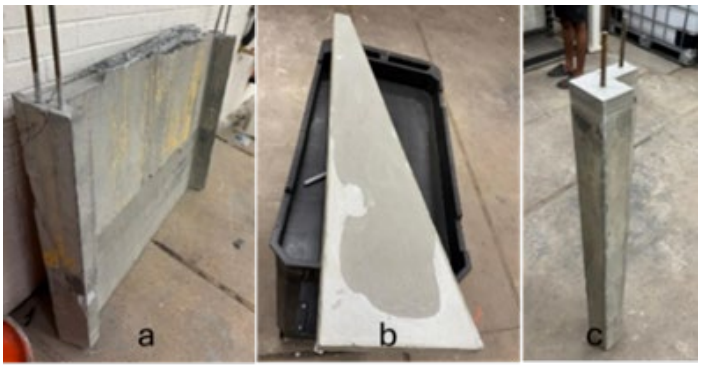


Figure 4. Comparison of cast roof modules from phase one. (A) flat roof module exhibiting visible cracks, (B) side panel with a distinctly different surface texture, and (C) L-shaped connection illustrating variation in form and finish quality.

Before full-scale casting with *Sikacrete®-733 W 3D*, preliminary tests were conducted using *SikaControl® NS* to evaluate casting workability. Water was kept constant at one cup (236.6 ml), while dry mix varied across four trials. The optimal 1.75:1 dry-to-water ratio produced a firm set and good workability, while lower ratios were too wet (1:1).

Phase Two Casting

Table 5. Phase 2 Casting Material Quantity Table.

Part Name	Dry Mix (lb.)	Water (L)	Image
Flat Roof Base Panel	451	42.6	
Side Panel Module	33	3.2	
L-Shaped Connection Leg	59	5.5	

Casting Summary

In phase one, casting with *SikaControl® NS* at a 1.75:1 dry-to-water ratio showed workable consistency but led to cracking, low strength, and surface defects, making it unsuitable for long-term application. Phase two shifted to *Sikacrete®-733 W 3D*, where mix ratios of 2:1, 3:1, and 4:1 were tested; the 3:1 ratio provided the best balance of workability, flow, and compaction. MDF molds, however, warped and suffered water damage, necessitating replacement, sealing, and waterproofing, which increased both preparation time and cost. Rebar and mesh reinforcement were embedded to replicate the structural continuity of the 3D-printed modules. Overall, casting required about 50-55 hours—including mold design, CNC milling, assembly, pouring, curing, and finishing—with mold assembly alone consuming nearly half this duration.

Material Performance and Toolpath

3D Printing Concrete

The flat roof base panel was optimized for material performance and toolpath to ensure strength and accuracy, with #3 rebars zip-tied to fiberglass mesh after the second layer and subsequent layers forming a strong composite; a woven north-south/east-west toolpath minimized cold joints, improved bonding, and reduced sagging (Figure 6a). The side panel, printed flat and without reinforcement, served primarily as an alignment and enclosure component, ensuring uniform layer thickness and precise geometry for seamless integration with the base and L-shaped leg, though a U-shaped connection could have improved interlock and load transfer (Figure 6b). The L-shaped connection incorporated extended rebars anchoring into the base and side panels, acting as the main structural tie, with embedded reinforcement maintaining load continuity (Figure 6c).

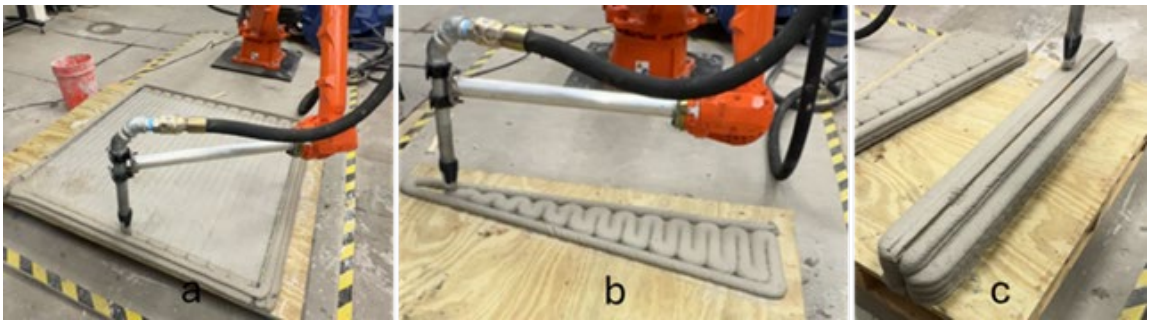


Figure 5. (A) Three-layer printing sequence with integrated rebar and fiberglass mesh. (B) 3D printing of first layer of the side panel. (C) L-shaped leg is being 3D-printed with #3 steel rebars inserted.

Casting

Phase one casting with *SikaControl® NS* at a 1.75:1 dry-to-water ratio initially showed workable consistency but resulted in severe cracking, proving unsuitable for long-term performance. Its high density and poor extrusion compatibility led to replacement with *Sikacrete®-733 W 3D* in phase two. Full-scale casting replicated the 3D-printed roof geometry for direct comparison of

fit, surface finish, and strength (Figure 7). Phase two trials tested 2:1, 3:1, and 4:1 water-to-dry ratios; 3:1 offered optimal workability and was adopted.

The casting specimens were fabricated using MDF molds, which may have influenced dimensional stability due to moisture absorption. MDF molds from phase one exhibited warping caused by water exposure, necessitating replacement and waterproofing measures, which increased both cost and preparation time. Future studies will employ sealed or reusable formwork to enable a more controlled and consistent comparison. Rebar and mesh reinforcement were embedded to ensure structural continuity with the printed modules.

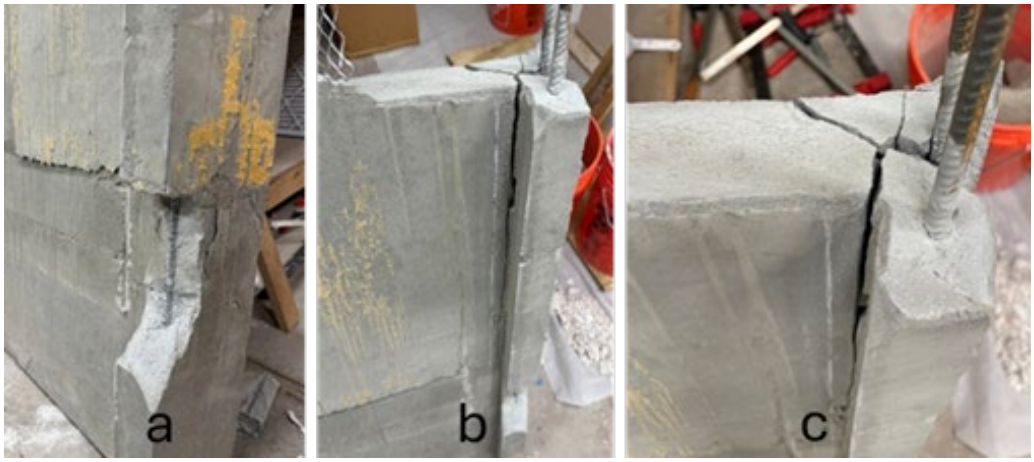


Figure 6. (A) Side portion exhibiting a large missing section due to material breakage. (B) Cracks forming around the rebar and side connection. (C) Multiple cracks propagating along the rebar lines.

Design Flexibility

This study examined the geometric flexibility of 3D-printed roof modules, highlighting their ability to accommodate design variations without custom molds, thereby reducing material waste, labor, and fabrication time while improving precision and expanding design possibilities. The sawtooth roof case study illustrates three key parametric variations (Figure 8.a-c):

• **Variable Length**: The angled roof plane can be adjusted to x, 2x, or x/2, enabling modular adaptability without the need for additional formwork.

• **Angled and Tapered Walls**: Supporting walls form a tapered rectangular profile beneath a linear roof plane, introducing formal complexity while maintaining structural integrity. These geometries can be generated computationally and translated directly into 3D-printing toolpaths, eliminating complex molds.

• **Curved Roof Geometry**: The roof's front-facing portion transitions into a symmetrical curve, longer and more pronounced at the front and shorter at the back. This variation

enhances spatial dynamics and aesthetics while preserving control over material deposition.

The sawtooth roof module was chosen as the case study, because it combines environmental performance (daylighting and ventilation) with prefabrication potential, allowing controlled comparison between 3DCP and casting.

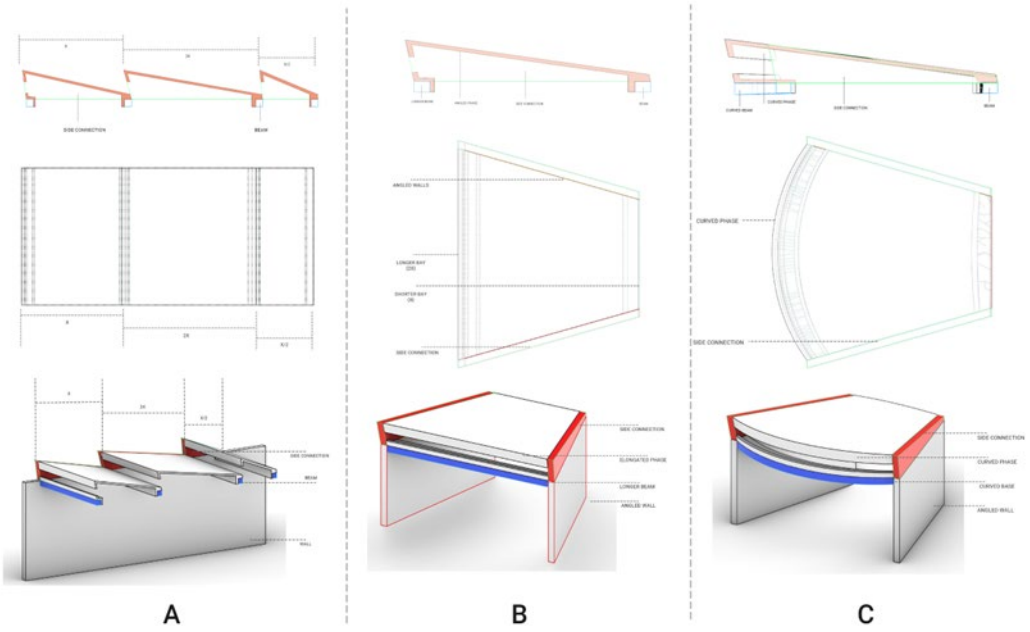


Figure 7. (A) Length variable. (B) Tapered wall. (C) Curved roof geometry on tapered wall.

DISCUSSION

This study shows that 3DCP enhances prefabricated roof modules with greater geometric control, flexibility, and efficiency than conventional casting. Optimized toolpaths and nozzle sizing improved dimensional accuracy; modular printing enabled rapid customization without extra formwork; and integrated reinforcement with layer-by-layer deposition reduced reliance on temporary molds. Despite these advantages, several challenges remain. In addition to high equipment costs, curing control requirements, and evolving regulatory frameworks, 3DCP faces well-documented technical limitations related to interlayer bond strength, reinforcement integration, and long-term durability. These aspects were beyond the scope of this study and were not mechanically tested. The investigation was limited to small- to medium-scale modules, and long-term performance under thermal, fire, or environmental loading was not evaluated. Future research should focus on full-scale validation, mechanical and durability assessment, and scalability, including potential integration of sensing technologies.

SUMMARY AND CONCLUSION

This study demonstrates that 3D concrete printing (3DCP) is a highly effective alternative to traditional casting for prefabricated roof modules. 3DCP drastically reduces fabrication time from approximately 50-55 hours to around five hours by eliminating labor-intensive mold assembly and demolding. It maintains tight geometric tolerances (±2-3 mm), accurately reproducing complex features such as sawtooth ventilation slits and tapered edges, outperforming casting (±10-15 mm deviations). Layer-by-layer deposition improves material efficiency, enables direct reinforcement embedding, ensures uniform interlayer bonding, and minimizes sagging. Additionally, 3DCP lowers labor and mold costs, reduces waste, and minimizes environmental impact, and fiber-reinforced micro-concrete limits shrinkage and post-processing, making it both cost-effective and sustainable. Overall, 3DCP provides superior speed, precision, and environmental benefits compared to conventional casting methods.

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Advancing Sustainable Construction: Robotic 3D Printing and Failure Analysis of Clay-Hemp Composite Structural Walls

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ABSTRACT

The application of robotic 3D printing in conjunction with bio-based construction materials presents a transformative opportunity for sustainable infrastructure development. This study investigates the feasibility and structural performance of clay-hemp composite walls fabricated through robotic 3D printing. Key research components include the development of printable, buildable, and flowable material mixtures, toolpath design strategies, and optimization of printing parameters critical for ensuring structural integrity and print stability. Experimental work involves extrusion and printing of various geometries, such as solid beams, cylinders, and cubes, as well as complex patterns, including zigzag and honeycomb wall structures.

To better understand the failure mechanisms, the study examines material deformation behavior, toolpath adaptability, and print quality under different conditions. A series of mechanical tests were conducted on printed elements to assess load-bearing capacity and failure modes. Additionally, the study proposes mitigation strategies such as hempcrete stabilization, optimized toolpaths, controlled print timing, and modular batch printing to enhance structural performance. These insights contribute to both the scientific understanding and practical application of sustainable 3D printed construction using clay-hemp composites, offering a pathway toward greener and more efficient building practices.

Keywords: Clay-Hemp Composite, Robotic 3D Printing, Sustainable Construction, Failure Mechanism, Toolpath Optimization, Natural Building Materials, Automated Fabrication.

INTRODUCTION

The construction industry is currently undergoing a period of rapid transformation, with three-dimensional (3D) printing emerging as a disruptive technology capable of reshaping how buildings are designed and delivered. Additive manufacturing in construction offers advantages that include high geometric flexibility, material efficiency, reduction in formwork, and automation of labor-intensive processes. However, despite these benefits, the majority of large-

scale 3D printing applications rely heavily on cement-based mortars. Cement production contributes an estimated 8% of global carbon dioxide emissions, raising significant environmental concerns (Marsh, 2022). The reliance on cement undermines the sustainability promise of 3D printing, motivating a search for alternative materials that can reduce environmental impact while maintaining adequate structural performance.

Earthen materials such as clay and cob have a long history in vernacular architecture. They offer advantages including low embodied energy, thermal regulation, and widespread availability. When combined with fibers such as hemp, these materials gain improved tensile resistance, crack control, and durability. Hemp-based composites, including hempcrete, have been increasingly investigated for their thermal insulation properties and carbon sequestration potential (Binega and Memari, 2023, "A review of Experimental Studies"). However, their application in structural contexts remains limited, and their adaptation for automated extrusion printing remains largely unexplored.

Recent research into 3D printing with soil, adobe, and hemp-lime mixtures has shown that natural materials can be adapted to robotic fabrication. Yet challenges persist in extrusion consistency, layer adhesion, drying shrinkage, and geometric stability. Unlike cement-based mortars, natural composites have highly variable rheological properties that must be carefully tuned for printability. Moreover, their mechanical behavior under compressive and tensile stresses is less predictable, requiring systematic study (Binega and Memari, 2023, "Learning from Historical Building"). Unlike hemp-lime (hempcrete) systems that rely on lime carbonation and are primarily insulation materials, the clay-hemp composite studied here functions as a load-bearing earthen matrix reinforced with plant fibers, offering a distinct mechanical behavior and fabrication potential.

This study aims to address these gaps by investigating clay-hemp cobcrete as a printable material for robotic 3D printing of structural walls. The work specifically focuses on:

1. Optimizing mixture design to balance workability, extrudability, and green strength.

2. Developing toolpath strategies that enable varied geometries, including zigzag, contour, and honeycomb patterns.

3. Evaluating the mechanical performance of printed specimens compared to traditional cob.

4. Analyzing failure mechanisms during and after printing and developing mitigation strategies.

By systematically addressing these objectives, the paper contributes both to the material science of sustainable composites and to the field of digital fabrication in construction. The findings aim to demonstrate that clay-hemp cobcrete can serve as a viable eco-friendly alternative in additive manufacturing, supporting affordable and low-carbon housing initiatives worldwide.

LITERATURE REVIEW

Additive Manufacturing in Construction

Since the first demonstrations of large-scale 3D printed houses in the early 2010s, additive manufacturing has gained momentum as a tool for sustainable and rapid construction (Binega and Memari, 2023, "A Review of Experimental Studies"). The technology is used for printing concrete walls, bridges, and entire housing units. However, most research and commercial applications have centered on portland cement-based materials. While these mixtures provide the necessary strength and durability, they undermine environmental goals. The need for alternatives has motivated investigations into geopolymers, gypsum, and earthen materials.

Earthen Construction and Cob

Cob, a traditional building material composed of clay, sand, straw, and water, has been used for centuries across Africa, Asia, and Europe. Its popularity lies in its low cost, high thermal mass, and use of locally available resources (Binega and Memari, 2023, "Learning from Historical Building"). Yet conventional cob construction is labor-intensive, with long drying times and limited structural uniformity. Introducing digital fabrication to cob-based construction could overcome these barriers, offering speed and repeatability while retaining environmental benefits.

Hemp as a Reinforcement

Hemp fibers and shiv (the woody core) are increasingly used in construction materials due to their strength, light weight, and carbon sequestration properties. Hempcrete, a mixture of hemp shiv, lime, and water, has been widely promoted for insulation. Studies have shown that hemp reinforcement improves tensile strength and reduces cracking in clay-based composites. Despite this, hemp has rarely been tested in additive manufacturing systems beyond small-scale experiments.

Robotic Fabrication and Toolpath Design

Robotic arms allow greater flexibility in 3D printing compared to gantry-based systems, enabling curved, inclined, and multi-directional toolpaths. Grasshopper and HAL are common platforms for parametric toolpath generation. Previous work has explored lattice and honeycomb patterns to reduce material usage while maintaining load-bearing capacity. However, these strategies are rarely applied to earthen composites due to concerns about collapse during drying.

Research Gap

To date, limited studies have examined the combination of clay-hemp composites with robotic extrusion. While earthen printing has been demonstrated, systematic evaluation of mechanical performance, toolpath feasibility, and failure mitigation is lacking. This study contributes by bridging natural material science with digital construction technologies, aiming to advance knowledge on both fronts.

MATERIALS AND METHODS

This study adopted an experimental approach combining material formulation, robotic 3D printing, and structural testing. The methodology was designed to capture both the opportunities and challenges of adapting a traditional clay-hemp mixture to an automated fabrication process.

Materials and Mix Design

The base constituents included natural clay, river sand, hydrated lime, and industrially processed hemp shiv. Clay served as the binder, sand as the skeletal filler, lime as a stabilizer, and hemp as reinforcement. Preliminary mixtures were prepared to evaluate extrusion quality and mechanical stability. Through iterative testing, an optimized volumetric ratio of clay, lime, sand, hemp, and water was selected as shown in Table 1. The clay used in this study was a natural clay classified as a high-plasticity clay (CH) according to the Unified Soil Classification System. The liquid limit was approximately 58%, and plasticity index approximately 32%. The hemp shiv consisted of industrially processed woody core particles with an approximate length range of 5-15 mm and average particle width of 2-4 mm.

Moisture content was found to be a critical factor. Low water content produced stiff mixes prone to clogging, while excessive water resulted in slumping and interlayer collapse. A target water-to-solid ratio of approximately 0.45 was established after repeated extrusion trials (Binega and Memari, 2024, “3D Printing”). Hemp shiv contributed to reducing shrinkage cracks by providing distributed tensile resistance and increasing drying uniformity (Binega and Memari, 2024, “Incorporating Carbon-Negative”).

Table 1. Mixture of Cobcrete.

Raw Material	%
Clay	17.5
Sand	40
Lime	18
Water	22.5
Hemp	2
Additive	0
Total	100

Rheological and Printability Assessment
To assess printability, three criteria were evaluated:

- **Flowability**: Measured qualitatively by extrusion pressure required to maintain a continuous filament.
- **Buildability**: Evaluated by stacking 5-7 layers without collapse (Ashrafi et al., 2021).
- **Green Strength**: Assessed via indentation resistance immediately after deposition.

Flowability improved with slightly elevated water content, but buildability decreased. Hemp shiv mitigated deformation by stiffening the matrix. Each mixture was subjected to a simplified "stacking test," where 200 mm-high columns were printed and visually inspected for vertical deformation. The optimized mixture achieved vertical deviation of less than 5 mm over 200 mm height, deemed acceptable for wall construction.

Robotic Printing Setup
An ABB IRB 4600 six-axis robotic arm (Binega Yemesegen 2022; Binega and Yang, 2021) was employed, fitted with a custom extrusion nozzle connected to a pressurized mortar pump, as shown in Figure 1. The nozzle diameter was adjustable between 25 and 40 mm. Layer height and nozzle velocity were programmed through Grasshopper with the HAL plugin, enabling parametric control.

The robotic platform allowed printing on flat and curved toolpaths with positional accuracy of ±0.5 mm. Printing parameters were systematically varied to study their effects:

- **Nozzle Diameters**: 25, 30, 40 mm
- **Layer Thicknesses**: 15-20 mm
- **Print Speeds**: 50-120 mm/s
- **Extrusion Pressures**: 0.25-0.45 MPa

A vibration sensor was installed on the nozzle to detect clogging events, allowing adjustment of pump pressure.

Figure 1. Printing equipment.

Toolpath Design

Toolpaths were designed to evaluate the effects of geometry on structural performance, as shown in Figure 2. Three categories were generated:

1. **Zigzag Infill**: Straight parallel lines with alternating direction.
2. **Contour-Following**: Continuous paths tracing the perimeter of walls.
3. **Honeycomb Infill**: Hexagonal lattice structure providing strength-to-weight optimization.

Toolpaths were created in Rhino/Grasshopper with adjustable infill density and extrusion overlap. To avoid weak adhesion at corners, smoothing algorithms were applied to round sharp turns. For honeycomb paths, overlap at hexagonal junctions was increased by 5-10% to ensure continuity ("Honeycomb Infill," n.d.).

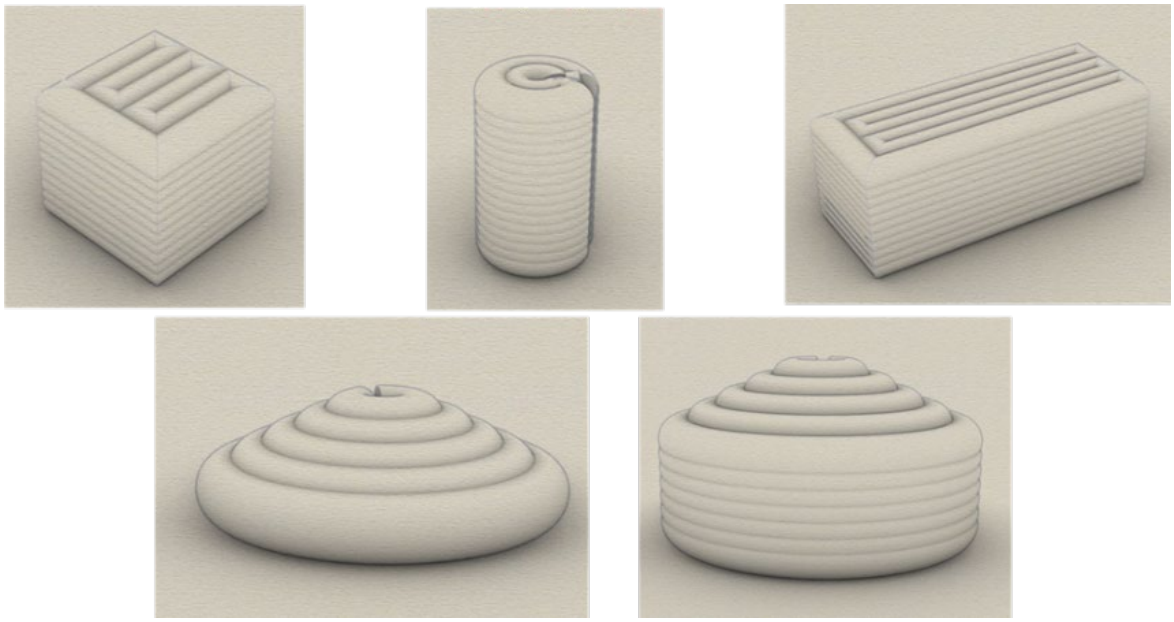

Figure 2. Toolpath design and generation of printable geometries.

Prototype Fabrication

A series of prototypes were printed to represent different scales and structural scenarios:

- **Beams**: 200 × 200 × 600 mm rectangular prisms.
- **Cubes and Cylinders**: 150 × 150 × 150 mm and Ø150 × 300 mm respectively, for material testing.
- **Curved Wall Sections**: 600 mm long with varying radii, to evaluate geometric stability.
- **Honeycomb Walls**: 1.0 m × 0.5 m × 0.2 m, representing lightweight but load-bearing panels.

Each prototype was printed in a controlled indoor environment at 21-24 °C with relative humidity 40-55%. Ambient fans were used to accelerate surface drying where needed (Pritchard, 2023).

Mechanical Testing Protocols

Mechanical testing followed adapted standards for earthen materials:

- **Compressive Strength**: Cylinders and cubes were tested using a universal testing machine (UTM) in accordance with ASTM C39 guidelines, adjusted for low-strength

materials as shown in Figure 3 (Binega and Memari, 2024, “Material Science”).

- **Splitting Tensile Tests**: Cylindrical specimens were tested along diametral axis (ASTM C496 adaptation), as shown in Figure 4.
- **Flexural Strength**: Beams were tested in three-point bending.
- **Dimensional Accuracy**: Photogrammetry was used to measure deviations from design geometry.
- **Failure Analysis**: High-resolution imaging of cracks and deformations for fiber pull-out observations.

All specimens were cured for 28 days before testing to ensure moisture equilibrium. At least three replicates were tested for each specimen type to establish statistical reliability.

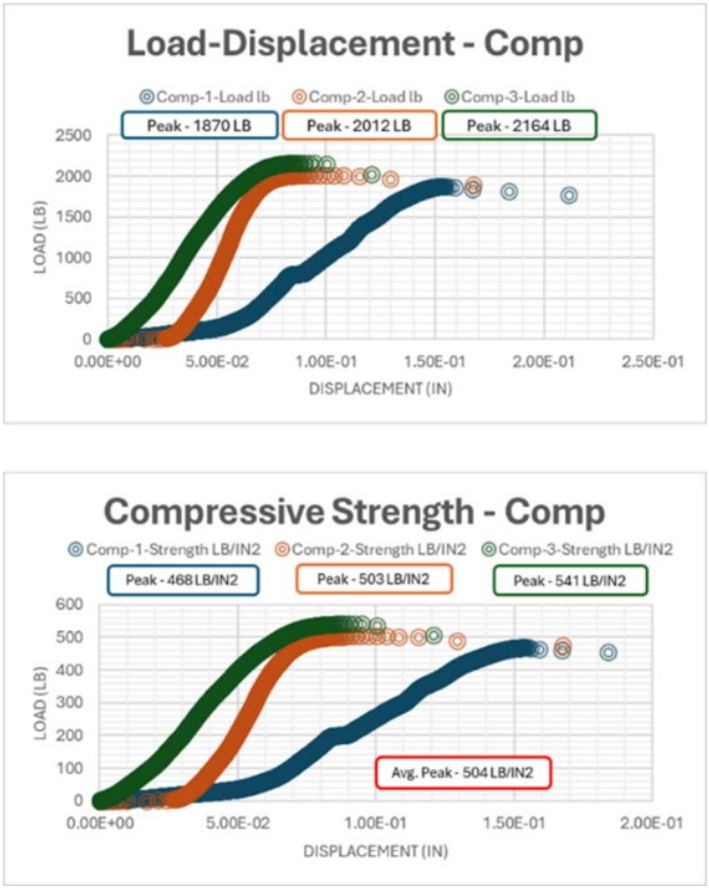

Figure 3. Load displacement and compressive strength test results.

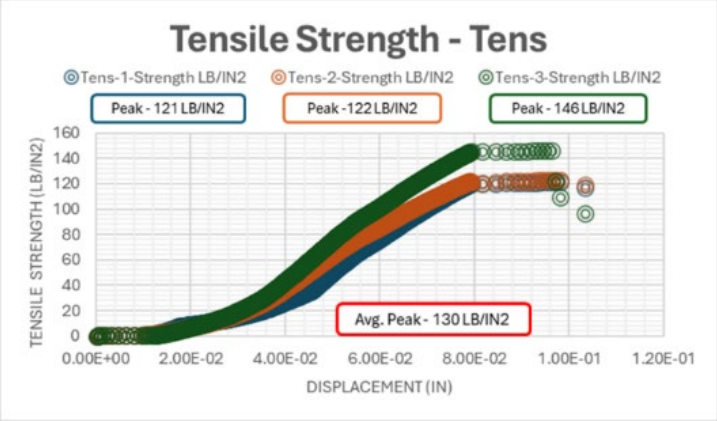

Figure 4. Tensile strength test result.

RESULTS

Material Behavior During Printing

The optimized clay-hemp mixture demonstrated stable extrusion through nozzles of 25-40 mm without clogging when pump pressure was maintained between 0.30-0.40 MPa. Flowability was directly influenced by water content; increasing the water-to-solid ratio beyond 0.50 improved extrusion smoothness but caused immediate slumping after three layers. The inclusion of hemp shiv reduced shrinkage cracks by approximately 30% compared to mixtures without fibers, confirming hemp's role as a stabilizer.

The stacking test revealed that printed columns of up to seven layers (≈210 mm) could remain upright without deformation when using the optimized mixture. However, exceeding this height without intermediate drying resulted in lateral bulging and plastic collapse.

Toolpath Performance

Toolpath geometry strongly influenced both print quality and structural capacity:

- **Zigzag Infill**: Provided rapid deposition but exhibited weak adhesion at line intersections. Failures occurred at corner joints where overlap was minimal.
- **Contour-Following**: Produced smoother surfaces and better interlayer bonding but showed less efficient load distribution in compression tests.
- **Honeycomb Infill**: Demonstrated the most favorable performance, with 40% higher strength-to-weight ratio compared to solid infill. The hexagonal nodes effectively distributed stresses, delaying crack propagation as shown in Figure 5.

Honeycomb geometries achieved the most efficient structural performance. While their absolute compressive strength (≈2.4 MPa) was slightly lower than solid zigzag specimens (≈2.6 MPa), the

honeycomb configuration used approximately 30% less material volume, resulting in a 40% improvement in strength-to-weight ratio.

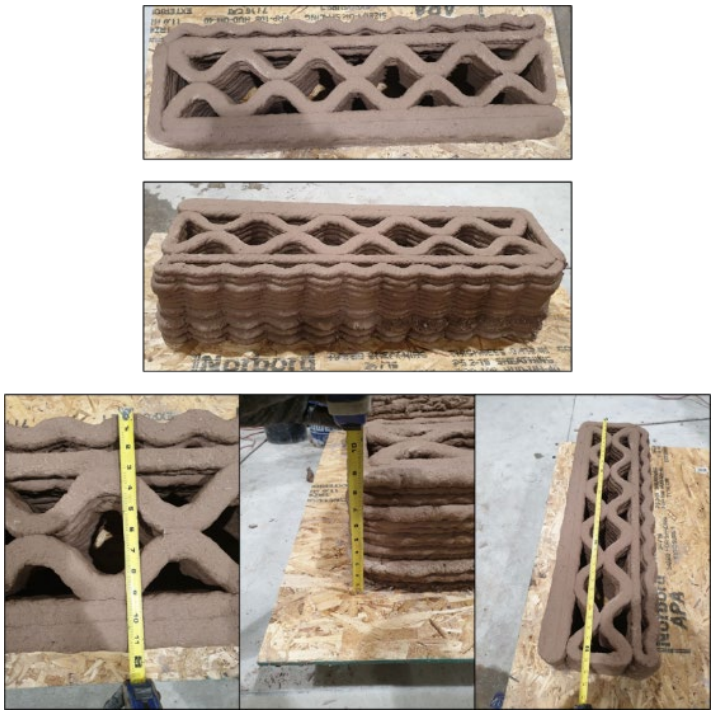

Figure 5. 3D printed rectangular textured honeycomb pattern wall and its measurements.

Failure Observations

Failure modes were categorized into four types:

1. **Plastic Collapse During Printing**: associated with high water content and insufficient drying between layers, as shown in Figure 6.

2. **Adhesion Failure**: separation at interlayer boundaries under tensile loads, often linked to insufficient overlap or nozzle misalignment.

3. **Buckling Deformation**: observed in tall slender wall prints where self-weight exceeded green strength.

4. **Material Cracking**: shrinkage cracks occurred during drying, reduced but not eliminated by hemp fibers.

Microscopic examination revealed fiber pull-out rather than fiber rupture, suggesting that mechanical anchorage between hemp shiv and clay matrix is the primary contributor to toughness (Suiker et al., 2020).

Figure 6. Plastic collapse of a curved contour parallel pattern wall.

DISCUSSION

The results confirm that clay-hemp cobcrete can achieve structural properties suitable for wall applications when carefully formulated and printed with optimized toolpaths. Compared to hand-formed cob, printed specimens exhibited up to three times greater compressive strength and significantly improved tensile behavior. This improvement is attributed to both material densification during extrusion and enhanced fiber alignment within layers.

Honeycomb geometries outperformed both zigzag and contour-filling strategies, highlighting the potential of parametric toolpath design for optimizing natural materials. However, challenges remain in scaling the process. Layer adhesion and drying control were the dominant constraints, emphasizing the need for adaptive printing schedules and environmental conditioning.

Failure mechanisms observed in this study provide critical insights for future practice. Plastic collapse can be mitigated by reducing water content or implementing staged drying. Adhesion failure requires precise nozzle control and intentional overlap design. Buckling can be addressed through hybrid systems, where vertical reinforcement (e.g., bamboo or timber dowels) is inserted during printing (Binega and Memari, 2025).

This study is limited to laboratory-scale prototypes under controlled indoor environmental conditions. The following limitations should be noted:

- Environmental durability (rain, humidity cycling, freeze-thaw) was not evaluated.
- Full-scale structural wall assemblies with openings and roof loads were not tested.

- Long-term shrinkage and creep behavior were not monitored beyond 28 days.
- Code compliance pathways for 3D printed earthen systems remain underdeveloped.

Future research should address full-scale housing prototypes, environmental exposure testing, and structural integration with hybrid reinforcement systems.

CONCLUSION

This research demonstrates the feasibility of robotic 3D printing with clay-hemp composites as a sustainable alternative to cement-based mortars in structural wall construction. The key findings are:

1. An optimized clay-hemp mixture achieved stable extrusion and exhibited improved crack resistance compared to traditional cob.
2. Mechanical testing showed compressive strengths up to 3.0 MPa and tensile strengths of 0.55 MPa, representing significant improvements over hand-formed cob.
3. Honeycomb toolpaths delivered superior strength-to-weight performance, validating the use of digital parametric design for structural optimization.
4. Failure mechanisms were identified and mitigated through controlled drying, improved overlap design, and fiber reinforcement.

The study highlights both the opportunities and challenges of integrating vernacular materials with advanced fabrication technologies. Future work should investigate full-scale housing prototypes, long-term durability under environmental exposure, and life-cycle assessments to quantify sustainability benefits.

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Analytical and Numerical Analysis of 3DCP Structures

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ABSTRACT

Structural analysis was carried out on hypothetical 3DCP buildings situated in Alaska (AK), Pennsylvania (PA), and California (CA). These states were selected due to their exposure to extreme conditions, such as earthquakes in California and heavy snowfall in Alaska, with Pennsylvania serving as a moderate reference point. The experimental data obtained on the structural capacity of 3DCP was employed to estimate the nominal capacity of these sections. The findings indicate that the strength of 3DCP exceeds the necessary requirements for low-rise buildings, demonstrating an ability to withstand significantly higher loads. Using the macro-model approach, a numerical analysis was conducted on the full printed structure to evaluate the stresses in the elements under the loads calculated from ASCE 7-16.

INTRODUCTION

In recent years, the integration of 3DCP technology into the construction sector has opened new frontiers in architectural design and structural engineering. Unlike traditional construction methods, 3DCP offers the potential to build complex geometric structures with increased speed and reduced material waste (Buswell et al., 2018). However, as the application of 3DCP expands, a critical need arises for a deeper understanding of the structural behavior of printed objects. Analytical and numerical analyses play a pivotal role in addressing these challenges, providing essential insights into the mechanical properties and stability of 3DCP structures under various loading conditions (Wolfs et al., 2018). This paper focuses on developing and applying advanced analytical and numerical tools tailored for 3DCP, aiming to optimize the design and ensure the structural integrity of printed buildings.

In addition to challenges regarding the material and construction method itself, the variation in location for a project introduces numerous parameters affecting the required capacity and structural integrity. The printing process prolongs the material's exposure to the open environment during the critical curing period, increasing the risk of insufficient curing. This risk is exacerbated in extreme environmental conditions, such as high temperatures, cold regions, and areas of low humidity, where optimal curing conditions are compromised (Kazemian et al., 2017). The impact of wind speed further complicates the situation, as higher winds can

significantly increase moisture evaporation from the concrete before it has fully cured. Additionally, direct sunlight can raise the concrete's surface temperature, accelerating moisture loss and potentially leading to uneven curing, undermining the material's strength and durability (ACI 305R-20, 2020).

During the printing process of concrete, these effective environmental parameters significantly affect the final quality, especially in the interlayer surface zone. Even the curing time affects the initial yielding strength of concrete and causes a variation in the deformation of layers during the printing due to the weight of the upper layers (Aminpour and Memari, 2024b). In a laboratory environment where environmental parameters are constant, this deformation is measured and considered in the design for the toolpath (height). However, if the environment changes, this deformation could cause imperfections in the structure and create weaknesses that could serve as points for failure initiation. Effective management of these environmental factors—temperature, humidity, wind, and sunlight—is essential during the printing and curing process to ensure that the concrete develops robust structural properties (Le et al., 2012).

At this point, the structural design of 3DCP elements is divided into three approaches. The first method is based on experimental results; it involves testing and licensing similar geometries intended for real projects (Bos et al., 2016). This approach directly applies practical insights gained from specific configurations to ensure safety and effectiveness. The second method treats the 3DCP shell merely as formwork, with the infill concrete designed according to ACI 318 (ACI, 2019) or similar standards like TMS 402 (TMS, 2016). Although this method aligns with established structural codes, it tends to reduce the efficiency of the section and leads to an overconsumption of materials. This conventional approach may not fully leverage the potential advantages of 3DCP in terms of material optimization and structural innovation. The third method incorporates recently developed standards specific to 3DCP, such as ICC AC509 or USACE ECB 2021-13 (ICC, 2019; USACE, 2021). However, these standards necessitate experimental testing to validate the structural performance of the printed elements and ensure compliance with safety requirements. By adhering to these specialized standards and conducting the required experimental testing, the design and execution of 3DCP projects can achieve higher efficiency and better performance.

The first part of this paper delves into the analytical approaches based on experimental results to predict the load-bearing capacity and deformation characteristics of 3DCP structures. Subsequently, the discussion transitions to numerical simulations, which are indispensable for investigating complex scenarios that are challenging to model analytically. Among other techniques, FEA is utilized to simulate the behavior of 3DCP structures under real-world conditions (Wolfs et al., 2018). Through the investigation of both analytical and numerical findings, this study aims to contribute to the standardization and optimization of 3D concrete printing processes.

Model Properties and Load Calculations

To understand the behavior, stress distribution, and failure modes of 3DCP using both FEM (Finite Element Modeling) and analytical methods, a simplified structure was assumed for

analysis. This study focused on a small room measuring 3.86 m x 3.86 m, printed with concrete, featuring a rigid concrete slab 20 cm thick on top. The walls were assumed to be constructed from printed concrete with infill cast concrete, each wall consisting of six panels that are 20 cm thick, 300 cm long, and 61 cm wide (Figure 1). Each panel was reinforced with two vertical Grade 60 steel rebars (number 5). The base of the structure was assumed to be connected to the ground with pinned support.

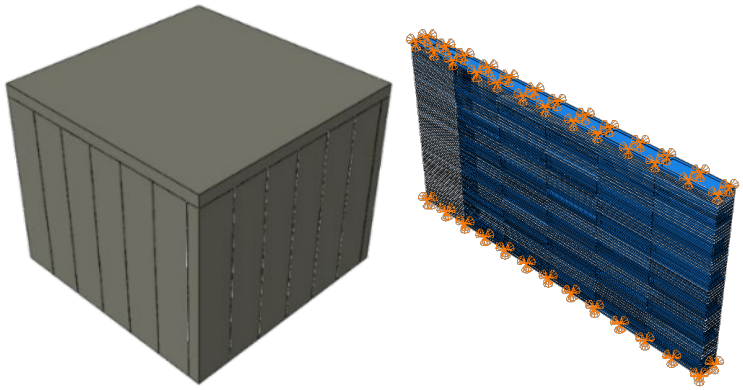

Figure 1. Model of 3DCP structure (left) and the analytical model of each wall (right).

The infill concrete used was categorized into light-weight (type L) and normal-weight (type N) concrete, with properties detailed in Table 1. Both house types were printed using the M0 material. The difference lay in the infill material for the walls. The C40 material was used for the L-type house, while for the N-type house, C0 was used for the infill. To address various types of loading, these structures were assumed to be located in three different states: California, Alaska, and Pennsylvania. These states were selected based on their distinctive environmental challenges: California is known for its high earthquake risk; Alaska experiences both earthquakes and significant snow loads, which can influence earthquake loading; and Pennsylvania is considered a moderate region. The design incorporates earthquake, snow, and dead loads, which are critical for evaluating the resilience and structural integrity of 3DCP in diverse climatic conditions. This comprehensive setup explored the practicality and performance of 3DCP structures under varying environmental impacts and loading conditions.

Table 1. Concrete Mixture Composition.

Composition (Volume Ratio)	M0	C0	C40
Cement	0.0%	14%	8%
Sand	0.0%	27%	16%
Gravel	0.0%	40%	24%
GCT	80%	0.0%	0.0%
EPS	0.0%	0.0%	40%
Water	20%	20%	12.60%
Superplasticizer	0	0	12.5 Kg/m3
Compressive strength (MPa)	22.1	21.8	6.1

The structure's dead load was assumed to include only the weight of the concrete sections, including the walls and roof, with an additional 10% allowance for mechanical and electrical equipment. The weight of the 24 wall panels was 15,032 kg for the L-type structure, and 21,254 kg for the N-type structure. The weight of the roof for both types was 5,529 kg.

The snow load is calculated based on ASCE 7-16. The structure was assumed to be partially exposed with surface roughness type C. The Ce value was assumed to be one for all three locations. The Thermal Factor (Ct) value was typically assumed to be one for residential structures. The ground snow load value was extracted from ASCE 7-16 based on the location. The snow load on flat roofs was calculated based on Equation 1 (Table 2):

$$p_f = 0.7 C_e C_t I_s p_g$$

Equation 1.

Table 2. Snow Load.

Location	pg (kN/m2)	pf (kN/m2)
Fairbanks, AK	4.6	3.22
San Francisco, CA	0.2	0.14
State College, PA	1.19	0.833

The structures were located on D type soil, which was the default soil type in ASCE 7. The risk category of the structure was assumed to be residential (Category II). The Equivalent Lateral Force (ELF) procedure was used to calculate the earthquake load on the structure. As the Response Modification Coefficient for 3DCP was not explicitly provided in ASCE, an average value was assumed. Since the material properties of 3DCP are between those of ordinary reinforced concrete shear walls (Ra = 4) and ordinary reinforced masonry shear walls (Ra = 2), an average value of Ra = 3 was assumed for 3DCP. The seismic response coefficient was calculated based on Table 3 obtained from ASCE 7 Hazard Tool:

Table 3. Seismic Response Parameters.

Location	S1	SDS	Cs
Fairbanks, AK	0.35	0.84	0.28
San Francisco, CA	0.6	1.15	0.38
State College, PA	0.039	0.1	0.03

The weight of 3DCP structures includes the printed walls, infill concrete, and the structure's roof. To calculate the weight for both N and L type structures, the roof load, in addition to half of the weight of the walls, was considered (Table 4). The remaining half of the weight of the walls was distributed directly to the ground. In addition, the 20% of snow load should be added to the effective weight if the flat roof snow load exceeds 1.44 kN/m2. Therefore, for AK the additional weight was considered.

Table 4. Effective Weight of Structure.

Total weight of L-type walls (kg)	Total weight of N-type walls (kg)	Weight of roof (kg)
7516	10627	5529

It was assumed that the load is applied perpendicular to two sides and parallel to the other walls. Therefore, two walls acted as shear walls, while the other two walls were connected to the ground and slab. The seismic base shear load was applied equally on both sides of the wall (Table 5 and Figure 2). The other two walls experienced out-of-plane flexure. The shear capacity of the walls was calculated based on ACI 318, using Equation 2 and assuming that only the core contributes to the shear due to uncertainties about the quality of interlayer bonding in 3DCP. The

results indicated that the shear capacity of the walls was significantly higher than the applied load. This suggested that not all wall panels need to be filled with infill concrete. Based on the results, the shear strength of the walls was significantly higher than the applied load.

$$V_n = \left(\alpha_c \lambda \sqrt{f_c'} + \rho_t f_y\right) A_{cv}$$

Equation 2.

Table 5. Comparison of Shear Load and Shear Strength of Walls.

Building Type	Location	Effective weight, W (kN)	Seismic base shear, V (kN)	Seismic base shear on each shear wall (kN)	Shear wall capacity $\emptyset V_n$ (kN)
L-type	Fairbanks, AK	135.72	38.00	19.00	86.25
	San Francisco, CA	127.84	49.01	24.50	86.25
	State College, PA	127.84	4.26	2.13	86.25
N-type	Fairbanks, AK	166.21	46.54	23.27	218
	San Francisco, CA	158.33	60.69	30.35	218
	State College, PA	158.33	5.28	2.64	218

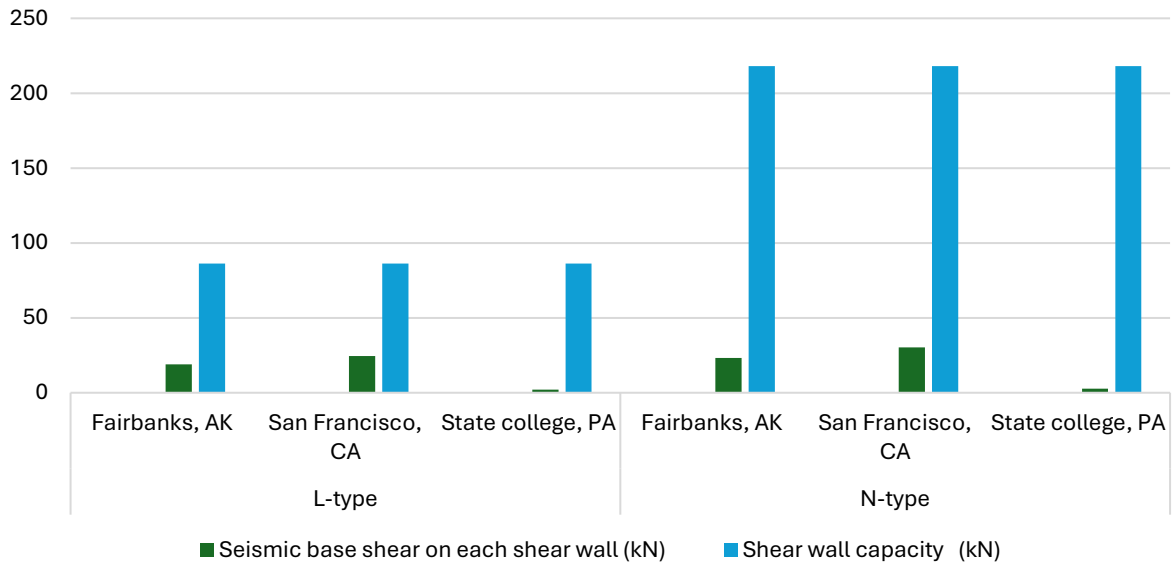

Figure 2. Comparison of shear load and shear strength of walls.

The out-of-plane flexural capacity of 3DCP walls filled with LWC and NWC was obtained by experimental test and is presented in Table 6 and Figure 3. The horizontal seismic design force (Fp) on the front and back walls (perpendicular to applied shear load) was calculated based on ASCE 7 section 13.3 using Equation 3. The weight of each panel was calculated, and the distributed load was determined based on the distribution of Fp on the panel. The moment on each panel was then calculated, assuming the panel was pinned and supported at both ends. The results indicated that the nominal moment capacity of the panels was considerably higher than the moment applied to each panel. The horizontal seismic design force (Fp) should be applied at the center of gravity of the component and distributed in accordance with the component's mass distribution. The Fp was calculated for each region and each wall type, assuming z and h are equal to 3 m. Additionally, the Rp for walls was taken as 2.5, aP was 1, and the SDS and WP were calculated based on the wall type and location.

$$Fp=(0.4a_P S_{DS} W_P)/(R_p/I_p) (1+z/h)$$

Equation 3.

Table 6. Out-of-Plane Flexural Load and Flexural Capacity of Walls.

Building Type	Location	Weight of each panel (kN)	Fp for each panel (kN)	Distributed load on panel surface (kN/m2)	Moment on each panel Mu (kN.m)	Nominal moment capacity $\emptyset M_n$ (kN.m)
L-type	Fairbanks, AK	6.14	4.12	2.29	0.52	4.6
	San Francisco, CA	6.14	5.65	3.14	0.71	4.6
	State College, PA	6.14	0.49	0.27	0.06	4.6
N-type	Fairbanks, AK	8.68	5.83	3.24	0.73	13.68
	San Francisco, CA	8.68	7.98	4.44	1.00	13.68
	State College, PA	8.68	0.69	0.39	0.09	13.68

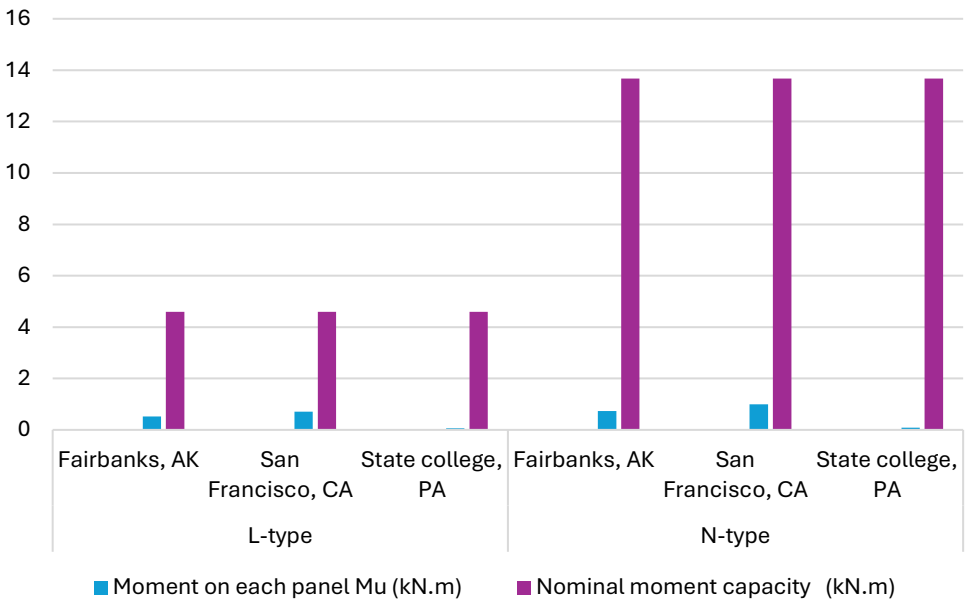

Figure 3. Out-of-plane flexural load and flexural capacity of walls.

Numerical Modeling and Analysis

Numerical analysis was conducted on the full model using macro-model approach. Abaqus was employed to perform finite element modeling, accounting for the nonlinear behavior of concrete using the Concrete Damage Plasticity (CDP) model, as well as the nonlinear interlayer bonding behavior. The material properties are presented in Table 7. The structure was assumed to be subject to snow, earthquake, and dead loads. The snow load was applied to the structure's roof. The dead load was applied as gravity load. The earthquake load was applied at the structure's rigid diaphragm (roof) level (Figure 4). The deformation of the structure was influenced by both shear loads applied to the side walls and out-of-plane flexure experienced by the front and back walls. The combination of these loading conditions contributes to the structure's overall behavior. Since the live load was not considered, the main load combination of 1.2D + Ev + Eh + L + 0.2S was used for the FEM model.

Table 7. Material Properties and Parameters for Numerical Analysis (N. Aminpour and A. Memari, (2024b)).

Concrete type	Ep (GPa)	Et (GPa)	v	Dilation angle	Kc	e	fb0/fc0	Viscosity parameter
M0	9.42	11.61	0.2	40	0.66	0.1	1.2	0.0
C0	16.1	-	0.2	35	0.66	0.1	1.2	0.0
C40	7.6	-	0.2	30	0.66	0.1	1.2	0.0

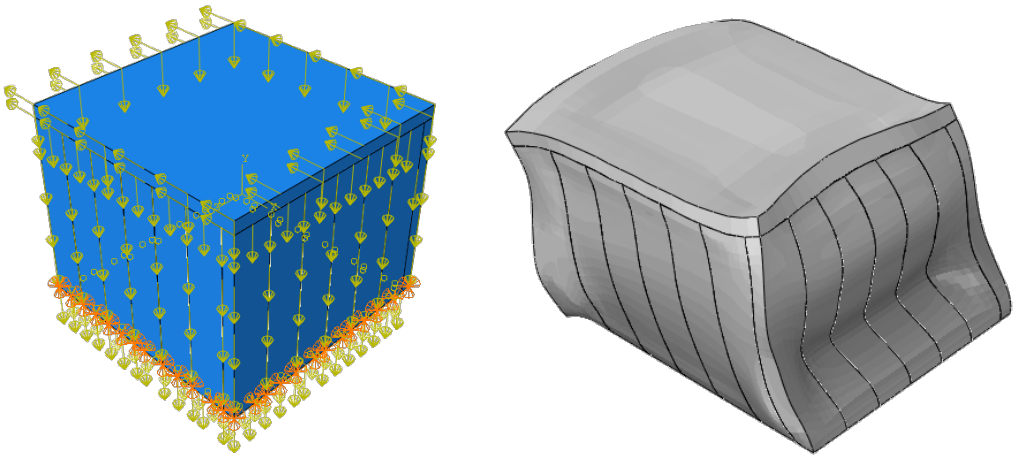

Figure 4. Applied loads on the structure and the potential exaggerated deformation.

The FEM results, presented in Figures 5 to 10, revealed that 3DCP structures across all three regions perform acceptably during seismic events, there was no indication of collapse. Of course, there were over-stress conditions, but such was not expected to cause overall failure (collapse). The analysis also revealed that in AK and CA, the seismic activity caused displacements that surpassed those induced by dead loads in both magnitude and parallel displacement. Conversely, in PA, the stress resulting from combined loads was notably lower, with vertical displacements due to axial and snow loads playing a more dominant role than earthquake effects. The most pronounced structural damage in CA was noted in the L-type structure, largely attributable to the infill material's vulnerability. Near the diaphragm, the shell underwent up to 81% material stiffness degradation (Figure 6, DAMAGET). For the California case, the N-type structure experienced the highest damage in tension under the roof, while damage in compression was most severe near the base in the shear walls. The shell of the structure reaches 81% damage; however, the core remains undamaged. The roof displacement under the load reached a total magnitude of 8 mm. In comparison, the L-type structure exhibited a lower roof displacement of 6.1 mm due to a reduced earthquake load, attributed to the structure's lighter weight. Despite this, the tension damage in the shell of the L-type structure was more extensive.

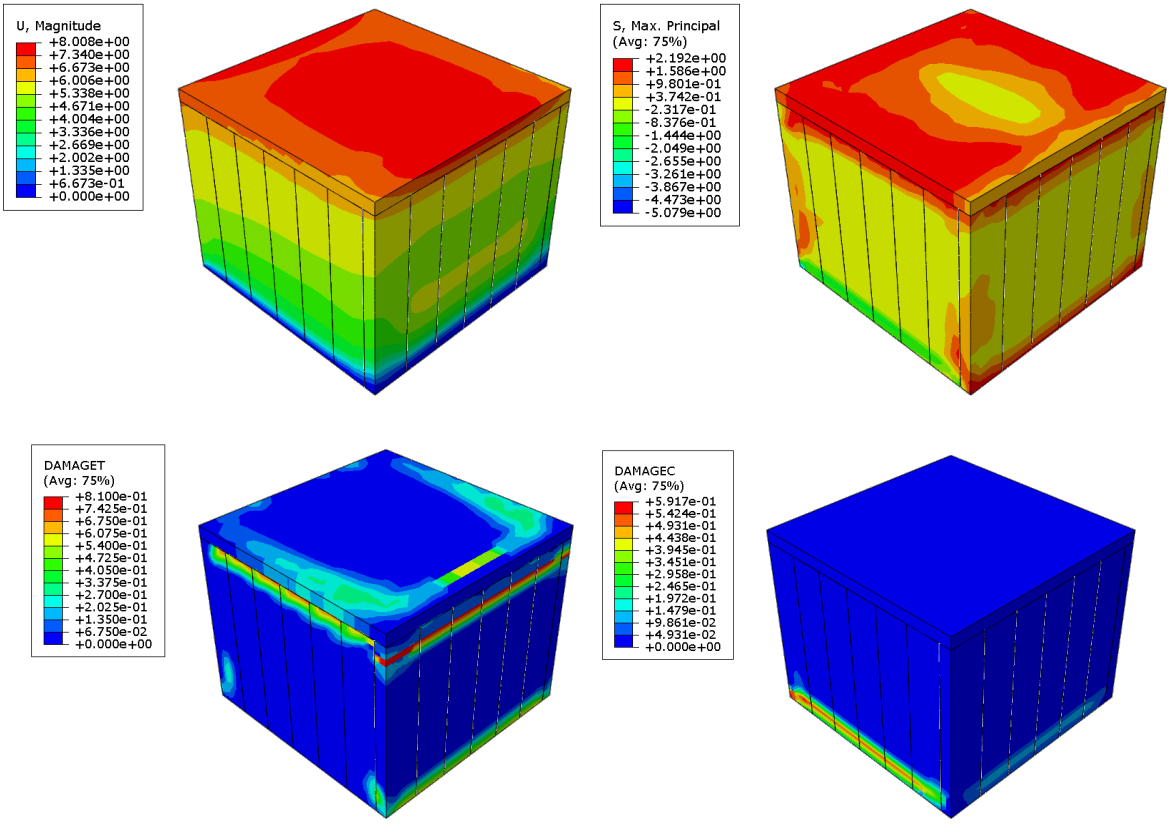

Figure 5. FEM analysis of the structure located in CA - N-type.

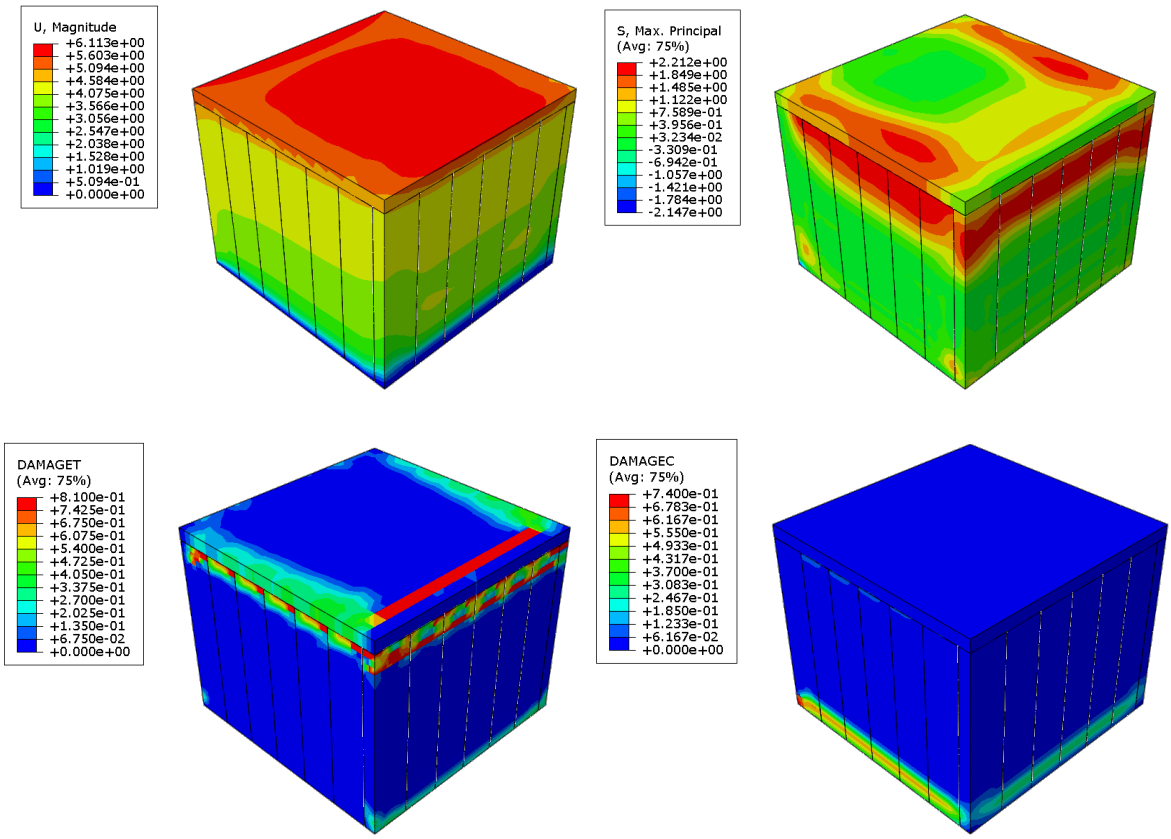

Figure 6. FEM analysis of the structure located in CA - L-type.

The results also indicated that earthquake load dominates the behavior of both the N-type and L-type structures based on the stress distribution analysis. In the N-type structure for the Alaska case, the damage was significantly lower compared to the California case. Tension damage was limited to 6.2%, and compression damage was only 3.4%. The displacement magnitude was 1 mm. In the L-type structure, the displacement remained at 1 mm; however, tension damage to the shell was 30%, and compression damage was 11%. As shown by analytical evaluation, the cores of these structures exhibit high strength due to thick concrete walls for only one story. However, damage to the shell is crucial since the shells in 3DCP structures are intended to remain exposed due to architectural design preferences. Cracking in the shell (the building's surface) is undesirable and must be minimized. Therefore, limiting cracking in the shell is essential to maintain the structure's integrity and aesthetic appeal.

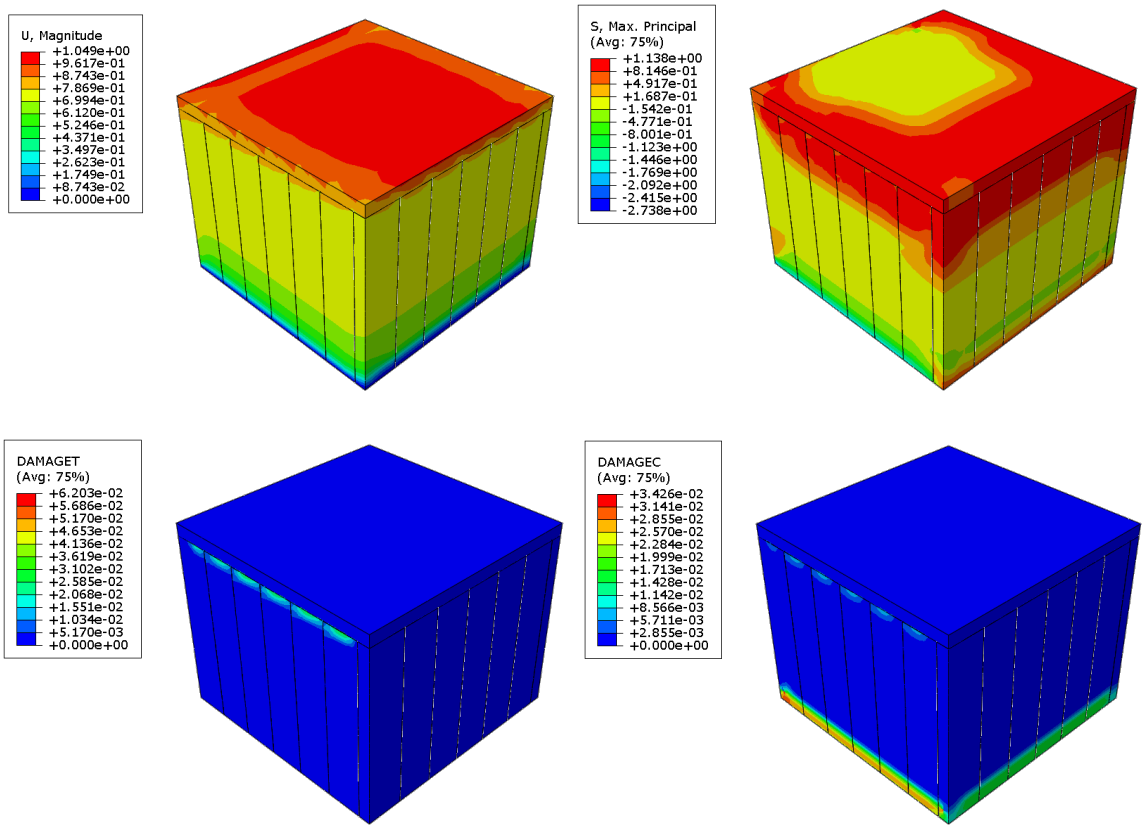

Figure 7. FEM analysis of the structure located in AK - N-type.

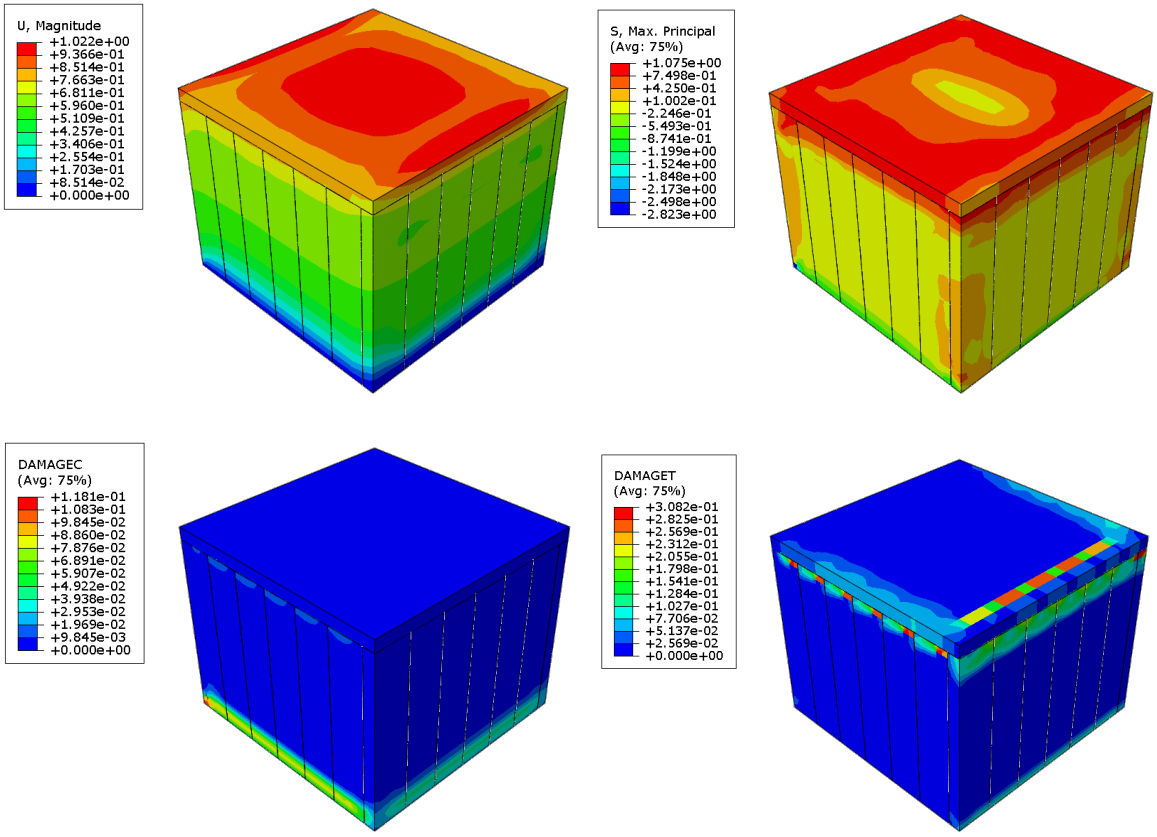

Figure 8. FEM analysis of the structure located in AK - L-type.

The N-type and L-type structures for the Pennsylvania case exhibited lower damage, displacement, and stress compared to those for Alaska and California cases due to the lower earthquake and snow loads in PA. Tension damage in these structures was limited to the connection between the roof and walls, where only rebars pass from the walls to the roof without any concrete contact. The displacement was negligible, primarily due to the heavy load of the concrete slab located on top of the structure. Stress distribution analysis indicated that vertical loads (dead load and snow load) dominate the loads on the structure.

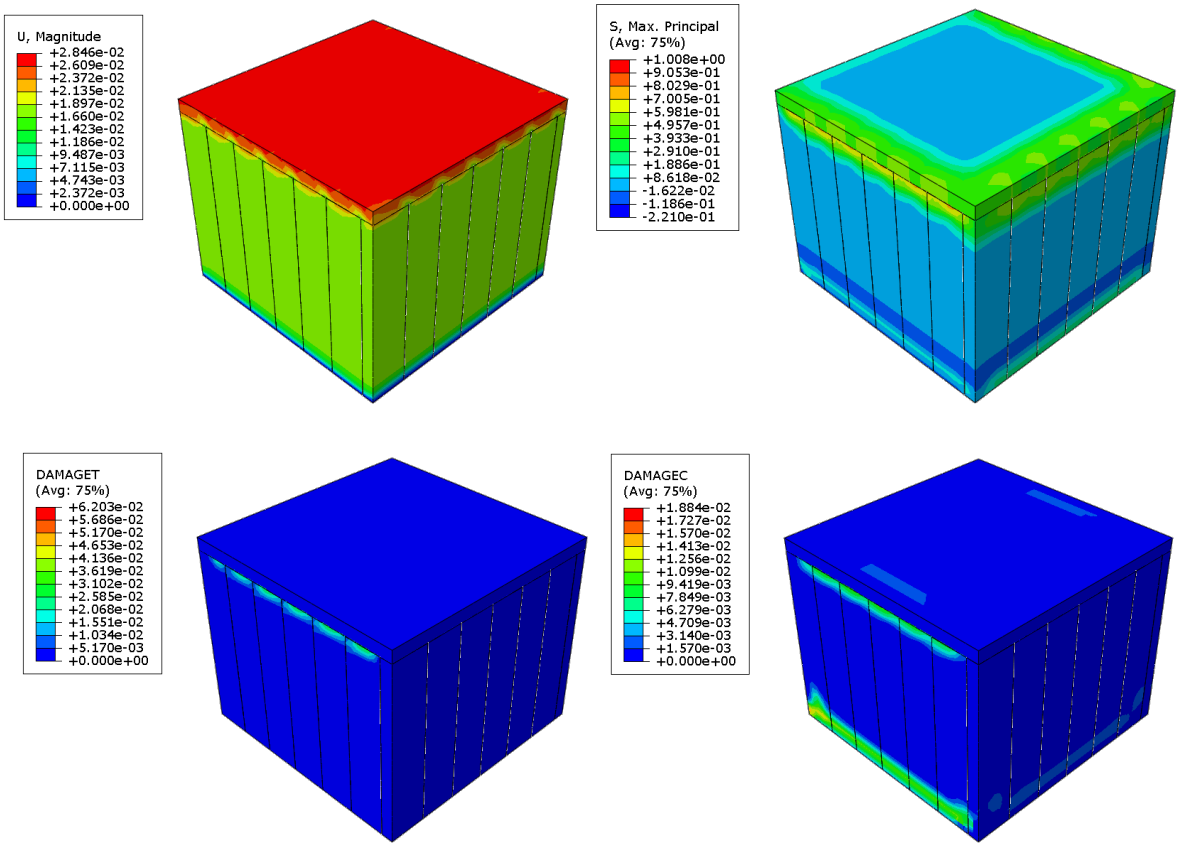

Figure 9. FEM analysis of the structure located in PA - N-type.

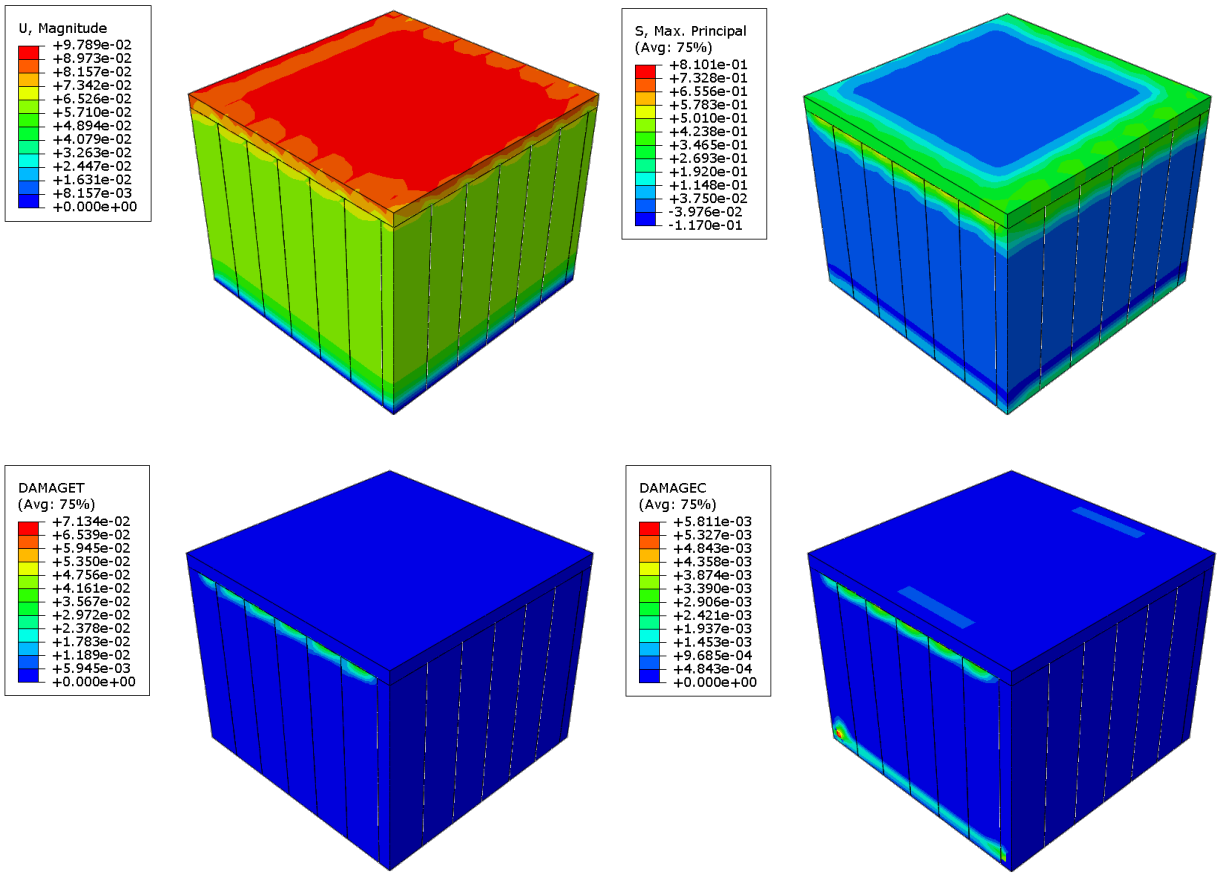

Figure 10. FEM analysis of the structure located in PA - L-type.

The analytical evaluation of 3DCP structures across three different regions, each subjected to varying loads and environmental conditions as per ASCE 7-16, demonstrates that 3DCP structure was a reliable construction method in all three regions, ensuring structural integrity during seismic events according to the ELF method. The FEA results corroborate this finding, revealing minimal structural damage, primarily confined to the shell of the structure due to material degradation. The FEA results indicate that the maximum principal stress in N-type structures reached 2.19 MPa, 1.138 MPa, and 1.00 MPa for CA, AK, and PA, respectively. For the L-type structures, the respective values were 2.21 MPa, 1.7 MPa, and 0.8 MPa. In both the N-type and the L-type structures, tension-induced damage to the shell reached approximately 80%.

CONCLUSION

This study conducted a preliminary structural analysis of 3DCP by employing both an analytical method, as outlined in ACI 318, ASCE 7 and FEM using a macro-modeling approach. The load parameters were derived from ASCE 7.

• The findings from both analytical and FEM approaches affirmed that 3DCP structures possess sufficient structural capacity to withstand the demands of harsh environments characterized by high seismic activity and heavy snow loads. This research analyzed panels of a consistent size but made from two distinct materials to assess their strength properties.

• This method proved valuable in streamlining the design process for 3DCP walls intended for use as primary shear walls, while also evaluating their resistance to out-of-plane flexural stresses to ensure safety.

• Structural Performance in Different Locations: The N-type and L-type structures in Pennsylvania (PA) showed lower damage, displacement, and stress compared to those in Alaska (AK) and California (CA) due to lower combination of earthquake and snow loads. In PA, tension damage was limited to the roof-wall connection, with negligible displacement caused by the heavy concrete slab on top. Vertical loads (dead load and snow load) dominated the stress distribution in these structures. Conversely, earthquake load significantly influenced the behavior of N-type and L-type structures in AK and CA.

• Damage Analysis and Structural Integrity: In Alaska, the N-type structure had limited tension (6.2%) and compression damage (3.4%) with a 1 mm displacement. The L-type structure also had a 1 mm displacement but with 30% tension damage and 11% compression damage. The wall cores for these structures remain strong due to thickness of concrete in these walls, but the shell damage was a critical concern due to the architectural design of 3DCP structures. In California, the N-type structure experienced significant tension damage under the roof and severe compression damage at the shear wall base, with an 81% shell damage but an undamaged core. The roof displacement reached 8 mm. The L-type structure in CA had a lower roof displacement of 6.1 mm, attributed to a lighter structure, but more extensive tension damage in the shell.

The study also explored the efficiency of additive construction techniques, particularly the printing of thick concrete walls. It was determined that filling all walls could lead to inefficiencies. Therefore, an optimized infill strategy for the panels is recommended. This approach not only significantly reduces the weight—and consequently, the seismic loads—of the structures, but also curtails material over-consumption, enhancing the overall sustainability of 3DCP applications. This research paved the way for more refined design protocols in the field of 3DCP, potentially setting the stage for broader adoption and technological advancements in sustainable construction practices.

NOTATIONS

aP = the amplification factor related to the response of a system or component as affected by the type of seismic attachment

Ce = exposure factor

Cs = slope factor

Ct = thermal factor

Fp = the seismic force acting on a component of a structure

h = average roof height of structure with respect to the base

Ip = the component importance factor

Is = importance factor

pf = snow load on flat roofs

pg = ground snow load

Ra = Response Modification Coefficient

Rp = component response modification factor

SDS = design, 5% damped, spectral response acceleration parameter at short periods

WP = component operating weight, in N

Z = height in structure of point of attachment of component with respect to the base

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Affordability, Health, and Social Aspects of Housing

Achieving Affordable Housing and High Indoor Environmental Quality: Solving the Housing Crisis

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ABSTRACT

The purpose of this paper is to demonstrate how the design industry and housing agencies can create affordable housing that achieves superior Indoor Environmental Quality (IEQ) standards while addressing the U.S. housing crisis. Despite widespread recognition that poor IEQ in affordable housing creates unsuitable living conditions and disproportionately affects vulnerable populations, current development practices often prioritize cost reduction over environmental quality. This systematic literature review, following PRISMA guidelines, analyzed 31 articles and government reports from 2000-2025 to identify evidence-based design strategies that simultaneously address affordability and IEQ concerns.

Key findings reveal that strategic IEQ improvements can reduce long-term housing costs while significantly improving occupant health outcomes, with documented benefits including reduced respiratory illness, improved sleep quality, and enhanced cognitive performance. The research identifies air quality, thermal comfort, and lighting as the three most critical IEQ factors for affordable housing residents, with cost-effective interventions ranging from low-cost solutions like biophilic design to comprehensive systems upgrades that provide positive returns. The study concludes that integrating IEQ considerations into affordable housing development is not only feasible but economically advantageous, providing a framework for designers and policymakers to create healthier, more sustainable communities. The comprehensive strategy framework presented offers actionable guidance for implementing evidence-based IEQ improvements that serve both public health and economic sustainability goals, contributing to the broader initiative of ensuring quality housing accessibility for all Americans.

INTRODUCTION

Seven fundamental elements are required for adequate housing: legal security of tenure; availability of services; materials; facilities and infrastructures; affordability; habitability; location and cultural adequacy. Despite housing being considered a "human right" by the U.S. government, the housing crisis has only grown worse and along with it their quality overall (Tars, 2020).

Efforts have been put into developing additional housing but with little regard for the long-term impact on the environment, the cost, its occupants, or the quality of the materials utilized. The housing crisis presents a significant public health threat, as poor-quality housing exposes residents to serious health risks. Indoor Environmental Quality (IEQ) is determined by the varying physical building attributes that contribute to the experience of an interior, including air, temperature, light, sound, odor, and vibration. IEQ serves as a reliable benchmark for determining occupiable housing healthiness, and it is important to recognize its impact on occupant health and wellbeing overall. The vast range of types of housing developments, while more affordable, creates unsuitable living conditions, typically offering only minimal living standards.

Currently, 30% of Americans live "paycheck-to-paycheck," making affordable housing increasingly difficult (Tinsley, 2024). Nationwide, no worker earning the federal minimum wage can afford a modest two-bedroom rental at fair market rent (National Low Income Housing Coalition, n.d.). The issue of housing affordability and the health of Americans must be addressed promptly by leading professionals to ensure a sustainable and healthy future.

SIGNIFICANCE

Poor IEQ can negatively impact mental, physical, and emotional health, ranging from acute symptoms like sleep disturbances to serious conditions including respiratory illness and mental disorders (Wu et al., 2007). Recent studies show poor IEQ contributes to substantial healthcare costs, with low-income populations bearing disproportionate burdens (Boch et al., 2020). Long term, poorly built affordable housing costs more to maintain than well-built affordable housing that also considers IEQ. Investing in higher quality building strategies reduces maintenance costs while improving occupant satisfaction and health. This paper explores practical solutions and suggests design strategies to eliminate the need to sacrifice building quality for affordability.

PROBLEM STATEMENT

Purpose of Research

Despite growing recognition of the housing crisis, significant research gaps remain in identifying evidence-based design strategies that achieve both affordability and high IEQ simultaneously. Most existing research addresses these issues in isolation, failing to provide integrated solutions that are practically implementable by design professionals (Ozer and Jacoby, 2024). This research addresses the critical need for interdisciplinary approaches that eliminate the false choice between building quality and affordability. Through a systematic literature review and cost-benefit analysis, this study identifies specific design strategies that enable designers, architects, and housing professionals to create affordable housing with superior IEQ outcomes.

The study addresses two key questions:

- How can housing affordability and high IEQ work in tandem to improve the current living conditions of American housing?

• What design strategies can design professionals utilize to improve affordable housing quality while maintaining high IEQ?

By addressing these questions, this research provides actionable guidance for designers and policymakers to implement evidence-based solutions that serve both economic sustainability and public health goals.

METHODOLOGY

A systematic literature review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, was conducted to identify evidence-based design strategies that address both housing affordability and IEQ. Multiple electronic databases, including Web of Science, Google Scholar, and ProQuest, were searched using keywords related to housing affordability, indoor environmental quality, occupant health and wellbeing, low-income housing, and cost impacts of housing. Inclusion criteria specifically required (1) peer-reviewed articles or government reports, (2) articles addressing affordable housing and/or IEQ, (3) articles published between 2000 and 2025, and (4) articles written in English. Cost-related data were limited to the most recent five years and focused on U.S. standards to ensure relevance for American designers and policymakers.

The initial database search yielded 112 records. After removing duplicates (n = 41), 71 records were screened based on title and abstract. Of these, 32 studies were excluded for lack of relevance to either IEQ or affordable housing. Thirty-nine full-text articles were assessed for eligibility, with eight excluded due to insufficient relevance to cost, health, or housing outcomes. A final sample of 31 studies was included in the synthesis.

Data from the included studies were analyzed and organized into two primary categories: IEQ factors (air quality, thermal comfort, and lighting) and housing affordability. These categories informed the development of actionable design strategies for practitioners, as presented in the Results section.

THEORETICAL FRAMEWORK

This study employs an interdisciplinary theoretical framework, as shown in Figure 1, that integrates five key perspectives to examine the complex relationships between housing affordability, environmental quality, and human wellbeing. This framework integrates Environmental Psychology Theory (how physical environments influence occupant behavior and health), Social Determinants of Health (housing quality as a public health factor for vulnerable populations), Maslow's Hierarchy of Needs (shelter requiring both safety and comfort, making IEQ essential), Environmental Justice Theory (poor conditions disproportionately affecting low-income communities), and Economic Theory (evaluating long-term IEQ benefits versus short-term costs). The approach recognizes that housing quality requires synthesizing health, economic, social, and environmental perspectives rather than relying on a single theoretical lens. Integrating this framework acts as a methodology to abstract the most relevant information from

literature that is pertinent to the research questions and organizes it into four themes: Housing Affordability, Environmental Quality, Occupant Health, and Social Equity. All themes work to determine the actionable design solutions that accompany and represent the major theories and themes they represent overall.

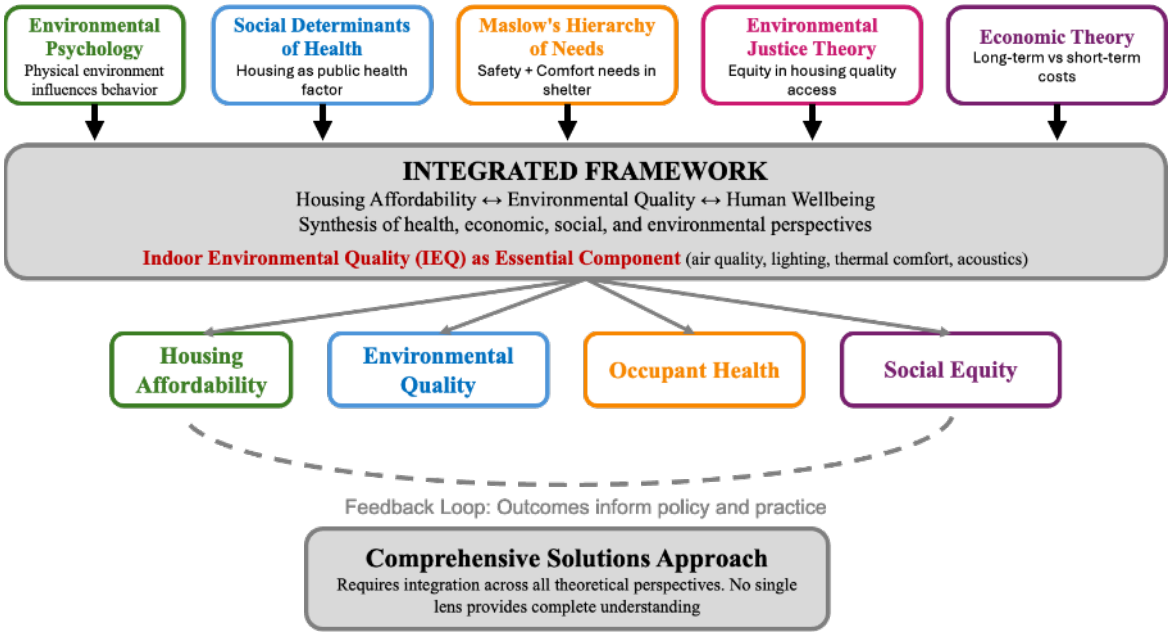

Figure 1. Integrated theoretical framework for housing affordability and IEQ.

RESULTS

Housing Affordability

The U.S. is experiencing a shortage of about 7.1 million affordable homes attainable by renters, "at or below the federal poverty guideline" (National Low Income Housing Coalition, n.d.). In 2024, the number of people experiencing homelessness, who were reported within emergency housing systems, unsheltered, or in transitional housing programs, was around "771,480 people– or about 23 of every 10,000 people" (Sousa and Henry, 2024). For people experiencing homelessness, 33.2% were sheltered people in families, 31.2% were sheltered individuals, 33.1% were unsheltered individuals, and 2.4% were unsheltered people in families" (Sousa and Henry, 2024). These figures represent a 12% increase from 2023, with unsheltered homelessness showing the most dramatic rise at 18% year-over-year, indicating that existing shelter capacity is insufficient to meet growing demand.

From 2000 to 2020, the cost of housing increased at a rate of 65%, while the median income level has not increased to match these prices (Feiveson et al., 2024). Although real median household income increased 4% from 2022 to 2023, "median rents [are rising] faster than

median household income in 88% of U.S. counties, home to 97% of the U.S. population" (Feiveson et al., 2024; U.S. Census Bureau, 2024). As the cost of living and inflation increase over time, the ability to afford housing anywhere within the U.S. is increasingly difficult.

IEQ and Occupant Health

Existing affordable housing issues in the U.S. are widespread, with 6.45 million households living in inadequate housing in 2023, including 3.5 million renter households, causing health problems for occupants (Zhao, 2025). Health hazards exist in over 23 million homes, due to vermin, moisture intrusion, paint deterioration, or faulty safety devices, while nearly six million additional units suffered from substantial problems with core infrastructure systems. Poor IEQ causes a myriad of poor health outcomes, especially for those who are disproportionately impacted by financial constraints (Joint Center for Housing Studies, based on AHS data). Design solutions can address ongoing health issues due to poor IEQ while being cost efficient. Lighting strategies can work to improve productivity, reduce headaches, reduce Sick Building Symptoms (SBS), improve alertness, memory, mood, performance, and concentration, and reduce evening sleepiness and eye discomfort, all while reducing energy loads by 27-88% (Loftness et al., 2007; Mills et al., 2007; Viola et al., 2008). For addressing air quality, systems that implement HVAC and ventilating outdoor air "reduce respiratory illness 9-20% and increase productivity by [up to] 11%, with a small energy cost for increasing outside air rates with heat recovery, or 25–50% energy savings for natural ventilation and mixed-mode conditioning" (Loftness et al., 2007).

Building Health and Quality

Careful consideration of building materials, building process, and longevity of the buildings are major components to consider in early design. Strategies such as selecting building materials with low-VOCs, implementing controls that monitor HVAC systems, and ensuring a well-sealed building envelope, may involve higher initial cost but are associated with documented long-term operational savings and reduced maintenance burdens (EPA 2025a). Considerations such as smart thermostats, operable windows, integrating controls for lighting, and ensuring the inclusion of natural lighting, can all help to achieve long-term cost savings. Ensuring proper maintenance and monitoring of HVAC, plumbing, and building systems will help to mitigate and minimize any issues that may arise from their improper or faulty functioning (EPA, 2025a). Emerging maintenance approaches that incorporate monitoring technologies have demonstrated potential to reduce maintenance demands while improving system performance, making higher-quality IEQ systems more viable for cost-constrained housing.

ANALYSIS

In this study, building quality is defined as the durability, performance, and maintainability of housing systems that directly influence indoor environmental conditions and long-term operational costs. Building quality is operationalized through material selection, building envelope integrity, mechanical system efficiency, and long-term maintenance capacity. These dimensions are directly reflected in the IEQ strategies summarized in Table 1, demonstrating how quality and cost efficiency are addressed concurrently.

To provide designers and housing professionals with practical guidance for implementation, the following analysis summarizes the most effective IEQ strategies identified through this literature review. Table 1 presents these strategies organized by the primary IEQ factors, air quality, thermal comfort, and lighting, along with their documented impacts on occupant health and cost implications. Strategies were only incorporated if they provided quantitative and qualitative data on health outcomes, user satisfaction, included cost-benefit analysis or economic impact data and demonstrated applicability to affordable housing contexts.

This evidence-based approach ensures that Table 1 serves not merely as a compilation of design ideas, but as a validated framework derived from the best available research, providing designers and housing professionals with strategies that have demonstrated effectiveness in real-world affordable housing applications.

Table 1: IEQ Themes, Their Associated Design Strategies, and the Impact on Occupants and Cost.

Themes	Design Strategies	Impact on Occupant Health and Wellbeing	Economic Impact
Air Quality	Operable windows	Control over the environment, access to natural ventilation and airflow	Low-cost improvements
	Biophilic design and inclusion of plants	Access to nature and connection with outdoors	Reduces energy consumption and ensures energy efficiency
	Sealed building envelope	Sealed buildings are less likely to cause poor IAQ or negative health impacts	Prevents gapping and loss of heat and air from the building, reducing overall consumption
	HEPA air filters	Removal of pollutants and air filtration prolongs good health, removes odors, and ensures safety of vulnerable populations	Overall cost savings
Thermal Comfort	Interior and Exterior shades and louvers	Reduce glare and heat gain Control over environment, ensuring user comfort	Can lead to a large amount of energy savings of up to 40-45%
	Operable windows	Access to views and connection to nature	Inclusion of natural ventilation can help ease HVAC loads and result in cost savings
	Insulation	Improved sleep quality and overall health	Reduced energy consumption
	Thermal Zoning	Improved satisfaction and control over env.	Minimize usage of HVAC system

	Smart thermostats	Gives accurate real time data and ensures balance between interior and exterior climates	Predictive technology ensures a long-lasting system Climate adjusting system reduces energy consumption
Lighting	Layout of lighting, layering, and zoning	Support productivity of tasks and comfortable visibility in spaces	Reduced energy loads and reduced energy consumption
	Maximizing daylighting	Increasing daylight will positively impact mood and keep in tune with the natural circadian rhythm	Reduction/prevention of heat gain
	LED fixtures	Better quality lighting improves productivity and sleep	Increased lifespan of bulbs
	Task Lighting	Direct light increases productivity and focus	Lighting for specific areas/tasks can reduce overall consumption
	Shaders/blinds	Control over the environment increases mood overall	Reduces glare, heat gain, and excess usage of cooling systems

Design Strategies to Utilize

The evaluated research findings have been narrowed down to provide specific actionable strategies for designers and industry professionals to utilize when developing affordable housing. When designing affordable housing, the IEQ factors listed in Table 1, above, have been paired with specific strategies based on research findings to address both cost efficiency and building quality.

When considering designing for affordable lighting, numerous factors must be considered—such as layout, zoning, layering, connection to the circadian rhythm, lighting types, location, climate, and building orientation—when implementing design strategies. Strategies to consider are designated lighting zones to support activities, visibility, reduced energy loads, inclusion of LEDs to maximize lifespan of lights, task lighting to reduce energy consumption, and interior shading to regulate temperature and control lighting (Mantzourani et al., 2020; Papinutto et al., 2022; Shum and Zhong, 2023; U.S. Department of Energy, n.d.). Maximizing daylighting is an inexpensive solution, as it can help to boost interior lighting, provide access to views, and improve mood and overall wellbeing. The overall lighting design must consider the improvement of the space overall and support indoor activities, visibility, and wellbeing, while ensuring cost savings and reducing heat gain.

Lighting and thermal comfort are intrinsically connected through solar heat gain which can make energy bills costly. One strategy to implement is the inclusion of smart thermostats which can result in significant energy savings as they can offer a return on investment in under two years

(Kyle Benne, n.d.). Smart thermostats help to address over-consumption by enabling geo-fencing and remote control of the system, while giving real-time data on the IAQ, like temperature and humidity levels. Other strategies to consider supporting thermal comfort are controls to adjust for personal preference and improved sleep quality and productivity; thermal zoning to regulate where the HVAC system operates and to reduce energy consumption; and building insulation, which can improve thermal comfort while eliminating noise (Rotondo et al., 2021).

Indoor air quality (IAQ) can be supported through strategies such as operable windows that enable natural ventilation when climate and outdoor conditions permit, particularly when combined with appropriate filtration and envelope design. An increasingly popular concept to support IAQ is through the integration of biophilic design to help remove airborne pollutants (Rasheed and Jayasree, 2025). Air filtration should also be considered, as the inclusion of HEPA air filters could remove up to 99.7% of indoor air pollutants, resulting in long-term cost savings and improved health outcomes (EPA, 2025b; Intermountain Medical Center, 2018). Air flow is also significant, as stagnant air can lead to poor air quality, odor, and potentially more pollutants. A tightly-sealed building will ensure there are no gaps or potential for air to enter or exit the building and negatively impact air quality, as well as contributing to increased energy use and overall cost.

DISCUSSION

It is imperative that housing affordability and high IEQ must be considered in tandem when developing new housing. It is important to recognize and understand one is not sufficient without the other; housing affordability should not be sacrificed for cheap materials, and IEQ developments should be inexpensive. By suggesting a variety of design solutions that consider cost implications and the health and wellbeing of occupants, this paper attempts to start the major discussion of real change to address the housing crisis and lack of care for IEQ. Designers can be the first to make a true impact on this issue and make for a more equitable, sustainable, and lasting impact on the future.

Implementation pathways identified in the literature include modular construction, adaptive reuse, and targeted retrofit strategies, which have demonstrated potential to reduce construction and lifecycle costs while maintaining acceptable IEQ standards in affordable housing contexts. These approaches highlight how procurement and delivery methods can support IEQ improvements without increasing upfront financial burden.

LIMITATIONS AND FUTURE RESEARCH

While this study draws on a broad range of literature, its scope is limited primarily to U.S.-based data, lacking a comprehensive global perspective on the cost, material, and feasibility aspects of affordable housing. It does not include real-time case studies or direct occupant feedback, which limits the depth of insight into the lived experience of residents and the real-world implications of poor indoor environmental quality (IEQ). Future research should expand to include diverse geographic regions, cultural and climatic contexts, and incorporate longitudinal studies, occupant

surveys, and controlled trials. Key areas for further investigation include the development of standardized IEQ assessment tools, policy incentives for better housing standards, innovative financing mechanisms, and emerging technologies to enhance IEQ affordably.

CONCLUSION

Designers can play a crucial role in aiding the end of the housing crisis by demonstrating the feasibility and benefits of integrated affordable housing and IEQ solutions, providing evidence-based recommendations that policymakers can use to inform legislation and funding priorities. The path forward requires immediate action on multiple fronts: (1) integration of IEQ standards into affordable housing policy; (2) development of financing tools that recognize long-term cost savings; (3) creation of design practices and guidelines to make IEQ integration practice accessible; and (4) establishment of monitoring systems to track health data outcomes. The convergence of mounting healthcare costs, climate change, and housing affordability creates an unprecedented opportunity to transform how we approach affordable housing design. By embracing this integrated approach, we can create healthier communities, reduce long-term costs, and ensure that quality housing is truly accessible to all Americans.

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Casino Proximity and Housing Prices: An Empirical Analysis of Housing Markets in Small Oklahoma Cities

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ABSTRACT

This study examined the relationship between casino proximity and home sale prices across three small cities in Oklahoma. With 143 gaming casinos generating significant revenue for tribal nations in Oklahoma, their impact on surrounding housing markets has not been explored. Using Multiple Listing Service (MLS) data spanning three years since 2022, this research analyzed 2,382 property transactions across three cities (populations 20,000-25,000) with established casino operations to determine whether casino proximity affects home sale prices. Hedonic price regression models were conducted with sale price per square foot as the dependent variable, using distance from casino, house size, property size, property age, and days on market as independent variables. The analysis showed significant spatial heterogeneity in casino proximity effects across markets. Only one out of three study cities demonstrated a statistically significant negative relationship. The other two cities showed directional consistency, but without statistical significance. Traditional property characteristics impacted the sale price determination across all markets. Property size emerged as the strongest predictor, with property age consistently reducing the sale price. These findings challenge assumptions of uniform casino impacts on home sale prices, demonstrating that local market conditions, housing characteristics, and community contexts significantly mediate casino proximity effects.

INTRODUCTION

The gaming industry has experienced substantial growth across the United States over the past few decades, with tribal gaming operations representing a significant component of this expansion. This trend is evident in the state of Oklahoma, where 143 gaming casinos operated by tribal nations generated more than $7 billion in gaming revenue in 2023 and contributed more than $20 billion to the state's total economic output (Dean, 2025). These gaming facilities are playing a role in changing the economic landscape of many small Oklahoma cities, creating employment opportunities, attracting tourism, and generating substantial tax revenues for local

governments. However, despite their economic significance, the broader impacts of casino operations on local housing markets remain a topic that hasn't been explored adequately, particularly in the context of small cities where a single sizeable casino can be a dominant economic entity.

The relationship between casino proximity and housing prices could be analyzed from the perspectives of several key theoretical frameworks of economics. Alonso's bid-rent theory (1964) and broader location theory suggest that proximity to places of employment and amenities should increase housing prices through improved accessibility and reduced transportation costs. Similarly, Tiebout's (1956) positive externality theory predicts that casinos may generate positive effects such as creating employment and contributing to local spending. On the contrary, Pigou's (1920) negative externality theory could consider the casinos as a disamenity, generating negative externalities such as traffic, noise, and crime that negatively impact surrounding housing prices. Hedonic pricing theory, as developed by Rosen (1974), provides the analytical framework for measuring how location-specific attributes like casino proximity impact housing prices. These competing theories show there is a need for further exploration of the topic to determine the effect of casino proximity on residential property markets in specific contexts.

Recent empirical studies have provided additional evidence of this complexity. Research examining Canadian casino markets found substantial negative effects on housing value growth, with properties near casinos experiencing a loss in home value growth over five years (Huang et al., 2018). Similarly, studies focusing on urban casino proximity have identified relationships between casino accessibility and various socioeconomic indicators, including poverty levels and gambling-related problems (Philander et al., 2022). However, these studies have predominantly analyzed urban markets where casinos represent one of many economic anchors, potentially masking the more pronounced effects that may be seen in smaller communities where a casino represents a major economic entity. This study stems from the lack of a comprehensive empirical investigation about the relationship between casino proximity and housing prices, especially single-family housing in small cities. Oklahoma's tribal gaming network provides a unique opportunity for examining the relationship between casino operations on the housing market in small cities.

Purpose of the Study

The purpose of this study is to empirically examine the relationship between casino proximity and sale prices of single-family homes across multiple small Oklahoma cities with established gaming operations. Using three years of Multiple Listing Service (MLS) data, this research used hedonic price regression analysis to quantify the effects of distance from casino facilities on home sale prices while controlling for relevant property characteristics. This study addresses the following research question: Does proximity to casinos significantly affect sale prices of single-family homes in small Oklahoma cities?

Significance of the Study

This study addresses a significant gap in the literature by providing the first comprehensive multi-city analysis of casino proximity effects on sale prices of homes in small markets. The findings will inform policy discussions regarding tribal gaming development, local zoning decisions, and economic development strategies in small cities. Additionally, the results will contribute valuable insights for real estate professionals, property investors, and homeowners in communities with existing or proposed gaming facilities. The study's focus on Oklahoma's unique tribal gaming environment provides insights relevant to similar jurisdictions with significant Native American gaming operations.

The remainder of this paper is structured as follows: the following section presents a literature review examining the specific impact of casino proximity on home sale prices. This is followed by a detailed description of the research methodology. Subsequently, the results are presented, followed by discussions of the study's contributions to the body of knowledge.

LITERATURE REVIEW

Impact of Casinos on Housing Prices

The relationship between casino proximity and housing prices has generated very little research. The findings remain mixed and generalizable to only specific geographic locations. A study by Wenz (2007) using hedonic pricing methodology to examine casino impacts on housing markets found that the benefit of casino gambling represented approximately two percent of housing value for properties located near casinos. This positive finding suggested that employment and economic activity benefits due to the casinos outweighed potential negative aspects. However, subsequent research has revealed that the benefits vary significantly by geographic context and market conditions.

Existing studies have also claimed evidence of negative impacts on housing prices from casino proximity. Huang, Humphreys, and Zhou (2018) analyzed Canadian casino markets using data from facilities opened between 1986-2007, finding substantial negative effects on housing value growth. Their research documented that properties near casinos experienced nearly an eight percent point loss in home value growth over five years, with effects being most pronounced near casinos but diminishing with distance. This study represents empirical examinations of casino proximity effects on housing markets, utilizing long-term data across multiple locations to establish causal relationships.

The study by Philander et al. (2022) expanded understanding of casino proximity effects by examining the relationship between casino accessibility and socioeconomic outcomes. Using a large sample of Canadian gamblers (n = 6,234) and geolocation data relative to 110 domestic casino locations, they found that nearby casinos increase risk for residents, with frequency of casino visits mediating the relationship between access convenience and gambling-related problems. While not directly measuring housing price, this research provides insight into the mechanisms through which casino proximity may affect neighborhood desirability and housing price.

The mixed findings in existing literature highlight the importance of context-specific analysis, particularly regarding market size and the relative economic significance of casinos within local economies. Most previous studies have focused on large metropolitan areas where casinos represent one component of diversified economic activity. Limited research has examined casino proximity effects in smaller markets where gaming facilities may constitute more dominant economic influences, representing a significant gap in the current literature that this study addressed.

RESEARCH METHOD

This study employed a quantitative research approach utilizing hedonic price regression analysis to examine the relationship between casino proximity and single-family home sale prices in small Oklahoma cities. The hedonic pricing model, originally developed by Rosen (1974), provides a robust framework for analyzing how location-specific attributes impact housing prices. The research method adopted for this study is discussed in the following sections, and a flowchart is presented in Figure 1.

Data Collection and Sample Selection

MLS data spanning three years (since the beginning of 2022) was the data source for this analysis. The study focused on home sales across three small Oklahoma cities with populations ranging from 20,000 to 25,000, each having established casinos that were operational for the entire study period. The study cities are referred to as City A, City C, and City D in this document, using only the initials of their actual names. To protect sensitive market data, the exact names and geographic locations of these cities are not disclosed in this study. This population range was selected to ensure that gaming facilities represented significant economic anchors within their respective communities while maintaining sufficient housing market activity for statistical analysis.

The dataset comprised all single-family home sales within the three study cities during the three years, with properties filtered to exclude outliers and non-representative transactions. Properties with incomplete data for key variables were removed from the analysis to maintain data integrity and model reliability.

Variable Specification

Dependent Variable

The hedonic price regression employed sale price per square foot as the dependent variable to control for size differences across properties and provide a standardized measure of housing prices. As the MLS data spanned multiple years, all pricing data were adjusted for inflation to present-day dollars to eliminate the effects of general price level changes over the study period. This approach follows established practices in real estate research and allows for meaningful comparisons across properties of varying sizes and transaction dates.

Independent Variable
Casino proximity, the independent variable, was calculated as the straight-line distance measured in miles from each property to the nearest casino facility using continuous distance measurements. Given the computational complexity of calculating individual distances for over 2,000 property addresses, the authors used a Python script to automate distance calculations based on property addresses extracted from MLS data and corresponding casino facility addresses. This automated approach ensured consistent and accurate distance measurements while maintaining efficiency in processing the large dataset.

Control Variables
Several property-specific and market-related control variables were included to isolate the effect of casino proximity:

- **House Size**: Total interior square footage of the dwelling
- **Property Size**: Total lot size in acres
- **Property Age**: Age of the structure at the time of sale, calculated as the sale year minus the construction year
- **Cumulative Days on Market**: Total number of days the property was listed before sale

Model Specification
The hedonic price regression model is as follows:

$$\text{Price per Square Foot} = \beta_0 + \beta_1(\text{Casino Distance}) + \beta_2(\text{House Size}) + \beta_3(\text{Property Size}) + \beta_4(\text{Property Age}) + \beta_5(\text{Days on Market}) + \varepsilon$$

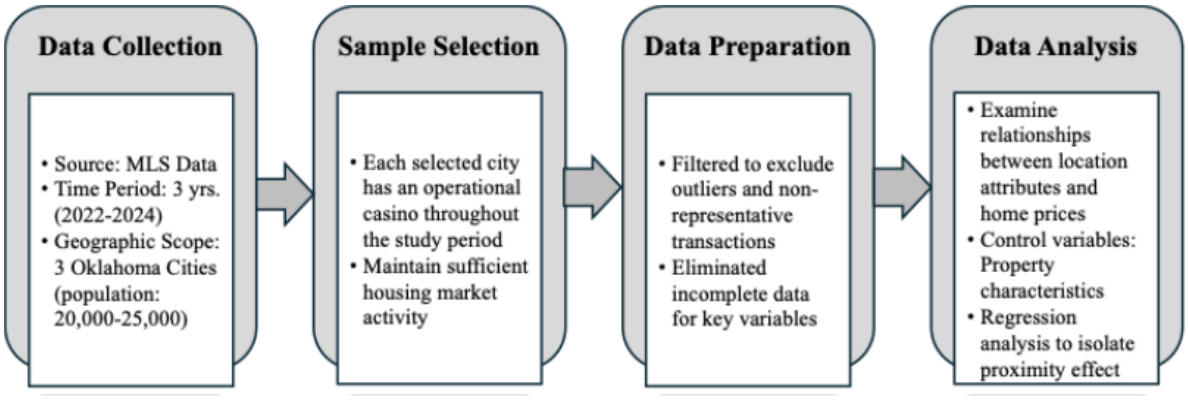

Figure 1. Flowchart depicting the research method.

RESULTS

Table 1, below, presents the descriptive statistics in housing market characteristics across the three study cities, providing context for understanding casino proximity effects on home sale prices. The analysis included 2,382 property transactions spanning three years (since the beginning of 2022), with 896 observations (37.6%) for City A, 889 observations (37.3%) for City C, and 597 observations (25.1%) for City D.

Property Values and Market Characteristics

Variations are noticed in home prices across the three cities, with City C having the highest average sale prices at $166.40 per square foot (SD = $62.46), followed by City D at $155.17 per square foot (SD = $51.11), and City A at $135.92 per square foot (SD = $61.80) (Table 1). The price difference between the highest and lowest markets represents approximately a 22% increase for City C over that of City A. City D demonstrates the least price volatility with the smallest standard deviation.

As shown in Table 1, home sizes remain relatively consistent, ranging from 1,657.85 square feet in City A to 1,717.52 square feet in City D, indicating comparable home sizes across the study cities. However, property sizes vary dramatically, with City C featuring significantly larger lot sizes averaging 2.17 acres (SD = 13.08) compared to City A's 1.22 acres (SD = 6.90) and City D's notably smaller 0.08 acres (SD = 2.18). Property age distributions also differ, with City C having the newest housing stock, averaging 38.31 years (SD = 24.83), followed by City D at 43.11 years (SD = 29.38), and City A with the oldest average age of 52.71 years (SD = 28.48). Market dynamics, as reflected in days on market (Table 1), show considerable variation with City D experiencing the longest average marketing periods at 49.41 days (SD = 71.37), compared to City C at 32.16 days (SD = 60.42) and City A at 27.93 days (SD = 56.94). The extended marketing periods in City D, combined with its high price levels, may indicate a more selective buyer market or unique property characteristics that require longer selling periods.

Casino Proximity Patterns

Table 1 shows that the three study cities have different proximity relationships to their respective casinos. City A shows the closest average distance to casinos at 2.99 miles (SD = 2.13), while Cities C and D demonstrate similar average distances of 4.52 miles (SD = 2.12) and 4.59 miles (SD = 1.37), respectively. City D exhibits the most concentrated distance distribution with the smallest standard deviation (1.37), suggesting a more uniform spatial relationship between residential properties and casino facilities.

Table 1: Descriptive Statistics of Housing Market Characteristics.

Variables	City A		City C		City D	
	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)
Sale Price/SF ($)	896	135.92 (61.8)	889	166.40 (62.46)	597	155.17 (51.11)
Dist. from Casino (mile)	896	2.99 (2.13)	889	4.52 (2.12)	597	4.59 (1.37)
House Size (SF)	896	1657.85 (737.03)	889	1710.21 (710.26)	597	1717.52 (745.72)
Property Size (Acre)	896	1.22 (6.90)	889	2.17 (13.08)	597	0.08 (2.18)
Age (years)	896	52.71 (28.48)	889	38.31 (24.83)	597	43.11 (29.38)
Days on Market	896	27.93 (56.94)	889	32.16 (60.42)	597	49.41 (71.37)

Hedonic Regression Analysis for City A

The hedonic regression model for City A shows strong explanatory power with an R-squared of 0.535, indicating that the included variables explain approximately 53.5% of the variance in home sale price for City A. The model achieves statistical significance ($F = 204.846$, $p < 0.001$), confirming meaningful predictive capability across the 896 property transactions analyzed. The model demonstrates excellent statistical properties with no multicollinearity concerns (all VIF values < 1.2, tolerance > 0.86).

Casino Proximity Effects

Casino proximity shows a modest but statistically nonsignificant relationship with home sale prices. The distance from the casino yields a positive coefficient of 1.103 ($p = 0.119$), suggesting that each additional mile from the nearest casino is associated with a $1.10 increase in price per square foot. However, this relationship is not statistically significant.

Property Characteristic

Traditional property characteristics emerge as the primary determinants of the sale price. Property size demonstrates the strongest relationship (coefficient = 5.141, $p < 0.001$, $\beta = 0.574$), with each additional acre increasing value by approximately $5.14 per square foot. Property age shows substantial negative impact (coefficient = -0.780, $p < 0.001$, $\beta = -0.359$), reducing value by $0.78 per square foot annually. House size exhibits a small positive relationship (coefficient = 0.007, $p = 0.001$), while days on market shows a negative association (coefficient = -0.102, $p < 0.001$), indicating longer marketing periods correlate with lower final prices.

Hedonic Regression Analysis for City C

The hedonic regression model for City C demonstrates moderate explanatory power with an R-squared of 0.327, indicating that the included variables explain approximately 32.7% of the variance in home sale price for City C. The model achieves statistical significance ($F = 85.674$, $p < 0.001$), confirming meaningful predictive capability across the 889 property transactions analyzed. The model demonstrates excellent statistical properties with no multicollinearity concerns (all VIF values < 1.3, tolerance > 0.81).

Casino Proximity Effects

Casino proximity shows a statistically significant positive relationship with home sale prices. The distance from the casino yields a positive coefficient of 3.116 ($p < 0.001$), indicating that each additional mile from the nearest casino is associated with a $3.12 increase in price per square foot. This relationship is statistically significant and suggests that properties located further from casinos command higher prices in City C's market.

Property Characteristics

Traditional property characteristics emerge as primary determinants of sale price. Property size demonstrates the strongest relationship (coefficient = 2.176, $p < 0.001$, $\beta = 0.456$), with each additional acre increasing value by approximately $2.18 per square foot. Property age shows substantial negative impact (coefficient = -0.756, $p < 0.001$, $\beta = -0.300$), reducing value by $0.76 per square foot annually. House size exhibits a small but significant negative relationship (coefficient = -0.008, $p = 0.002$), while days on market shows a positive association (coefficient = 0.084, $p = 0.006$), indicating longer marketing periods correlate with higher final prices in City C, possibly reflecting premium property characteristics that justify extended marketing efforts.

Hedonic Regression Analysis for City D

The hedonic regression model for City D demonstrates moderate explanatory power with an R-squared of 0.316, indicating that the included variables explain approximately 31.6% of the variance in home sale price for City D. The model achieves statistical significance ($F = 54.542$, $p < 0.001$), confirming meaningful predictive capability across the 597 property transactions analyzed. The model demonstrates excellent statistical properties with no multicollinearity concerns (all VIF values < 1.3, tolerance > 0.80).

Casino Proximity Effects

Casino proximity shows a positive but statistically nonsignificant relationship with home sale prices. The distance from the casino yields a positive coefficient of 2.342 ($p = 0.097$), suggesting that each additional mile from the nearest casino is associated with a $2.34 increase in price per square foot. However, this relationship is not significant.

Property Characteristics

Traditional property characteristics emerge as the primary determinants of sale price. Property size demonstrates the strongest relationship (coefficient = 5.171, $p < 0.001$, $\beta = 0.220$), with each additional acre increasing value by approximately $5.17 per square foot. Property age shows substantial negative impact (coefficient = -0.830, $p < 0.001$, $\beta = -0.477$), reducing value by $0.83

per square foot annually. House size exhibits a small but significant negative relationship (coefficient = -0.005, p = 0.044), while days on market shows no significant association (coefficient = 0.013, p = 0.614), indicating that marketing periods do not significantly correlate with final prices in City D's market.

DISCUSSION AND ANALYSIS

The empirical findings reveal significant spatial heterogeneity in how casino proximity affects home sale prices across the three study cities, challenging the assumption of uniform market responses to gaming facilities. Most notably, only City C demonstrates a statistically significant relationship between casino distance and home sale prices, with each additional mile from the casino associated with a $3.12 increase in price per square foot. This finding aligns with the negative externality hypothesis prevalent in the existing literature (Huang et al, 2018), which suggests that proximity to casinos may reduce home sale prices due to concerns about increased crime, traffic congestion, and social problems.

Conversely, Cities A and D exhibit positive but statistically non-significant relationships with casino proximity, indicating that while the directional relationship mirrors City C, the data do not reach statistical significance. This pattern of mixed results reflects the broader ambiguity in the casino proximity literature, where studies have documented both positive and negative effects depending on local market conditions, regulatory environments, and community characteristics (Wenz, 2007; Huang et al., 2018).

Market-Specific Factors and Casino Impact Heterogeneity

The differential casino proximity effects across the three cities can be further examined through the lens of varying market characteristics and economic contexts. City C, which exhibits the only significant casino proximity effect, possesses several distinctive features that may amplify sensitivity to casino externalities. With the highest average home sale prices ($166.40 per square foot) and the newest housing stock (average age 38.31 years), City C represents a premium market segment where quality-of-life considerations may carry greater weight in purchasing decisions. The relatively short marketing periods (32.16 days) suggest an active market where buyers have multiple options, potentially making them more selective regarding proximity to perceived negativity of casinos.

In contrast, City A, despite having the closest average proximity to casinos (2.99 miles), shows no significant price sensitivity to casino distance. The absence of significance in City A may reflect market adaptation, where long-term exposure to casino operations has normalized their presence in the local housing market. Additionally, City A's older housing stock (average age 52.71 years) and lower average prices ($135.92 per square foot) suggest a more value-oriented market where proximity convenience might offset any negative perceptions.

City D presents an interesting case where, despite having home sale prices in the middle range ($155.17 per square foot) and the most uniform spatial distribution relative to casinos (smallest standard deviation of 1.37 miles), casino proximity effects remain statistically insignificant. The

extended marketing periods (49.41 days) in City D may indicate market inefficiencies or buyer selectivity based on factors other than casino proximity, such as the notably smaller lot sizes (0.08 acres) that distinguish this market from the other two cities.

Traditional Property Characteristics Dominance

Across all three cities, traditional property characteristics demonstrate consistent and significant effects on home values, reinforcing established findings in the hedonic pricing literature. Property size emerges as the strongest predictor in all models, with remarkably similar coefficients ranging from $2.18 to $5.17 per square foot per additional acre. This consistency suggests that land scarcity premiums operate uniformly across different market contexts, regardless of casino proximity considerations.

LIMITATIONS AND FUTURE RESEARCH

The hedonic regression models demonstrate moderate explanatory power with the highest R-squared value at 0.535, indicating that factors not included in the model continue to influence home sale prices across the three study markets. While the models successfully capture traditional property characteristics and casino proximity relationships, the remaining unexplained variance suggests opportunities for enhanced model specification. This study's focus on casino proximity as the primary spatial variable has not considered other potentially significant location-based factors that could impact the property values. Future research should incorporate additional variables, such as school district quality, neighborhood amenities like parks, to improve predictive capability and potentially reveal more nuanced casino proximity effects that may be masked by omitted variable bias.

The three-year observation period spanning 2022-2024 provides contemporary market data but may not capture longer-term market effects. Extended longitudinal analysis covering multiple market cycles could reveal whether the observed heterogeneity in casino proximity effects represents permanent structural differences across markets or temporary adjustment phases following the global pandemic in 2020. Additionally, the three-year observation period limits assessment of potential changes in casino impact as communities might adapt to gaming facility presence over extended periods.

CONCLUSION

The purpose of this study was to empirically examine the relationship between casino proximity and sale prices of single-family homes across multiple small Oklahoma cities with established gaming operations. The heterogeneous findings across the three study cities highlight the limitations of generalized assessments of casino impacts on home sale prices. The significant negative proximity effect in City C suggests that casino externalities can indeed affect home sale prices, but this impact appears contingent on local market conditions rather than representing a universal phenomenon. The absence of significant effects in Cities A and D indicates that casino proximity may be dominated by other location and property characteristics in many market contexts.

These findings suggest that policymakers and developers should adopt a nuanced, market-specific approach when evaluating potential casino developments. The assumption that casinos uniformly reduce nearby home sale prices lacks empirical support in this multi-city analysis, indicating that local economic conditions, housing market characteristics, and community contexts play crucial roles in determining the magnitude and direction of casino proximity effects.

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From Scar to Spine: Progressive Housing as an Anchor to Corridor Redevelopment Along Baltimore's Highway to Nowhere

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ABSTRACT

The Franklin–Mulberry (I-40) Corridor, better known as the "Highway to Nowhere," is a 1.39-mile scar through West Baltimore—a remnant of an abandoned highway project that displaced over a thousand residents and fractured neighborhood life. Today, vacancy, disinvestment, and infrastructural isolation remain entrenched.

This paper proposes Progressive Housing, a model that links affordable housing with personal upward mobility to the collective prosperity of the community. It allows mid to low-income residents to stay and rise by integrating affordable rent-to-own pathways, incentives for entrepreneurs and community drivers, and modular building systems that adapt to changing household needs and community function. Through hybrid housing typologies, live-up retail, and interwoven community infrastructure, the model ensures that individual success fuels neighborhood vitality and that community vibrancy enhances resident stability.

Two architectural exemplars anchor this vision: Midtown Edmonson (Area A) Condominiums, which transform underpass and overpass infrastructure into civic markets and plazas, and a Hybrid live-up townhome/apartment building that rises over a memorial pathway, embedding remembrance into the daily experience of home. The anticipated Red Line transit corridor, if constructed underground, would free the trench for parks, housing, and economic spaces, amplifying the model's potential to turn a symbol of displacement into a spine of resilience.

INTRODUCTION: FROM SCAR TO SPINE

The Highway to Nowhere is more than a gap in the urban grid; it is an unresolved chapter in Baltimore's storied history. Built in the 1970s as part of an interstate I-70 expansion that never materialized, the trench displaced more than 1,500 residents, most from African American neighborhoods, and erased hundreds of homes and businesses (Maryland Department of Transportation, 2024, p. 4). What remained was a 1.39-mile void: concrete retaining walls, chain-link edges, and a long shadow over the surrounding communities (Blue Water Baltimore, 2023).

Half a century later, its physical and economic impacts of the now I-40 corridor persist. Vacancy rates in some blocks exceed 70%, unemployment in surrounding neighborhoods is five times the Maryland average, and daily needs such as fresh food, healthcare, and reliable jobs are often more than a mile away.

Against this backdrop, Progressive Housing is a proposal to transform the corridor from a scar into a civic spine. It is designed for permanence: residents are not "transitioned out" when they succeed. Instead, they can stay, rise, and reinvest in their own community.

HISTORICAL AND SOCIOECONOMIC CONTEXT

The Highway to Nowhere originated as part of a larger mid-century transportation plan intended to connect Baltimore's western neighborhoods to downtown and beyond. Instead, it became a case study in failed urban renewal plan. The construction razed more than 700 homes, displaced over 1,500 residents, and erased vibrant cultural corridors. The planned interstate connection was never completed, leaving an underused trench that cuts through the heart of predominantly Black working-class neighborhoods such as Midtown-Edmondson, Harlem Park, Penrose/Fayette, Poppleton, and Franklin Square.

Today, these neighborhoods face compounded challenges: low occupancy rates (ranging as low as 30%, 15% and even 6% in some areas), low homeownership, disinvestment in public infrastructure, and limited economic opportunity. Vacancy maps show concentrated abandonment in areas adjacent to the corridor, underscoring how the physical disruption of the highway continues to perpetuate cycles of disinvestment and population loss.

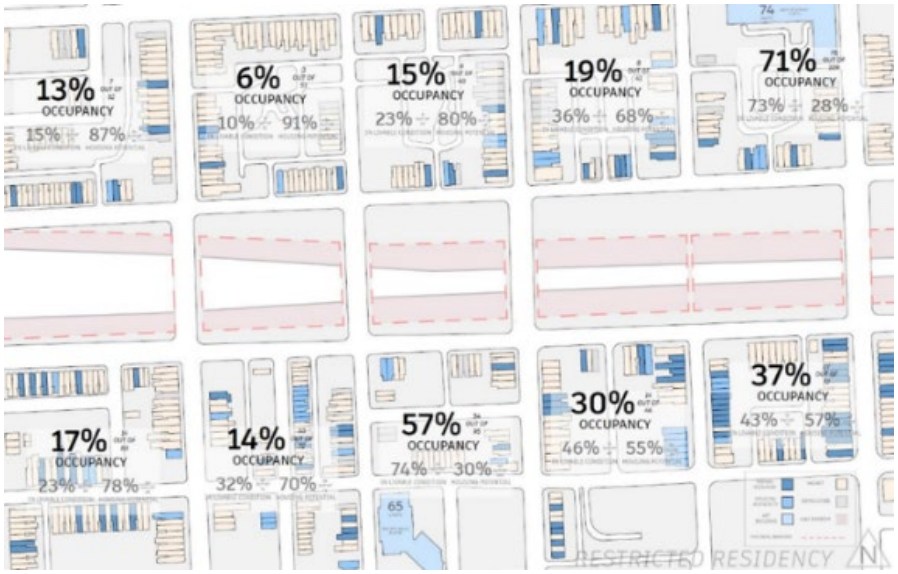

Figure 1. Map analysis illustrating current occupancy rates and housing conditions of surrounding Harlem Park and Franklin Square neighborhoods, adjacent to the "Highway to Nowhere" corridor. The data highlights extreme vacancy in several blocks, with occupancy rates as low as 6–19% in many parcels, juxtaposed with pockets of higher occupancy such as the 71% block at the corridor's edge. The coding differentiates between owner-occupied units, vacant properties, housing authority holdings, and demolished structures, revealing how physical barriers and the legacy of the highway have fragmented community cohesion. Course work developed in the Community Design Studio at Morgan State University, School of Architecture + Planning.

WHY CURRENT AFFORDABLE HOUSING FALLS SHORT

Traditional affordable housing models often unintentionally trap residents in cycles of economic stagnation. Eligibility for subsidized housing is frequently tied to strict income thresholds. As residents earn slightly more, they risk losing critical support, a phenomenon commonly referred to as the "benefits cliff" or "cliff effect." This creates a structural disincentive for pursuing higher-paying work or entrepreneurial ventures. Research highlights how even marginal income increases can disqualify families from support programs, leaving them worse off despite improved wages (Sylvester et al., 2021; National Conference of State Legislatures, 2024). Furthermore, affordable housing developments are often isolated interventions, with limited integration into surrounding economic ecosystems, which further undermines opportunities for upward mobility.

In West Baltimore, this issue is compounded by decades of systemic disinvestment, racial segregation, and exclusionary zoning policies. Without models that allow residents to remain in place as they achieve upward mobility, these developments risk perpetuating displacement, forcing families to leave the very communities they helped sustain. The Progressive Housing model aims to disrupt this cycle by establishing residency through adaptable rental and ownership structures, while embedding economic engines directly into the housing framework through entrepreneurship collectives that encourage progress.

REIMAGINING THE VOID AS A CONNECTED CORRIDOR

This re-envisioned I-40 corridor is organized into 4 primary development zones, areas A, B, C, and D, each anchored by an underground Red Line transit stop and a programmatic focus that integrates housing with complementary economic or cultural use. The phased approach ensures that each segment contributes uniquely to the corridor's identity while forming a cohesive connection between neighborhoods.

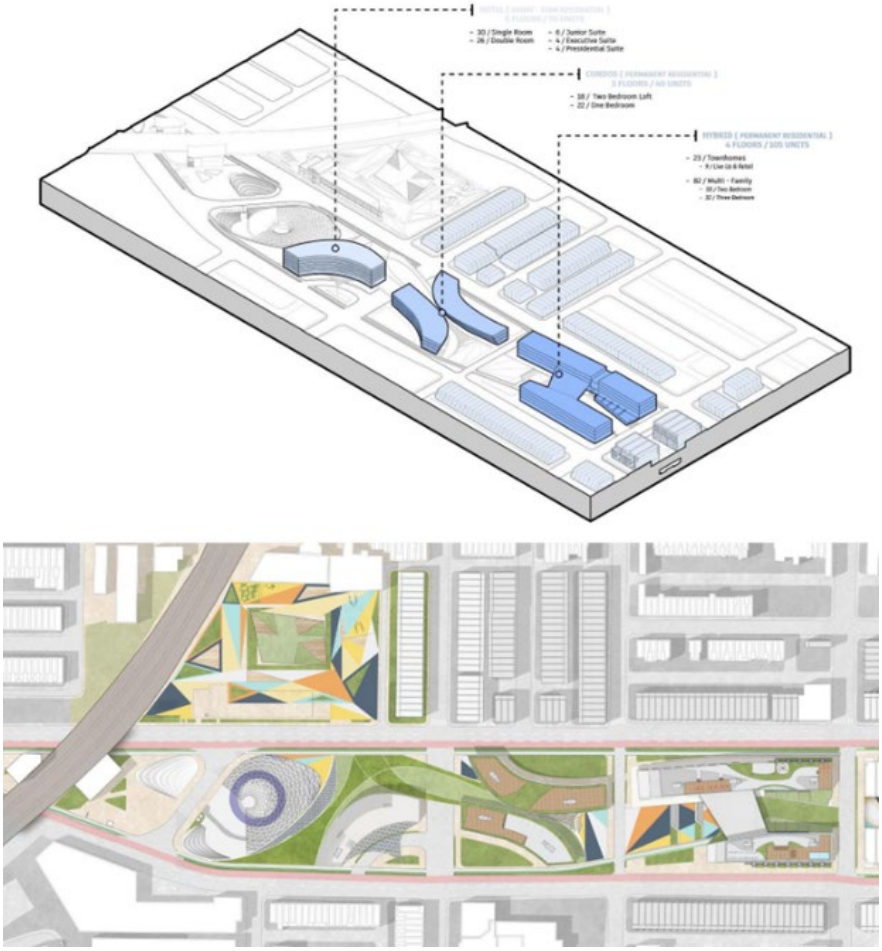

Figure 2. Top: Axonometric diagram of the Highway to Nowhere corridor master plan illustrating phased development Area A with the proposed underground Red Line stop at the transit hub for busses and MARC train. Residency is integrated through a 79-unit hotel, a 40-unit condominium complex, and a hybrid housing complex with 82 multi-family apartments and 23 townhomes with a retail option. Overpass and underpass systems are integrated to facilitate regular access to and through the residency areas from the transit hub

Bottom: Site plan of Area A highlighting its role as a transit-oriented hub that weaves high-density housing, retail, and public space into a cohesive urban fabric. Green corridors replace highway voids, creating elevated and ground-level public realms that link residents to economic opportunities and community amenities. Course work developed in the Community Design Studio at Morgan State University, School of Architecture + Planning.

Area A, the focal point of Phase 1 and the primary case study for this paper, is designed as a high-density transit hub combining permanent housing, hotel, commercial spaces, and civic amenities. Its location leverages heightened access to regional mobility while establishing an active ground level of retail, public plazas, and cultural programming.

CONDOMINIUM OVERPASS LIVING AS A COMMUNITY BRIDGE

Within Area A, the condominium development exemplifies the Progressive Housing model's capacity to merge private residency with public engagement.

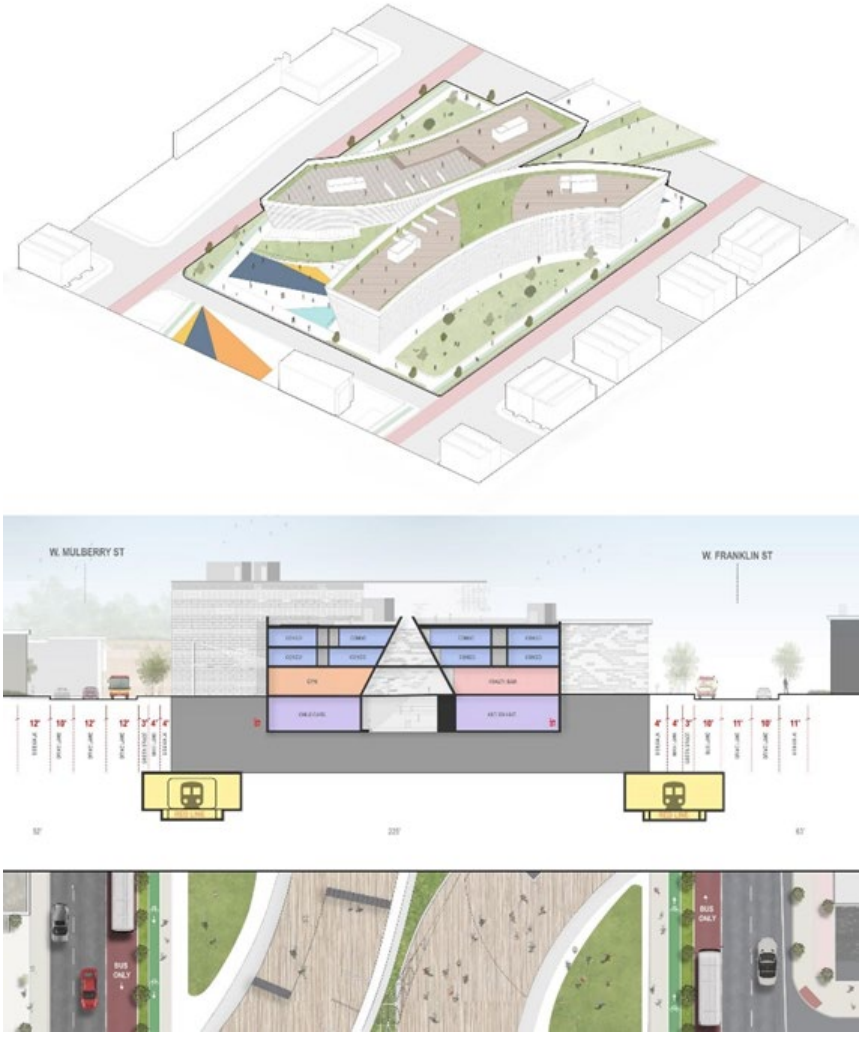

Figure 3. Top: Axonometric view of the Area A condominium complex, illustrating its integration of high-density residential units with multi-level public green space spanning over and under the former Highway to Nowhere corridor. The design leverages the existing infrastructural void to create layered community spaces, offering residents optional connections to event areas and pedestrian pathways through operable walls and terraces along the elevated greenway.

Bottom: Sectional diagram showing the vertical organization of uses above the proposed underground Red Line Station, including condominiums, fitness and wellness facilities, childcare, and an art exhibit space. This configuration reinforces the progressive housing model by embedding community-serving amenities within the residential structure, ensuring that transit access, economic activity, and social engagement are woven directly into the living environment. Course work developed in the Community Design Studio at Morgan State University, School of Architecture + Planning.

Within Area A, the condominium development exemplifies the Progressive Housing model's capacity to merge private residency with public engagement. Built adjacent to the repurposed Highway to Nowhere trench, the condos utilize both overpass and underpass spaces to create multi-level community interfaces. At the overpass level, a green pedestrian walkway weaves through the building massing, providing residents with direct access to public gathering areas, markets, and event spaces.

Optional operable wall systems at the condo's edge allow units to open directly onto these shared spaces during community events, or close for privacy as desired. Below, the underpass level is activated with commercial and cultural programs, transforming what was once a barrier into a vibrant node of social and economic activity. This dual-level activation maximizes the site's existing infrastructure while blurring the boundaries between living, working, and gathering.

HYBRID HOUSING FOR FLEXIBILITY AND ECONOMIC OPPORTUNITY

The hybrid housing model in Area A expands upon the progressive housing framework by integrating retail, townhouse, and multi-family spaces into a single typology.

Figure 4. Top: Axonometric view of the Area A hybrid housing complex, showcasing the integration of townhomes, multi-family residences, and retail spaces around a central elevated courtyard and green plaza. The design promotes flexibility through adaptable building typologies that allow units to transition between retail frontage along the outer street edge paired with privatized yards and an interior courtyard that repurposes the existing Highway to Nowhere void space into a vibrant, green community core.

Bottom: Elevation views illustrating the dual configuration of the hybrid housing units retail option with ground-floor storefront access to encourage entrepreneurship and street-level activation, and non-retail option offering traditional townhouse entry for fully residential use. This adaptability enables progressive housing strategies that respond to changing resident needs, while preserving community cohesion. Coursework developed in the Community Design Studio at Morgan State University, School of Architecture + Planning.

As shown in Figure 4, the building is oriented around a shared green plaza, with townhomes and multi-family units wrapping the courtyard to foster community interaction. This design approach offers residents the flexibility to modify the function of their units over time, shifting between live-up retail and non-retail townhouse configurations based on evolving household needs or economic opportunities. Such adaptability supports long-term residency by accommodating different life stages and entrepreneurial ventures without requiring relocation. The retail-option units at the street level are positioned to activate the pedestrian realm, strengthening connections between residential life and local commerce. Non-retail units maintain the same structural footprint, enabling seamless conversion to retail use if desired. This modular approach not only strengthens the economic base of the corridor but also ensures architectural cohesion regardless of individual unit function.

INTERWOVEN PROGRESSIVE COMMUNITY INFRASTRUCTURE

A defining characteristic of the Highway to Nowhere redevelopment is its emphasis on interwoven community infrastructure, physical, social, and economic systems designed to mutually reinforce one another. As illustrated in Figure 5, the plan integrates community-serving amenities directly into the housing framework, creating a feedback loop between residential stability and neighborhood vitality.

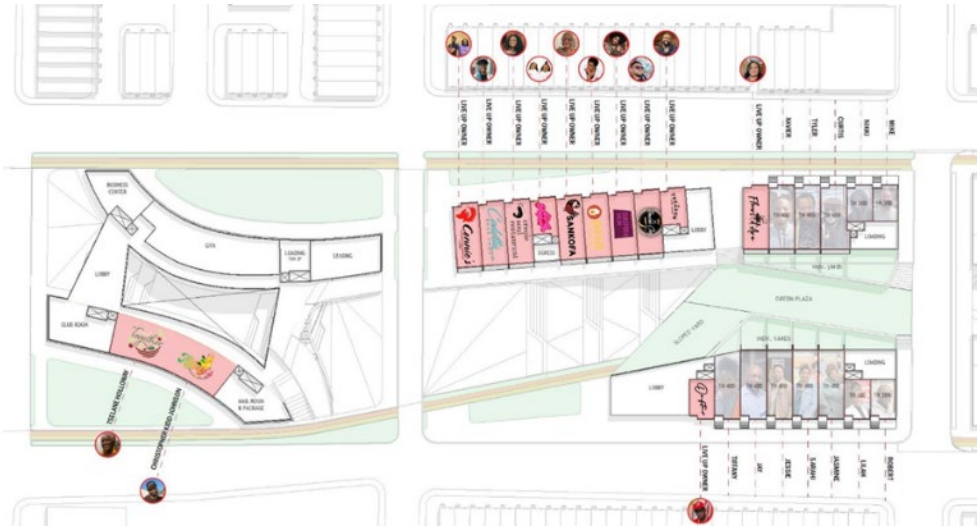

Figure 5. Site ground floor plan illustrates the coordinated integration of retail spaces, green plazas, and an active network of walkable inner-block and outer-block hardscapes. The design emphasizes seamless connectivity, with bike paths weaving through the development to encourage active transportation and multi-point access. Retail storefronts, occupied by neighborhood-based entrepreneurs and cultural vendors, are strategically positioned along primary pedestrian and bike routes to maximize visibility, foot traffic, and community engagement. Coursework developed in the Community Design Studio at Morgan State University, School of Architecture + Planning.

The vendor and artist integration strategy draws upon a catalogue of local entrepreneurs, creatives, and service providers, ensuring that economic activity generated within the redevelopment remains community anchored. Spaces for food vendors, art exhibitions, performance, and training are strategically positioned along key circulation paths to maximize visibility and participation. This approach builds upon established scholarship emphasizing that locally grounded economic systems strengthen resilience in historically marginalized communities (Jacobs, 1961, pp. 432-35; Fullilove 2013, pp. 96-8).

By embedding community enterprises into the daily patterns of residents, both physically and economically, the project fosters a transactional economy that directly benefits those living within the development. Events, markets, and cultural programming are not occasional add-ons but core components of the housing infrastructure, increasing access and engagement of the residents while elevating and amplifying local identity.

PROGRESSIVE HOUSING FOR THE INDIVIDUAL AND THE COLLECTIVE

Progressive housing within the Highway to Nowhere corridor is conceived not merely as a shelter strategy but as an economic and social mobility framework. The model supports flexible upward mobility by allowing residents to remain in place as their financial circumstances improve, leveraging rent-to-own pathways and affordable housing incentives targeted at entrepreneurs. This approach counters displacement pressures and promotes intergenerational stability.

Architectural adaptability is embedded in the building design, enabling spaces to evolve alongside resident needs. Modular units, convertible layouts, and shared amenities encourage organic shifts in use without major construction or relocation. The hybrid multi-family typologies function collectively to “raise all boats with one tide,” ensuring that community-wide success translates into improved opportunities for all residents.

Equally important is the interwoven community infrastructure that ties resident success to the broader neighborhood. Cultural events, local business corridors, and shared public spaces form a cohesive ecosystem where individual achievement reinforces community health and vice versa. As research on place-based development shows, such integrated approaches yield higher long-term retention and collective prosperity (Mallach, 2018, pp. 183-87; Chaskin and Joseph, 2010, pp. 299-300, 320-22).

A UNIFIED VISION FOR CORRIDOR TRANSFORMATION

The long-term vision for the Highway to Nowhere corridor envisions a continuous, phased transformation across Areas A through D, each anchored by a Red Line transit stop and a unique programmatic emphasis. Area B focuses on high density retail and integrated residency by establishing the inner spine of the void as a Retail Walk that extends from its own metro stop while maintaining street townhome presence on the outer edge of the blocks, fostering a creative backyard economy to its residents. Area C integrates health and wellness with community

infrastructure by creating a major sports complex, park pool, and an inter-generational center at the heart of its own transit stop. Area D highlights the final transit stop at the Lexington Mall Market, which is an interwoven green walkway that outlines a large farmers market, parks, public library and daycare. Together, these areas create a dynamic spine that both stitches together and empowers the full 1.39-mile corridor and the surrounding neighborhoods of Poppleton, Franklin Square, Harlem Park, Midtown Edmondson, and Upton.

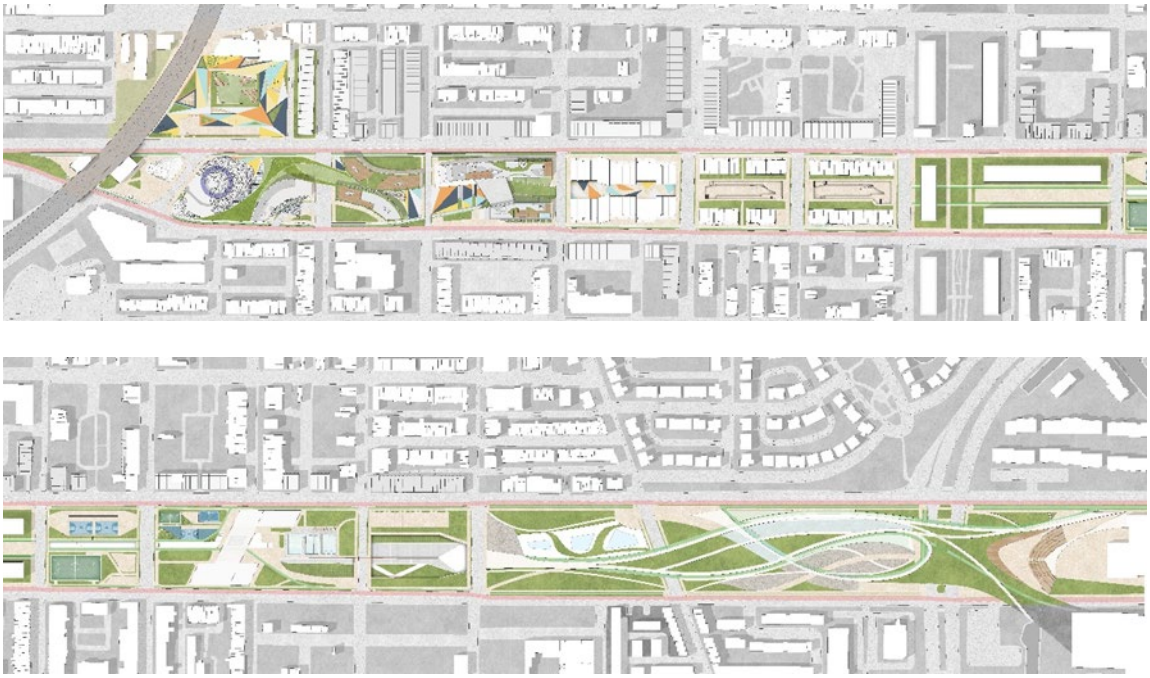

Figure 6. Phased master plan of the Highway to Nowhere corridor transformation, illustrating Areas A through D and their respective Red Line transit stops. The split site plan shows the integration of progressive housing, commercial corridors, and community infrastructure along a continuous green spine, reconnecting the neighborhoods of Poppleton, Franklin Square, Harlem Park, Midtown Edmondson, and Upton while activating the void left by the former highway.

The anticipated outcomes extend beyond physical redevelopment to include measurable improvements in economic mobility, housing stability, and community cohesion. By building above and around the void left by the former highway and relocating the Red Line underground, the project recaptures critical urban land for productive use, reconnects severed neighborhoods, and maximizes the development potential of the corridor.

In Area A, early implementation will serve as both proof-of-concept and catalyst, setting the tone for subsequent phases. Success here will demonstrate the viability of integrating progressive housing, commercial activation, and transit infrastructure in a manner that uplifts residents without displacement.

REPLICABILITY AND TRANSFERABLE PRINCIPLES

While the Highway to Nowhere corridor presents a unique configuration of spatial, historical, and social conditions specific to Baltimore, the Progressive Housing model and design strategies developed here offer transferable principles applicable to other abandoned or underutilized infrastructure corridors across the United States. Cities such as Detroit, Milwaukee, Syracuse, and Rochester face similar legacies of incomplete or decommissioned highway projects that fragmented urban neighborhoods and displaced predominantly Black and working-class communities (Mohl, 2004). The core framework of integrating affordable rent-to-own pathways, modular housing adaptability, and embedded community economic infrastructure can be adapted to these contexts, provided certain foundational conditions are met: political commitment to equitable development, community participation in planning processes, and access to transit or mobility infrastructure that enhances rather than isolates residents.

Key site-specific elements, such as the proposed underground Red Line transit and the particular overpass/underpass infrastructure of Baltimore's I-40 corridor, are not universally replicable. However, the underlying principles of adaptive reuse of existing infrastructure, integration of memorial or acknowledgment elements that honor displacement histories, and the hybrid live-work typologies that anchor economic activity within residential communities are broadly applicable. The emphasis on preventing resident displacement through economic mobility rather than forced transition addresses a systemic challenge common to affordable housing models nationwide. Cities seeking to transform infrastructural scars into productive urban assets can draw upon this model's integration of housing, commerce, and public space as a framework, tailoring programmatic and architectural responses to their own local contexts, community needs, and available resources.

CONCLUSION

Transforming the Highway to Nowhere from an infrastructural scar into a thriving urban spine demands more than traditional redevelopment. It requires an intentional fusion of progressive housing models, adaptable architecture, and embedded community infrastructure, all grounded in local context and history. By centering residents as both beneficiaries and active participants in the redevelopment process, the proposed framework seeks to replace cycles of disinvestment with systems of shared prosperity. The integration of flexible ownership pathways, modular design, and locally anchored economic engines offers a replicable model for other cities grappling with the legacy of infrastructural injustice. In doing so, it reclaims not only the land but the future of West Baltimore's communities.

ACKNOWLEDGEMENTS

The author wishes to express deep gratitude to the residents of the communities surrounding the "Highway to Nowhere" in West Baltimore, past and present, whose resilience, lived experiences, and determination have been a constant source of inspiration. Their stories, both of loss and of

perseverance, provide the foundation for this work and serve as a reminder of the human cost of infrastructural injustice.

Special thanks are extended to the National Organization of Minority Architects Students (NOMA) for providing a platform through its student design competition to envision and communicate transformative solutions for historically disinvested urban communities. This project was developed as part of the NOMA student design competition and reflects a broader, years-long commitment by the Morgan State University School of Architecture + Planning to studying and addressing the impacts of the "Highway to Nowhere." Our school remains committed to this work until authentic, positive change is achieved, where the physical scars are healed, the social and economic divisions are mended, and the communities most affected can thrive on their own terms.

The author also extends sincere appreciation to the students of the Community Design Studio at Morgan State University's School of Architecture + Planning, whose creativity, dedication, and countless hours of hard work brought this vision to life. Their collaborative spirit, attention to detail, and commitment to engaging with community narratives were instrumental in shaping a proposal that seeks not only to repair a fractured urban landscape but also to empower the people who call it home

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The Impact and Adoption Patterns of WELL Building Standard Certification for Multifamily Residences: A Global Analysis of the Health and Wellness-Focused Residential Market

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ABSTRACT

The WELL Building Standard represents a paradigm shift in design and construction, prioritizing occupant health and wellness through evidence-based strategies addressing air, water, nourishment, light, fitness, comfort, and mind. This study examines global adoption patterns, geographic distribution, and certification characteristics of WELL-certified residential projects to understand emerging trends in health-focused housing design. A comprehensive analysis of the global WELL project database encompassed 162 certified residential projects across multiple certification pathways (WELL v1, v2, Core, and Pilot), focusing on geographic distribution, certification achievement levels, and industry sector engagement.

Residential applications represent 8.1% of total WELL-certified projects (n=1997), with notable geographic concentration in China (126 projects, 77.8%) and the United States (19 projects, 11.7%). The certification distribution demonstrates strong market commitment of health and wellness-focused design principles, with 77.2% achieving Gold and 10.5% reaching Platinum certification. Analysis reveals substantial future growth potential with 505 registered projects and 138 pre-certified projects in the pipeline. Cross-industry engagement spans real estate (59.9%), building design and construction (27.8%), and financial services sectors, indicating WELL integration across diverse housing typologies.

WELL residential certification demonstrates significant global momentum with high achievement rates indicating serious commitment to health-focused design principles. The substantial project pipeline suggests continued growth, though geographic concentration in developed markets highlights barriers to broader adoption and the need for strategies expanding WELL principles to diverse socioeconomic contexts.

INTRODUCTION

Modern sustainable building practices were initially shaped by certification systems like BREEAM, created in 1990 (Mistry, 2007), and LEED, created in 2000 (Vierra, 2016), which prioritized environmental performance through metrics such as energy efficiency, water

conservation, and responsible material use, leading to their widespread global adoption (Fowler and Rauch, 2006; Reed et al., 2009). However, growing scientific and economic evidence has highlighted the profound impact of the built environment on human health, especially as people spend over 85–90% of their time indoors, much of it at home (EPA, 2025; WHO, 2014). This recognition has driven a major paradigm shift from purely environmental frameworks to comprehensive human-centric design strategies that integrate wellness with sustainability. In response, the WELL Building Standard, launched by the International WELL Building Institute (IWBI) in 2014, became the first certification system focused exclusively on promoting human health in buildings, grounded in rigorous medical and scientific research (Matos, 2014). Covering seven key areas—i.e. air, water, nourishment, light, fitness, comfort, and mind—WELL emphasizes third-party verification to ensure measurable health outcomes. Its evolution from WELL v1 to WELL v2 has significantly expanded its applicability across building types, including multifamily residential projects. WELL v2 introduced a flexible, points-based system and removed many of the rigid prerequisites that had limited early residential participation, opening the door for more diverse and widespread adoption (Kokatnur et al., 2025). The pace of WELL adoption in the residential sector has accelerated markedly since 2020. Between 2020 and 2024, the number of residential WELL certifications grew by more than 300%, driven by increasing awareness of indoor environmental quality following the COVID-19 pandemic and growing market acceptance of health-focused real estate (Honey-Rosés et al., 2021; Kokatnur et al., 2025). Furthermore, new pipeline data identified from WELL-registered project database, IWBI (2025), indicates strong future growth, with nearly 40% of registered projects globally now falling under the residential typology.

In multifamily markets, growing tenant demand for wellness amenities and sustainability should have encouraged developers to pursue certifications for competitive advantage and premium rents. Overall, these trends highlight key factors that should influence WELL certification uptake in residential settings. While the benefits of healthy housing are well established as reducing healthcare costs, improving productivity, and mitigating health risks such as respiratory illness, mental distress, and developmental delays (MacNaughton et al., 2017; Singh et al., 2010), the adoption of WELL in the residential sector remains limited. This gap is particularly evident in low- and middle-income contexts, where barriers to implementation persist. WELL certification for residential sector remains concentrated in a few countries, with China and the U.S. alone accounting for nearly 90% of all certified residential projects. Barriers in emerging markets limited public awareness, high energy use, high construction costs, and high certification costs (Kokatnur et al., 2025). Therefore, this study examines the global adoption patterns, geographic distribution, and certification characteristics of WELL-certified residential projects, aiming to understand emerging trends in health-focused housing design and identify factors influencing implementation across diverse markets.

Theoretical Framework

This study applies Rogers' (2003) Diffusion of Innovation Theory and Market Transformation Theory (York and Rosa, 2003) to understand residential WELL adoption patterns. The geographic concentration in China (77.8%) and the U.S. (11.7%) aligns with diffusion theory's "innovator" and "early adopter" categories, while the substantial project pipeline (505 registered,

138 pre-certified) and institutional evolution from WELL v1 to WELL v2 indicate market transformation from niche innovation toward mainstream integration.

RESEARCH OBJECTIVES AND QUESTIONS

Despite the proven health benefits of WELL-certified environments, multifamily residential projects account for only a small fraction of WELL certifications globally, despite people spending most of their time at home. This mismatch signals a critical research gap in understanding adoption patterns, regional disparities, and barriers to residential implementation. To analyze global trends, geographic distribution, and project characteristics of WELL-certified multifamily housing and identify key factors influencing adoption across diverse markets. research questions:

- What are the global geographic patterns of WELL-certified residential projects?
- What certification levels are most common in residential applications?
- Which market sectors are driving WELL adoption in housing?
- What does the project pipeline reveal about future growth in residential WELL adoption?

This research bridges a major gap in the literature by offering the first global assessment of WELL adoption in residential market, providing evidence to inform policy, guide market strategies, and support healthy housing initiatives, especially in underserved and resource-constrained settings.

METHODOLOGY

This study employs a quantitative approach to assess global adoption patterns of the WELL Standard in residential markets through descriptive statistics and geographic analysis. The primary data source is the IWBI's public project directory (IWBI, 2025), covering all certified, pre-certified, and registered WELL projects worldwide from 2014 to end of 2024. Residential projects were defined as developments with five or more dwelling units, including apartments, condominiums, and townhouses, consistent with IWBI's multifamily category (WELL, 2024). Mixed-use projects were included if residential space constituted a major component.

Projects were classified by six key variables: 1) project type (apartments, condominiums, mixed-use); 2) project size (certified square footage); 3) certification pathway (WELL v1, v2, Core, Pilot); 4) certification level (Bronze, Silver, Gold, Platinum); 5) project stage (registered, pre-certified, certified); and 6) industry sector (real estate, construction, finance). Geographic data was coded by country and aggregated into global regions. The analysis employed descriptive statistics to summarize certification characteristics and geographic distribution patterns. Pipeline analysis assessed market momentum by examining projects at various certification stages.

Comparative analysis positioned residential WELL trends within the broader certification market context to understand adoption dynamics and growth trajectories.

RESULTS

The analysis of the global WELL project database reveals that residential applications represent a significant and growing segment of WELL-certified projects. Of the 1997 total projects in the database, 162 projects (8.1%) are classified as residential, encompassing dwelling units and residential developments (IWBI, 2025). These projects represent 35,789,180 square feet of certified residential space, with an average project size of 220,921 square feet (IWBI, 2025). Project scales range from 3,827 to 2,320,822 square feet, indicating implementation across diverse residential typologies from boutique developments to large-scale housing complexes and mixed-use communities. The residential portfolio comprises 97 dwelling unit projects (59.9%) and 65 residential projects (40.1%), demonstrating that WELL certification is being applied across the full spectrum of residential environments, from traditional multifamily housing to innovative residential developments and mixed-use projects with residential components.

Geographic Distribution and Market Concentration

The geographic distribution of WELL-certified residential projects demonstrates significant market concentration with emerging global diversification. China leads the residential WELL certification landscape with 126 projects (77.8% of all residential certifications), reflecting the country's rapid adoption of health-focused building standards in residential development and substantial market investment in premium housing. The United States follows as the secondary market with 19 projects (11.7%), representing significant adoption in the North American market (IWBI, 2025).

Additional markets show distributed adoption patterns across 12 countries, with Canada, Ireland, Spain, Japan, and Netherlands each contributing two projects (1.2%), while Brazil, the Czech Republic, Denmark, Taiwan Region, France, Haiti, and Thailand each represent single projects (0.6%). This geographic distribution indicates that while WELL residential certification remains concentrated in major markets with advanced building performance frameworks, adoption is expanding globally across diverse regulatory and economic contexts.

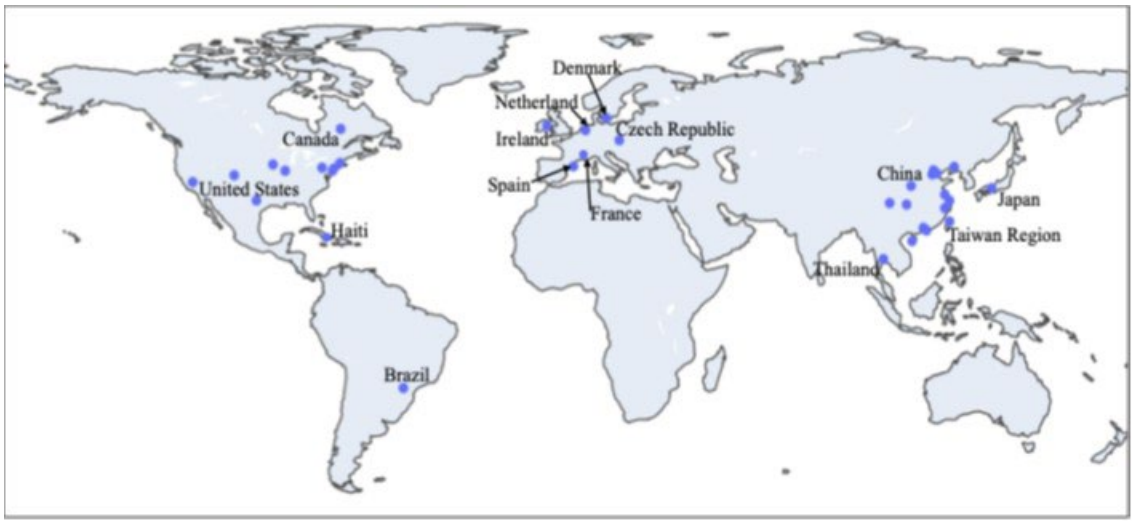

Figure 1: Geographic distribution of WELL-certified residential projects showing concentration in innovator (China) and early adopter (United States) markets.

Certification Achievement Patterns

The certification level distribution reveals consistently high-performance outcomes among residential projects. Gold certification represents the dominant achievement level with 125 projects (77.2%), confirming residential developers' commitment to comprehensive health and wellness implementation. Platinum certification, representing the highest standard, was achieved by 17 projects (10.5%), while Silver certification accounts for 18 projects (11.1%). Only two projects (1.2%) fell into other certification categories (IWBI, 2025).

Figure 2: WELL certification achievement levels showing 87.7% Gold/Platinum commitment indicating relative advantage focus.

These achievement patterns demonstrate that 87.7% of residential projects achieve Gold or Platinum certification levels, indicating that residential developers pursuing WELL certification invest in comprehensive health and wellness strategies rather than minimum compliance approaches. The high Gold certification rate particularly suggests that developers view WELL as a premium market differentiator requiring substantial implementation commitment.

Standard Evolution and Adoption Pattern

The analysis of WELL version adoption reveals balanced utilization across standard generations with stronger adoption of newer versions. WELLv1 accounts for 65 projects (40.1%), representing substantial ongoing utilization of the original standard, while WELL v2 versions collectively represent 59.9% of residential projects. Within WELL v2, Certification pathway leads with 45 projects (27.8%), followed by Pilot with 42 projects (25.9%), and Core representing 10 projects (6.2%).

This distribution suggests that residential markets demonstrate familiarity with multiple certification pathways, with growing preference for WELL v2 approaches reflecting developer confidence in the refined standard's market value and implementation efficiency.

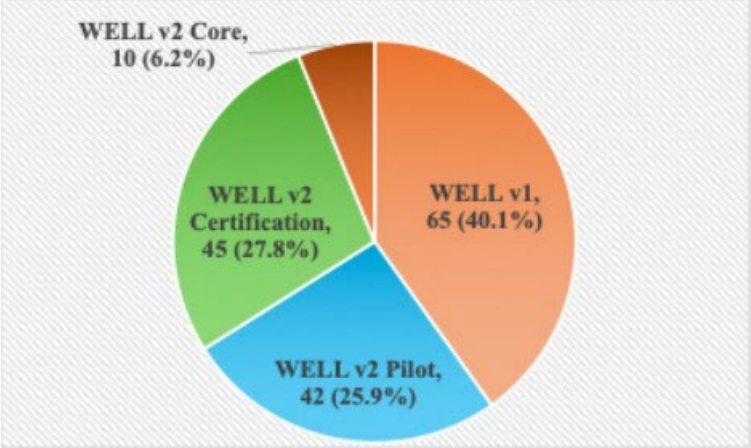

Figure 3: WELL standard version adoption showing institutional adaptation from v1 to v2.

Temporal Development and Industry Sector Analysis

Certification timeline analysis reveals steady growth with notable acceleration in residential WELL adoption. Early adoption began with two projects in 2017, followed by moderate but consistent growth through 2018-2021, ranging from 7-13 projects annually (Figure 4). The market experienced substantial expansion in 2022 with 39 certifications, representing the peak year for residential WELL achievement. This was followed by sustained high volumes, with 34 projects in 2023 and 26 projects in 2024, while the first portion of 2025 shows 17 projects already certified. This temporal pattern indicates that residential WELL certification achieved

sustained market momentum beginning in 2022, potentially reflecting increased awareness of indoor environmental quality following global health concerns, developer confidence in market differentiation value, and maturation of health-focused design expertise within the residential development community.

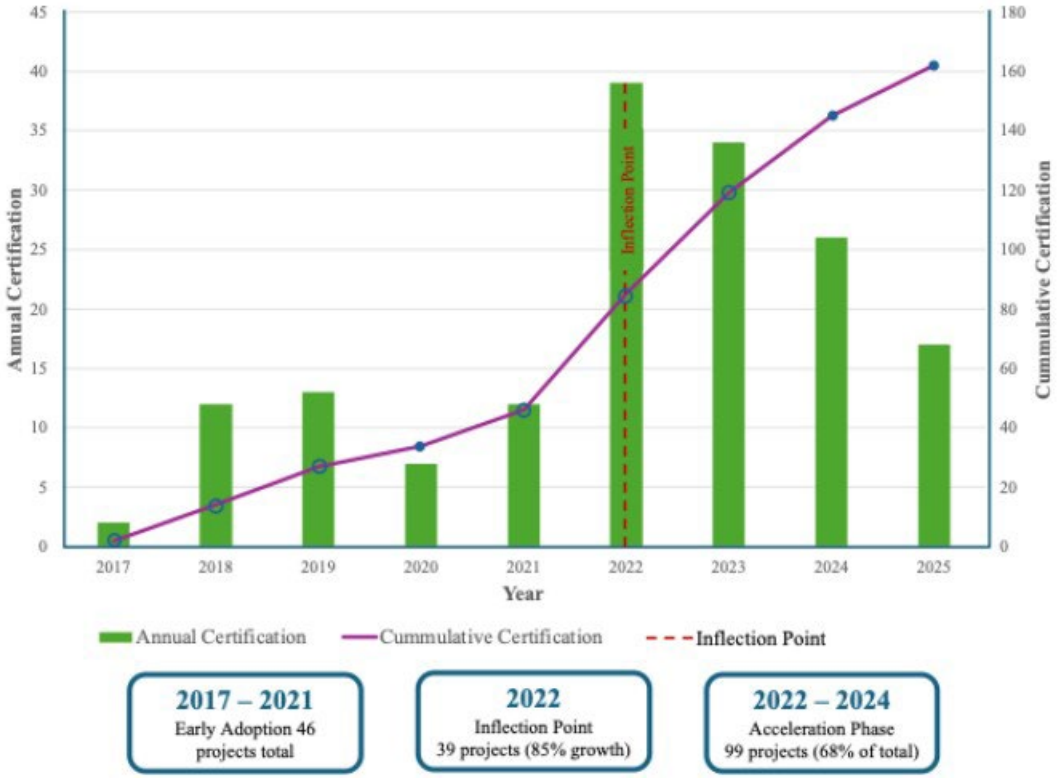

Figure 4: WELL certification adoption timeline showing S-curve pattern characteristic of innovation diffusion.

The sector analysis reveals clear patterns in residential WELL certification adoption across major market segments. Real Estate represents the dominant sector with 97 projects (59.9%), encompassing traditional residential developers, real estate investment firms, and property development companies. This substantial representation confirms that mainstream residential development has embraced WELL certification as a core market strategy rather than a specialized niche application. Building design and construction accounts for 45 projects (27.8%), representing architecture firms, engineering companies, construction contractors, and design consultancies leading residential WELL implementation. This significant participation indicates strong professional community engagement and suggests that design and construction expertise is driving innovation in health-focused residential development. Financial services and insurance contributed six projects (3.7%), reflecting banking and insurance sector investment in residential real estate with health and wellness components. Professional services and business support

accounted for three projects (1.9%), while smaller sectors including hospitality, public service, transportation, demonstrate diverse cross-sector interest in residential health and wellness applications.

Project Scale and Market Impact

The comprehensive residential WELL certification data demonstrates substantial market penetration with significant growth potential. The 35.8 million square feet of certified residential space represents meaningful market impact, with individual projects averaging over 220,000 square feet, indicating focus on substantial residential developments rather than small-scale projects. The 8.1% share of total WELL projects aligns closely with industry estimates and indicates growing recognition of health and wellness principles in residential development (IWBI, 2025). The sustained high certification volumes since 2022, combined with geographic expansion beyond initial concentration markets and strong certification achievement levels, suggests that residential WELL certification is positioned to become the dominant global healthy building movement. The diverse project typologies and cross-industry engagement establish a foundation for continued market expansion and standardization of health-focused residential design practices across global markets.

DISCUSSION

The residential segment of the WELL certification market is undergoing a notable transition from early adoption to broader integration within mainstream development practices. Since its launch in 2014, WELL Standards has evolved from a largely commercial-focused certification system to one that now includes over 35.8 million square feet of certified residential space which accounts for about 8.1% of the total WELL portfolio, with adoption accelerating significantly in recent years. This evolution demonstrates the classic S-curve pattern predicted by diffusion of innovation theory, where innovations initially experience slow uptake among innovators before accelerating as they reach early adopter and early majority markets (Rogers, 2003).

Evolution of WELL Certification in Residential Projects

WELL v1, introduced in 2014, initially targeted commercial office buildings with a focus on performance across seven concepts: Air, Water, Nourishment, Light, Fitness, Comfort, and Mind. By 2016, residential adoption was limited, with fewer than 250 WELL-certified or registered projects globally, and most of those concentrated in institutional and office settings. Residential certification remained exploratory, limited to pilot initiatives, often led by design innovators in high-end markets. This early phase exemplifies the “innovator” category in diffusion theory, characterized by risk tolerance, substantial resources, and willingness to experiment with unproven technologies (Rogers, 2003).

A turning point occurred with the release of WELL v2 in 2020, which introduced a streamlined, flexible, point-based structure and broadened its applicability to diverse building types, including multifamily and large-scale residential projects. This reconfiguration of the framework significantly improved the feasibility of WELL certification in the residential sector, removing previous barriers related to rigid prerequisites and sector misalignment. The institutional

adaptation from WELL v1 to v2 reflects what diffusion theory identifies as improved "compatibility" and reduced "complexity"—two critical attributes that influence innovation adoption rates (Rogers, 2003). This evolution represents market transformation theory's concept of institutional efficacy, where certification systems adapt to reduce barriers and broaden applicability (York and Rosa, 2003).

The shift is evident in certification trends when residential project certifications peaked in 2022 with 39 projects and have sustained high volumes through 2024. This sustained momentum reflects an institutionalization of WELL principles in residential real estate. Larger developers in China and United States are likely no longer treating WELL as a novel concept but rather as a deliberate market strategy, which is a clear indication of the transition from the "early adopter" phase to the beginning of "early majority" adoption, where innovations become strategic business tools rather than experimental initiatives (Rogers, 2003).

Notably, this shift is evident in large-scale developments that demonstrate commitment to comprehensive health and wellness integration. Projects like the Yuyue Yaju Community Buildings #1-#7 in Jiangsu, China (2.32 million sq ft, Gold certified, 2024) and One Paseo Living in California, U.S. (800,000 sq ft, Gold certified, 2024) illustrate how WELL is being applied at a significant large scale, far beyond the scope of early pilot programs.

The global footprint, though still concentrated, is expanding. Early pioneers, such as the Qianhai One Excellence Tower-4 (China, 2018) and the Yuanyang Tianjiao series in Guangdong Sheng, China, laid the groundwork. More recently, Latin America has joined the movement, with Brazil's Pinah (141,545 sq ft, WELL Platinum certified, 2024) becoming the region's first residential project to achieve this level of certification. The overall geographic expansion follows diffusion theory's prediction that innovations spread from innovator market to new regions as early majority adopters observe successful implementations and gain overall confidence.

Certification Levels and Economic Strategy

A compelling trend in the data is the high rate of certification achievement with 87.7% of residential WELL projects reaching either Gold (77.2%) or Platinum (10.5%) levels. This reflects a strategic preference for depth of implementation over minimal compliance for WELL certification, positioning it not as a checklist but as long-term value-added consumer providing substantial relative advantage over conventional development practices. This aligns with diffusion theory's concept of "relative advantage," where early adopters pursue innovations not for minimal compliance but for significant competitive differentiation (Rogers, 2003). Platinum-level certifications, such as CGDG Tianjin Tibei Luneng Mansion in Tianjin, China (1.25 million sq. ft.) and China World Apartments in Beijing, China (861,112 sq. ft.), demonstrate that developers in certain markets are willing to make substantial investments when the value proposition aligns. These premium-level implementations reflect the risk-taking behavior and substantial resource commitment characteristic of "innovator" and "early adopter" categories, who are willing to invest significantly in innovations they perceive as providing competitive advantage.

The residential WELL portfolio also demonstrates adaptability across project scales. While many high-profile projects are expansive, smaller efforts like Rayzor Ranch 6 Plex A in Texas, U.S. (22,693 sq. ft.) show that WELL implementation is feasible at more modest sizes, though larger developments likely benefit from economies of scale. This scale diversity indicates improving "trialability"—the ability for potential adopters to experiment with the innovation at various levels of commitment, which diffusion theory identifies as crucial for broader market penetration.

Geographic Concentration and Sector Engagement

Despite signs of market growth, WELL residential certification remains geographically concentrated. China alone accounts for 77.8% of all residential certifications, followed by the U.S. Together, these two countries represent 89.5% of the global market, a reflection of supportive regulatory frameworks, mature construction industries, and strong consumer demand in those regions. This concentration pattern perfectly exemplifies diffusion theory's adopter categories, with China functioning as the primary "innovator" market and the United States as the leading "early adopter" market. The dominance of these two markets reflects the high resource requirements, institutional support, and cultural compatibility necessary for early-stage innovation adoption (Rogers, 2003).

While residential WELL activity has been recorded in 14 countries, most markets show only marginal participation. Limited representation from developing regions, such as Brazil, Haiti, and Thailand, each with only one residential WELL project, suggests possible economic or technical barriers. Even in nations with mature construction ecosystems, such as Ireland, Spain, Japan, and the Netherlands, the WELL adoption rate remains modest. This suggests that financial and technical capacity alone is insufficient; regulatory incentives, public policy alignment, and cultural prioritization of health and wellness also play critical roles in scaling adoption.

The active involvement of sectors beyond real estate, particularly financial services (3.7% of residential projects), highlights growing institutional confidence in the long-term value of health-focused housing. For instance, the Grand Milestone series in Shaanxi, China, signals that WELL-certified housing is viewed not just as a lifestyle upgrade but as a financially sound investment. Similarly, the participation of design and construction professionals (27.8% of projects) suggests that market development is being driven by experienced industry players, not just client demand.

Implementation Barriers and Access Challenges

Several systemic barriers may limit the broader diffusion of residential WELL certification:

- **Cost Constraints**: The clustering of certifications in large-scale projects points to the high upfront costs of implementation. These costs may deter mid-sized or affordable housing developers, potentially exacerbating inequities in access to health-focused living environments. These cost barriers reflect what diffusion theory identifies as resource requirements that limit innovation access to well-funded "innovator" and "early adopter" organizations, potentially slowing diffusion to "early majority" and "late majority" markets that require more accessible implementation models.

• **Expertise Dependency**: Successful WELL certification often requires specialized knowledge in health-driven design and engineering, along with familiarity with WELL-specific standards (Kokatnur et al., 2025; Shari and Soebarto, 2012). This need for expertise presents a hurdle in regions lacking WELL-accredited professionals or advanced construction practices.

• **Regulatory Misalignment**: In many countries, local building codes and standards may not align seamlessly with WELL requirements, complicating implementation and increasing administrative burden.

• **Market Perception**: In less mature markets, developers and consumers alike may still view WELL as a luxury rather than a necessity, dampening demand in both new developments and retrofits.

Nonetheless, the consistent high performance of certified residential projects confirms the technical feasibility of WELL implementation, especially when paired with committed resources and stakeholder alignment. Residential settings, in particular, benefit from longer occupant exposure times and greater developer control over environmental conditions, both of which complement the WELL framework's health-centric goals. The successful implementation by early adopters provides the "observability" of results that diffusion theory predicts will influence broader market adoption as evidence of benefits accumulates and becomes visible to potential adopters.

IMPLICATIONS AND FUTURE DIRECTIONS

Though residential sector constitutes only 8.1% of WELL certified project globally, the residential sector may offer unique advantages for WELL implementation. Compared to commercial buildings, residences involve longer occupant exposure times and greater developer control over indoor environmental conditions factors that align well with the goals of health and wellness certification. With over 35.8 million square feet of certified space, WELL has achieved critical mass in residential markets, influencing supply chains, regulatory interest, and industry transformation toward health-centric design as a new norm.

In addition to the current 162 fully certified projects analyzed in this study, the IWBI WELL certified project database demonstrates substantial future growth potential with 505 registered projects and 138 pre-certified projects. The registered project pipeline represents approximately 3.1 times the current certified project volume, indicating significant market momentum and developer confidence in WELL market value. Diffusion theory analysis reveals that this pipeline structure indicates a critical transition from early adopter to early majority markets. The substantial registered project volume (62.6% of total pipeline) exemplifies the "trialability" behavior characteristic of early majority adopters who engage in careful evaluation before full commitment. This positioning suggests the next two-four years will be decisive for determining whether WELL achieves mainstream market penetration or remains a niche innovation.

CONCLUSION

The WELL Building Standard's residential portfolio has entered a phase of mainstream integration, characterized by large-scale projects, institutional investor confidence, and somewhat expanding geographic representation. With over 35.8 million square feet of WELL-certified residential space and certification frameworks tailored for scalability, the standard is no longer a niche innovation but is a driver of industry transformation.

The path forward requires deliberate efforts to reduce certification barriers, build local expertise, and advocate for policy mechanisms that support health-focused housing at all scales. If these conditions are met, WELL residential certification can play a significant role in reshaping global housing markets to prioritize occupant well-being, resilience, and environmental performance. Diffusion theory analysis suggests this transformation is at a critical juncture, with the next two-four years determining whether WELL residential certification achieves mainstream market adoption or remains concentrated in innovator markets.

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The Impact of Residential Healthcare Facility Proximity on Single-Family Sale Prices

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ABSTRACT

The overall objective for this research was to examine the relationship between residential healthcare facilities and home sale prices in a small city (population between 10,000 and 25,000) in Oklahoma. With the increase in adults needing adult care and with an expected increase in occupancy in residential healthcare facilities, this study explored the impact of these facilities on the sales price of single-family homes in their surrounding areas. This is important because most of the baby boomer generation has already reached age 65. One of the primary research objectives was to determine whether there was a statistically significant difference in the sale prices of homes located near residential healthcare facilities compared to those not in proximity, and, if so, whether these homes sold for a higher or lower price. Data collected from the Multiple Listing Service (MLS) for the specific city in question was examined. Using a quantitative approach, the results indicate an increase in housing sale prices for homes sold near residential healthcare facilities.

DEFINITIONS

Walking Distance: In the context of this research, "walking distance" is defined as 0.5 miles or less, consistent with previous U.S. Department of Transportation guidance, where the Federal Transit Administration (FTA) notes that passengers typically walk up to one-quarter mile to reach a bus stop and walk up to one-half mile to access light or heavy rail stations (FTA, n.d.).

Urban Areas: A population of 50,000 or more people (Census, 2012).

Urban Clusters: A population of at least 2,500 and less than 50,000 (Census, 2012).

Rural: Encompasses all population, housing, and territory not included within an urban area (Census, 2012).

INTRODUCTION

When individuals or families buy a home, they tend to review several different factors, including home prices, size of the home, commute to work, quality of schools, as well as the distance from other amenities within the proximity, including residential healthcare facilities. The study could help homebuyers, developers, and city planners better understand whether these facilities add

value or create concerns for surrounding neighborhoods. This research project investigates the range of economic, psychological, health, and aging needs that relate to how single-family homes are priced for sale, with particular attention to the trends involving the baby boomer generation's housing and health needs.

The baby boomer generation is approaching an age where many need to reevaluate their housing and living arrangements. In the past century, the share of the U.S. population aged 65 or older has more than tripled, rising from 4.7 percent in 1920 to 16.8 percent in 2020 (Jones and Neelakantan, 2024). In 2020, about one in six people in the United States were age 65 and over. In 1920, this proportion was less than one in 20. The rapid growth was largely driven by aging baby boomers (born between 1946 and 1964) who began turning 65 in 2011 (Census, 2023). As the senior population grows and the need for residential healthcare facilities rises, it is important to understand how these developments impact nearby home values, whether positively or negatively.

This document will introduce a proposed research study on single-family values in cities in Oklahoma, near the University of Oklahoma where the study is being conducted, with urban cluster populations between 10,000 and 25,000 people. These urban cluster populations will allow the study to be conducted to represent the growing small-town environments where development pressures and aging population needs intersect. The proposed study will include homes within walking distance of residential healthcare facilities measured by 0.5 miles or less. The City of Altus, Oklahoma, was the test site for the initial research that will be conducted. Altus is in the southwest corner of the state of Oklahoma with a population of approximately 18,600.

This research is important because it can help homebuyers, developers, and city planners better understand whether residential healthcare facilities positively or negatively impact surrounding neighborhoods. The research interest and objectives involved examining the relationship between single-family houses near residential healthcare facilities to conduct a comparative analysis of selling prices between houses that are within walking distance (0.5 miles) to a residential healthcare facility.

One objective for this study was to examine the existing literature on the factors influencing single-family home pricing, with a particular emphasis on proximity to residential healthcare facilities. Additionally, the research objectives focused on how residential healthcare facilities in urban clusters in Oklahoma may or may not influence single-family housing prices that surround these types of senior facilities. One of the primary research objectives was to determine whether there was a statistically significant difference in the sale prices of homes located 0.5 miles from residential healthcare facilities compared to those that are not, and if so, whether these homes sold for a higher or lower price.

The research questions this study included were:

(1) Does proximity to residential healthcare facilities impact the price of single-family

homes in Oklahoma?

(2) If there was a statistically significant effect in previous studies, was it positive or negative?

Scope

This study drew primarily from previous literature reviews and peer reviewed articles published across the United States. It focused on skilled nursing facilities, assisted living facilities, and independent living facilities, recognizing that each provides a distinct level of care. The study analyzed data from the Multiple Listing Service (MLS) spanning a 10-year period from the beginning of 2014 to the end of 2024.

Delimitations

More recent literature reviews and peer-reviewed studies were prioritized over older research studies. In terms of data selection for this study, large cities such as Oklahoma City, Tulsa, Moore, Edmond, and Norman were excluded to prioritize the impact on smaller communities.

This research focused on the ten years' worth of MLS data collected; discussed previous literature regarding single-family properties, as well as residential healthcare facilities; created a hypothesis; and evaluated the data by conducting one multiple linear regression.

LITERATURE REVIEW

This literature review included both U.S. and international research, with international sources limited to factors influencing home purchases for broader context, while studies focused on the selling prices of single-family homes near residential healthcare facilities were drawn exclusively from U.S.-based research.

Factors Impacting Home Purchases and Home Prices

When buying a home, people have several factors to think about. Some of the factors could be home prices, size of the home, commute to work, quality of schools for their children, higher educational opportunities, access to public transportation, commercial and retail nearby, crime statistics, and environmental concerns, among other factors. For example, Hassan et al. (2021) conducted a research study in Malaysia that identified six key factors that influence home purchase. The six different factors in their study include: demographic, financial, location, dwelling characteristics, neighborhood, infrastructure facilities, environmental, developer service quality, and superstition beliefs. House choice is also associated with some elements influencing the decision-making for house purchase, which varies for each individual (Hassan et al., 2021). Finances, property location, corporate image, and property attributes have also been identified as key influences behind home purchases (Xuan, 2024).

Factors influencing home-buying decision-making also vary by the level of education and family size. Mang et al. (2018) reported that people who have higher education qualifications and those with larger families are more influenced by a location close to the workplace. The proximity of

the house to a school was also highly correlated with the decision to purchase a home (Mang et al., 2018).

Proximity to business districts has also been found to be influential in other countries. For example, a study in Shanghai, China found that easier commutes to the central business district center resulted in an average house price appreciation of 3.75 %, with the most distant residential zone enjoying the largest appreciation (Zhou et al., 2021). In another study, regarding parks and green spaces, house values rose as proximity to a park increased; properties immediately adjacent to a park sometimes had a lower additional value than dwellings a block or two away from it (Crompton and Nicholls, 2020). On the other hand, proximity to undesired locations has been shown to have negative effects on home prices. A study in Eden Prairie, Minnesota showed negative house price effects associated with landfill proximity (Nelson et al., 1997). These studies all represent that proximity to specific facilities or factors affects home values.

Some studies look at the factors listed above in general terms, but not many include whether proximity to specific types of service-oriented facilities might increase or decrease a home's value. This literature review examined the growing senior population in the United States, with the focus on how the proximity of senior living communities may impact single-family home values.

Providing Support for America's Baby Boomer Generation

The baby boomer generation is approaching an age where many of them need to reevaluate their housing and living arrangements. The United States aging population has grown at an increasing rate because the leading edge of the baby boomer generation has already reached age 65 (Kim, 2020). The number of people aged 65 years and older is projected to more than double from 40.3 million in 2010 to 83.7 million in 2050, increasing the proportion of the American population aged 65 years and older from 13.0 percent to 20.9 percent (Zahirovic-Herberta and Giblerb, 2020). As one example, assisted living is an increasingly important residential care option for vulnerable older adults. Approximately 900,000 individuals reside in assisted living facilities (ALF) nationwide, with the demand expected to grow significantly. The number of older adults (aged ≥ 65), who are at risk of needing assisted living, is anticipated to exceed 80.8 million by 2040 (Son et al., 2024).

It is crucial to focus on senior housing developments and their surroundings because the large baby boomer cohort is on the brink of being in the stage of needing adult care. With the increase in adults needing adult care and with an expected increase in occupancy in residential healthcare facilities, it makes sense to wonder what kind of an impact residential healthcare facilities may have or already have on their surrounding areas.

Few studies have been conducted regarding the impact of assisted living facilities and skilled nursing facilities on nearby single-family residential property values (Zahirovic-Herberta and Giblerb, 2020; Caroll et al., 1999; Galster and Williams, 1994; Farber, 1986). These studies have been conducted on either assisted living facilities or skilled nursing facilities, but not necessarily on both. This research gap highlights the importance of examining both assisted living and

skilled nursing facilities to uncover new insights. Fewer studies have been conducted on both types of facilities, highlighting the importance of this subject as a research topic. The following sections will present a review of previous literature related to housing prices near residential healthcare facilities.

Negative Impact on Single-Family Home Prices

Most of the literature reviewed included studies that established a negative perception, meaning the residential healthcare facilities had a statistically significant negative influence on the sales price of single-family houses.

Zahirovic-Herberta and Gibler (2020) conducted a standard hedonic pricing model on a sample of 9,588 single-family detached housing sales between January 2008 and March 2016. The researchers used the Multiple Listing Service (MLS) to obtain observations of Lake Mary, Longwood, and Sanford, Florida, as well as other areas within Seminole County which is just north of Orlando. The objective of this study was to shed some light on why buyers may discount house values near group homes due to negative perceptions of the residents or the structure (Zahirovic-Herberta and Giblerb, 2020). The results indicate that the presence of a senior group home, especially a nursing home, within one-half mile has a significant negative effect on single-family house prices (Zahirovic-Herberta and Giblerb, 2020). They also discovered that if the property type is a nursing home, then the negative effect is even greater. The negative price effects of locating senior group homes near single-family houses may be attributed to several sources. One possibility is the classic not in my backyard (NIMBY) response to any other use than single-family in an otherwise homogeneous neighborhood. Although everyone may want housing options to exist for aging residents, younger and healthier residents may want those options to be offered somewhere else, because they do not feel it is fair that they shoulder the burden (Zahirovic-Herberta and Giblerb, 2020). The negative effect was stronger in neighborhoods with less elder residents.

Similarly, Caroll et al. (1999) applied the hedonic model to investigate the effect of low-income and senior housing on the value of nearby residential properties. The results of this study show that while public housing in general and senior housing in particular have an initial negative impact on nearby property values, the effect is neither substantial nor long-lasting (Caroll et al., 1999). Additionally, the researchers found that much larger facilities decrease property values more than smaller facilities. Having a new (as opposed to converted) project, or a for-profit increases property value.

Galster and Williams (1994) examined how severely mentally disabled dwellings affect the housing sales prices nearby. This study found that types of dwellings in particular kinds of neighborhoods that are occupied by particular sorts of severely mentally disabled clients can produce large, statistically significant reductions in nearby properties (Galster and Williams, 1994).

The three studies above concluded that residential healthcare facilities had a negative effect on the sale price of single-family houses. One study found no statistically significant effect, and one

of the previously mentioned studies found a positive perception as a subset of the researcher's broader theme.

No Impact on Single-Family Home Prices

Unlike the negative perceptions listed above, one study found that there was no statistically significant effect.

In a study in Shreveport-Bossier City, Louisiana, Farber (1986) studied whether property values were affected by being near group homes for intellectually disabled and emotionally disturbed people in a medium-sized city in the southern United States from 1975 to 1982. This study separated the housing market into high and below-average socioeconomic markets with both being mostly white. The sample observations for this study consisted of 127 house sales along with nine group homes. Unlike the previously mentioned results from other research, the researcher finds for the group homes opening in high socioeconomic markets, there was no observable and statistically significant effect of such a home on housing prices in their vicinity. However, there was some evidence that the opening of a group home in these markets may have increased the time a house remained on the market before being sold (Farber, 1986).

In the present literature review, this study was the only one that reported with no statistically significant effect of residential healthcare facilities on the sale price of nearby single-family homes. On the other hand, two previously mentioned studies (Farber and Caroll et al.) found at least one positive perception when reviewing subset themes of the closing costs for single-family homes near residential healthcare facilities.

Positive Impact on Single-Family Home Prices

The studies by Farber (1986) and Caroll et al. (1999) each had overall negative perceptions or no impact to the themes of their research yet had instances of positive perceptions for single-family homes near residential healthcare facilities.

For example, in below-average socioeconomic areas where housing markets were weak, there was an observable and statistically significant increase in the price of houses sold near the group home site. Both the time-on-the-market effect in the high socioeconomic market and the price effect in the below-average socioeconomic market diminished with distance from the site (Farber, 1986). On a separate note, new projects, as opposed to projects converted from another use or for-profit projects, increased in value (Caroll et al., 1999).

CONCLUSION

In conclusion most of the literature published in the past leans towards a decrease in the value of single-family houses near residential healthcare facilities. At least one study found no statistically significant effect, while three studies indicated an overall decrease in single-family home values near residential healthcare facilities. However, secondary analyses suggest that in certain cases, property values may increase if the residential healthcare facility is situated in a lower socioeconomic area with a weak housing market, is a new development, or a for-profit

facility. This literature review highlights a notable gap in research regarding the effect of proximity to service-oriented facilities, such as residential healthcare facilities, on single-family home sale prices.

PROPOSED METHODOLOGY AND HYPOTHESIS

This research initially emphasizes using a quantitative method after selecting key MLS characteristics for the primary model. The study proposes a traditional multiple linear regression model to examine how residential healthcare facilities in proximity to homes affect the selling prices of single-family houses. The proposed model is formulated below with the variables defined in Table 1:

$$\text{ClosePrice} = \beta 0 + \beta 1\text{Sf} + \beta 2\text{Age} + \beta 3\text{Baths} + \beta 4\text{HalfMIle} + u \quad (1)$$

equation

where ClosePrice is the selling price of the house; Sf is the total square footage of the property; Age represents how old the property is; Baths depict how many baths each home has; and HalfMile is the dummy variable indicating whether the house is 0.5 miles away from a residential healthcare facility.

Table 1: Definitions of the Variables in the Analysis

Variable		
ClosePrice	=	closing price expressed in 2025 dollars
Sf	=	the total number of square feet of finished living space
Age	=	this variable indicates the age of the property
Baths	=	the total number of baths (full plus half)
HalfMile	=	a binary variable indicating whether the property was located 0.5 miles to a senior living facility (=1 if yes, =0 otherwise)

The initial method tested the above regressors to discover whether they had a significant statistical effect. Hypothesis 1 was a two-tailed test used to examine whether sales might have a positive or negative effect after conducting the preliminary analysis of the data in Altus, Oklahoma. The main hypothesis of this study is:

> Null Hypothesis 1 (H0): Being near a residential healthcare facility (0.5 miles or less) on a given single-family house has no effect on the selling price. H0 = 0.
>
> Alternate Hypothesis 1 (Ha): Being near a residential healthcare facility (0.5 miles or less) on a given single-family house has an effect on the selling price. Ha ≠ 0.

SAMPLE AND DATA DESCRIPTION

Altus, Oklahoma (Preliminary Sample)

As for the initial review of the data, a sample of housing transactions in Altus, Oklahoma was selected with data ranging between January 01, 2014, and December 31, 2024. The MLS was the source, which consisted of 2,896 total transactions during this period. Of these transactions, all 2,896 (100.0 percent) total transactions made the initial sample, representing single-family residential homes. It is important to note that in the final sample of data, it is expected that not all observations will be used in the regression model.

The variables for single-family transactions encompass a range of characteristics, including but not limited to property address, closing price, total building area, the year built, acres, the closing date, fireplace, garage space, pool, school district, total bathrooms, and full bathrooms.

In Altus, properties within half a mile of residential healthcare facilities were identified by mapping a 0.5-mile radius around each site in Google Earth Pro, then checking street names and addresses in Google Maps to meticulously examine and make sure they were within the radius. Regarding the residential healthcare facilities, the following Altus facilities were included in this study: English Village Skilled Nursing and Therapy, Magnolia Creek Skilled Nursing and Therapy, Magnolia Creek Memory Care Assisted Living, and Tamarack Assisted Living Center. Of all single-family sales, 646 sales (22.4 percent) were identified as 0.5 miles away from a residential healthcare facility.

Table 2, the summary statistics below, shows the selling prices of homes as ClosePrice for the entire community ranges from $4,500 to $725,000 with a mean of $161,550. The total square footage of the properties shown as Sf ranges from 580 to 6,615 square feet, with a mean of 1,827 square feet. Table 2 also displays the Age for the lots and ranges from 1 year old to 122 years old with a construction age mean of 41.13 years. Bath is used to describe how many baths are in homes and range from 0 baths to 6 baths with a mean of 1.89 baths. Regarding the descriptive statistics, one dummy variable was created. It was HalfMile and depicts whether the properties are within 0.5 miles from a residential healthcare facility or not. Table 2, below, is the summary statistics for selling price, total building area, age, number of bathrooms, and whether the property is a half mile from a residential healthcare facility or not.

Table 2: Descriptive Statistics

Variable	Mean	Sd. Dev.	Min.	Max
ClosePrice	161549.62	93730.00	4500	725000
Sf	1827.05	611.05	580.00	6615.00
Age	41.13	21.46	1.00	122.00
Baths	1.89	0.56	0.00	6.00
HalfMile	0.22	0.42	0.00	1.00

PRELIMINARY RESULTS FOR THE PROPOSED STUDY

As a recap, of the 2,896 houses in the sample that sold between 2014 and 2024, 646 residences, accounting for 22.4 percent, are homes located near one of four residential healthcare facilities in Altus, Oklahoma. During the initial modeling test, the following results were derived from Microsoft Excel.

Interpreting the coefficients of this model in Table 3, the expected value of the selling price of a house is $78,266 when all four regressors above are equal to zero. Furthermore, a one percent increase in the building area increases the selling price by $75, holding other variables constant. An additional year a property is older decreases the selling price by $1,992. Furthermore, for every extra bathroom a home has increased the selling price by $14,307, holding all other variables constant. Testing whether a home is near a residential healthcare facility returns a result that is statistically significant particularly because it has a p-value lower than 0.05 percent. In this case the p-value for HalfMile is 0.0004 percent. Moreover, a home that is less than 0.5 miles from a residential healthcare facility results in a $7,856 (4.86 percent) increase in home value, while keeping all other variables constant.

In this model (Table 3), total square feet, age, number of baths, and whether the property is 0.5 miles from a residential healthcare facility are all statistically significant. The R^2 in this model is 0.7354 and the adjusted R^2 is 0.7351 and tells U.S. how much the dependent variable is being explained using the independent variables.

Table 3. Summary Regression for Estimating the Selling Price of Single-Family Homes.

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.8576							
R Square	0.7354							
Adjusted R Square	0.7351							
Standard Error	48243.09426							
Observations	2896							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	4	1.8705E+13	4.68E+12	2009.21775	0.0000			
Residual	2891	6.7285E+12	2.33E+09					
Total	2895	2.54335E+13						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	78265.45	4811.22	16.267	5.311E-57	68831.6822	87699.2105	68831.682	87699.210
SF	74.60	2.13	35.040	1.69E-224	70.425	78.774	70.425	78.774
Age	-1991.95	47.68	-41.775	7.803E-299	-2085.450	-1898.460	-2085.450	-1898.460
Baths	14307.26	2277.26	6.283	3.8295E-10	9842.039	18772.490	9842.039	18772.490
HalfMile	7855.64	2227.92	3.526	0.00042845	3487.167	12224.119	3487.167	12224.119

CONCLUSION

In conclusion, this study seeks to contribute to the existing body of real estate pricing literature by investigating the impact to housing prices and values near both assisted living facilities and skilled nursing facilities. The research question addressed in this study aimed to investigate whether a single-family house may have an increase or decrease in either the property's assessed value or its selling price due to its vicinity to a residential healthcare facility. In the Altus, Oklahoma sample, houses 0.5 miles from a residential healthcare facility experienced an increase of around 4.86 percent on their selling prices. Overall, these findings align most with Farber's 1986 study in Shreveport-Bossier City, Louisiana where the effect in the below-average socioeconomic market resulted in a statistically significant increase in the closing price of the homes near residential healthcare facilities. With the preliminary test done, the next step is to repeat this study in at least ten more Oklahoma cities to continue the research.

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Live-Up Advancement Marketplace: Reclaiming Albina's Community Legacy Through Hybrid Housing and Retail Design

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ABSTRACT

This paper advances the traditional "live-up" residential model through the creation of a fully integrated system of homes and marketplaces designed to empower historically marginalized communities. Focusing on a site in the Albina community of Portland, Oregon impacted by systemic disinvestment and redlining, the proposed "Live-Up Advancement Marketplace" combines owner-occupied residential units with a centralized, community operated marketplace. Each of the 21 residential units is equipped with a production workspace that connects directly to a designated retail stall within a 34,330 SF community market hall. This spatial and programmatic integration allows residents to operate businesses from home, lease retail spaces to local entrepreneurs, or collaborate through cooperative ownership structures. The approach reimagines the historic "mom and pop" shop economy in a contemporary, sustainable format. Leveraging modular construction techniques, flexible floor plates, and income generating systems, the project establishes a scalable development model that can adapt to a variety of urban contexts. Detailed design and operational frameworks are presented, emphasizing the integration of residential life, entrepreneurial activity, and community resilience. Ownership structures are tailored to promote wealth building and resident control, ensuring that owners retain agency over the retail character of their neighborhoods. This research highlights how spatial design, construction innovation, and community governance can be combined to create economically resilient, culturally rich neighborhoods. The Live-Up Advancement Marketplace provides a replicable and construction-oriented strategy for revitalizing disinvested urban areas, while centering resident empowerment at every stage of development.

INTRODUCTION

Portland's Albina district was once the cultural and commercial heart of the city's Black community. By the 1960s, due to redlining, exclusionary housing practices, and urban renewal policies, this once-thriving district experienced systemic decline. At the intersection of North Russell and Williams Avenue, a dense corridor of live-up "mom and pop" businesses served as a keystone of economic and social life until it was cleared for the expansion of Legacy Emanuel Hospital, displacing over 188 families (Franz, 2016).

The erasure of Albina's retail residential infrastructure mirrors broader patterns of disinvestment in Black communities across the U.S. These historical injustices necessitate spatial solutions that not only provide shelter but also empower communities through ownership, entrepreneurship, and legacy-building. The Live-Up Advancement Marketplace (LUAM) seeks to respond to these

challenges by integrating resident-owned homes, on-site commodity production spaces, and co-governed retail into an expandable, modular live-up marketplace development. LUAM is designed not only to meet housing needs but to re-establish self-investment, cultural identity, and cooperative economic control.

The live-up typology has historical precedents in urban commercial districts across the United States, particularly in immigrant and working-class neighborhoods where integrated living and working arrangements provided economic efficiency and community cohesion (Hayden, 2003). However, LUAM advances this traditional model in critical ways:

(1) it structurally integrates production workspace within each residential unit rather than simply placing living quarters above retail;

(2) it employs a cooperative governance framework that distributes ownership and decision-making power among residents; and

(3) it utilizes modular construction techniques to ensure scalability and replicability.

While the live-work concept is established, LUAM's particular synthesis of resident ownership, direct marketplace access, and community land trust governance represents a novel application designed specifically to address wealth-building and anti-displacement goals in historically disinvested neighborhoods.

HISTORICAL AND URBAN CONTEXT

Lower Albina emerged in the early 20th century as the primary residential and cultural hub for Portland's Black community. During the 1940s and 1950s, it was home to the vast majority of African Americans in Albina and the overall Portland region along with significant populations of immigrant and working-class White families (City of Portland, 2020, pp. E-7-E-9).

Constrained by racially restrictive covenants, exclusionary zoning, and informal discrimination, most Black households were barred from purchasing property outside of Albina's boundaries. This geographic concentration fostered a dense network of churches, social clubs, and "mom and pop" businesses, often in live-up configurations, where shopkeepers lived above or behind their stores. The resulting mixed-use fabric supported strong neighborhood identity and intergenerational economic participation.

Yet, this vitality existed within the context of systemic marginalization. Limited access to capital, underinvestment in infrastructure, and discriminatory employment practices restricted wealth-building opportunities. Homeowners often relied on small, family-run enterprises to sustain livelihoods, while renters and boarders found housing in subdivided single-family homes. These arrangements created a vibrant but fragile local economy, one vulnerable to external policy shocks (see Figure 1 for examples of restrictive covenant language).

Lower Albina's negative trajectory was shaped by a combination of private law segregation initiatives and public policy. Decades before Portland's first zoning code (1924), racially restrictive covenants were already being recorded in property deeds. These clauses barred ownership or occupancy by anyone other than the "Caucasian race" and often listed specific groups, such as "Chinese," "Japanese," or "Negroes," by name (Smith, 2018, pp. 359-61). In 1919, the Portland Realty Board went further, adopting a code of ethics that made it "unethical" for agents to sell property in a White neighborhood to Black or Chinese buyers, a rule that remained in effect until 1956 (Hughes et al., 2019, p. 5). As documented in Figure 1, these covenants explicitly barred ownership or occupancy by specific racial and ethnic groups.

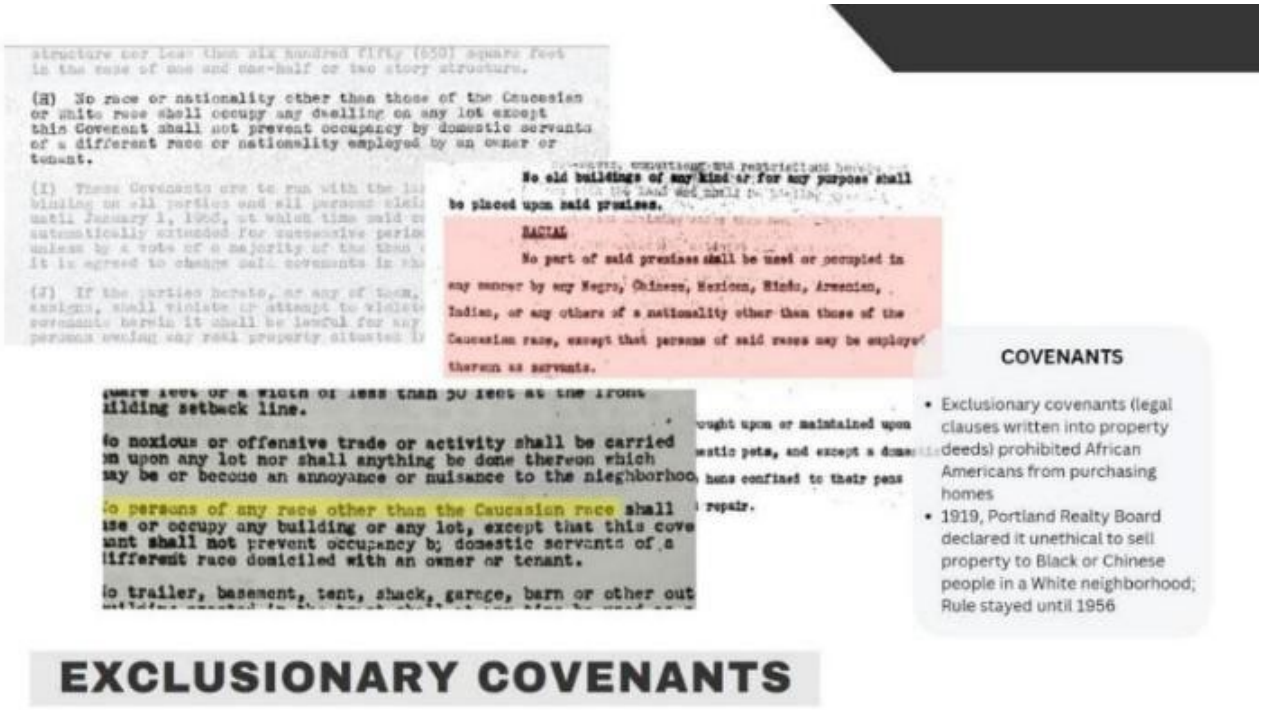

Figure 1. Examples of racially restrictive covenants recorded in Portland property deeds (c. 1910s–1940s). Common language barred occupancy by anyone other than the 'Caucasian race' and often listed specific ethnic groups. The Portland Realty Board's 1919 code of ethics institutionalized these practices in the real estate industry. Source: Oregon Historical Quarterly (Smith 2018, pp. 359–366); City of Portland Bureau of Planning and Sustainability (Hughes et al. 2019, p. 5).

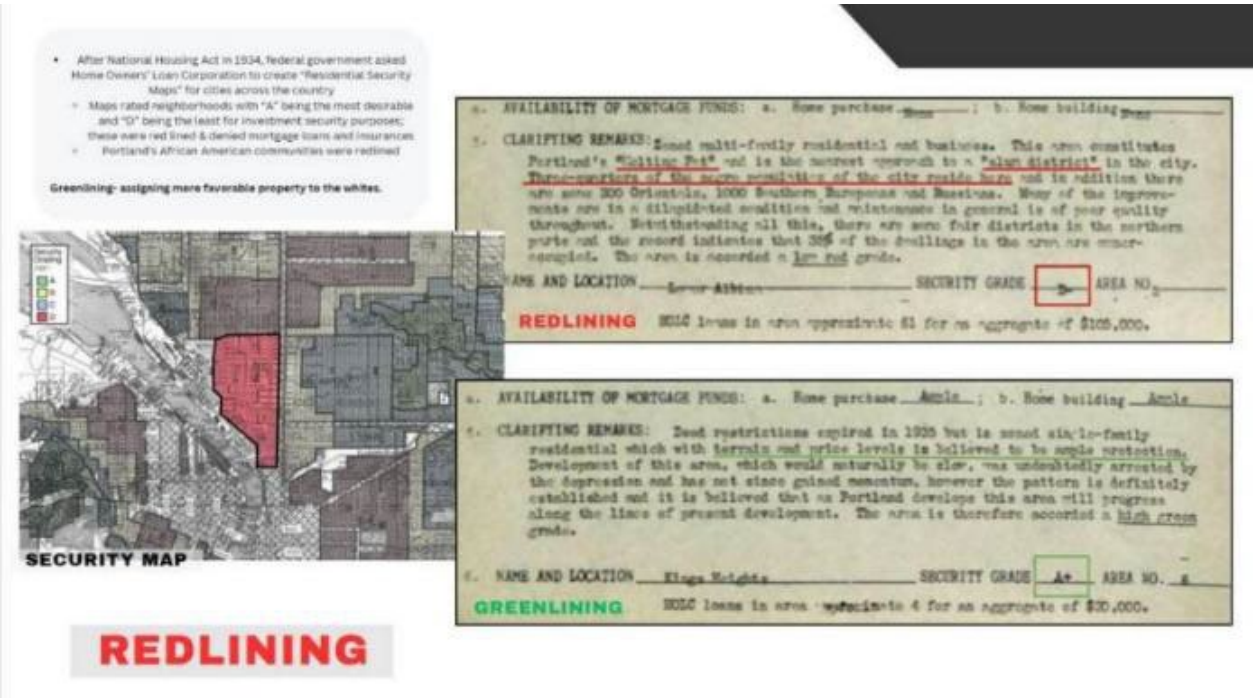

Figure 2. 1937 Home Owners' Loan Corporation (HOLC) Residential Security Map and appraiser notes for Portland. Albina appears in red as a "D" (hazardous) area; an appraiser described Lower Albina as Portland's "Melting Pot" and the city's "nearest approach to a slum district." Source: Mapping Inequality, University of Richmond Digital Scholarship Lab; City of Portland (2020), African American Resources in Portland, Oregon (p. E-24).

These private restrictions were reinforced by federal credit lenders in the 1930s. The Home Owners' Loan Corporation (HOLC) graded neighborhoods for perceived lending risk; Lower Albina was mapped as a red "D" (hazardous) area, while A-graded ("green") districts were typically White, single-family enclaves. An HOLC appraiser described Lower Albina as Portland's "Melting Pot" and "nearest approach to a slum district," explicitly tying risk to the presence of Black residents (City of Portland, 2020, p. E-24; see Figure 2 for the complete HOLC map and appraiser notes). The combined effect was to channel disinvestment into Albina and preferential lending into higher-graded areas (Hughes et al., 2019, pp. 8-9).

CONCEPTUAL FRAMEWORK AND DESIGN STRATEGY

The LUAM model advances the traditional live-up typology by combining residential ownership, production space, and direct retail access in a single spatial system. Each of LUAM's 21 for-sale units is connected to a retail stall within a 34,330 SF market hall. Figure 3 illustrates the ground-floor spatial organization, showing how each of the 21 owner-occupied townhomes connects directly to its designated retail stall within the centralized marketplace. On the ground floor, each townhome unit features a workroom with a storefront/display that directly connects to its dedicated retail frontage within the marketplace, enabling residents to produce and sell goods

without leaving their homes. This adjacency encourages self-promotion with daily interaction between residents and shoppers, fostering a neighborhood-scale economy rooted in shared space and local ownership. There is also an optional-use mechanism that empowers resident-owners with the option to operate small businesses themselves, lease stalls for passive income, or participate in cooperative enterprises.

Figure 3. Ground-floor retail plan (left) showing the centralized marketplace and alignment of owner-occupied townhomes, each with a workroom opening directly into a retail stall. Enlarged plan of a typical townhome first floor with den/workroom (right) illustrates the direct connection between residential space and marketplace. Drawn by students in the Morgan State University design studio.

This system reimagines the “mom and pop shop” as the “moms and pops shops” model: a collectively governed, economically self-reinforcing structure that distributes wealth and agency throughout the residential fabric. As stated by the Housing and Community Development Department (2021), “Community ownership means that the people most impacted by racial, economic, and environmental injustice have meaningful decision-making power over development” (p. 6). Similarly, Burlington Associates (n.d.) highlight community land ownership as a “platform for redistribution... putting property and power into the hands of people historically deprived of both.”

Similar integrations of housing and economic development have been implemented in historically marginalized communities with measurable success. The Dudley Street Neighborhood Initiative in Boston's Roxbury neighborhood demonstrated how community land trusts combined with resident-led planning can stabilize neighborhoods while preserving affordability for original residents (Medoff and Sklar, 1994). In Oakland, California, the Fruitvale Transit Village integrated affordable housing with Latino-serving retail and community facilities, creating over 700 construction jobs and 125 permanent jobs while maintaining cultural character (Blackwell et al., 2010). The East Lake neighborhood revitalization in Atlanta similarly combined mixed-income housing with commercial development and community services, resulting in a 95% reduction in violent crime and significant improvements in educational outcomes (Werwath, 2008). These precedents demonstrate that when community control and economic integration are centered in development, measurable improvements in stability, safety, and wealth-building can be achieved.

PROGRAMMATIC COMPONENTS AND COMMUNITY IMPACT

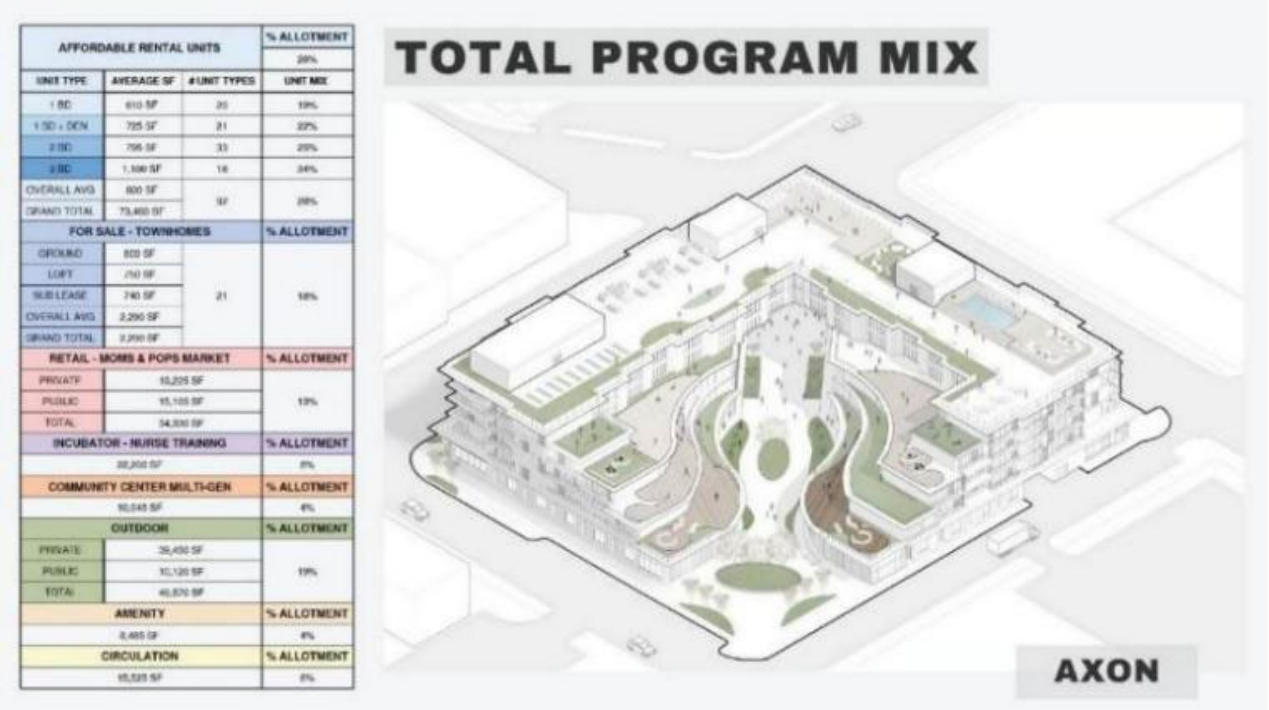

Figure 4. Total program mix diagram and axonometric view of the Live-Up Advancement Marketplace, showing the proportional distribution of housing, retail, community, and open space components. The program is structured to integrate economic, residential, and social infrastructure within a single cohesive urban block. Drawn by students in the Morgan State University design studio.

The Live-Up Advancement Marketplace's program distribution is intentionally designed to achieve a balanced integration of housing, commerce, and community infrastructure, serving a

broad and diverse age demographic. The ground level anchors the site with a 34,330 SF "Moms and Pops Market," composed of both privately owned retail bays (19,225 SF) and publicly accessible vendor stalls (15,105 SF). This marketplace functions as the economic engine of the development, providing residents with direct pathways into entrepreneurship while fostering a diverse range of locally generated goods and services.

The residential program integrates a mix of for-sale townhomes and affordable rental units. The 21 for-sale townhomes are three stories, averaging 2,290 SF, and are strategically placed to maintain direct connections to the marketplace, reinforcing a live-work integration model. Each townhome includes an optional third-level sublease unit that seamlessly integrates into the multi-family circulation system via separate public hallways and entrances. This flexibility enables townhome residents to age in place more effectively and monetize unused space over time. The 92 affordable rental units average 800 SF and offer a mix of one- to three-bedroom layouts, designed to meet a variety of household needs and income levels.

Specialized community-serving functions further diversify the program. A 22,200 SF business incubator and nurse training facility creates pathways for skill development and long-term employment. The integration of nurse training and traveling nurse housing leverages sublease units within the owner-occupied townhomes and aims to mend the historically strained relationship between the Legacy Emanuel Hospital and the surrounding community. By aligning the hospital's staffing and housing needs with community-driven economic benefits, the program channels both rental income and training opportunities back to local residents and re-imagines the hospital as a resource to the immediate community as opposed to its previous perception as a disruptor. A 10,045 SF multi-generational community center fosters intergenerational learning and social connection, accommodating users of all ages. Public and private outdoor spaces total nearly 50,000 SF, reinforcing the project's emphasis on accessible, shared open areas. Amenities (8,465 SF) and circulation (15,525 SF) are strategically integrated to ensure resident comfort, accessibility, and mobility throughout the site.

This comprehensive program mix ensures that economic activity, housing diversity, and social infrastructure are not treated as isolated components, but are instead interwoven to create a self-sustaining, resilient, and inclusive neighborhood core.

MODULAR CONSTRUCTION AND SUSTAINABILITY SYSTEMS

The following construction strategy builds directly on these programmatic priorities, employing principles of incremental urbanism and flexible design frameworks that support community adaptation over time (Hamdi, 2004; Kelbaugh and McCullough, 2008), ensuring that spatial design supports both the marketplace's social goals and its long-term adaptability. LUAM employs a modular building strategy to ensure both construction efficiency and long-term adaptability. The design separates ownership and rental typologies vertically placing for-sale townhomes on the lower levels to promote individual investment and generational wealth-building, while upper levels contain flexible rental units to accommodate a range of household sizes and incomes.

A “push-and-pull” façade strategy manipulates unit faces by four-foot and eight-foot extrusions, providing private balconies, improved natural lighting, and enhanced privacy. These volumetric shifts also create visual variation along the building edge, reducing the monolithic appearance common to large mixed-use developments. Figure 5 demonstrates the modular unit organization and the push-and-pull facade strategy that creates this variation while maintaining construction efficiency. At the ground level, the two 17,000 SF retail wings wrap the building’s inner edge, forming an active commercial frontage that is directly linked to the rear of each owner-occupied unit. This connection supports a “mom and pop shops” collective retail model, reinforcing both the economic and social sustainability of the community.

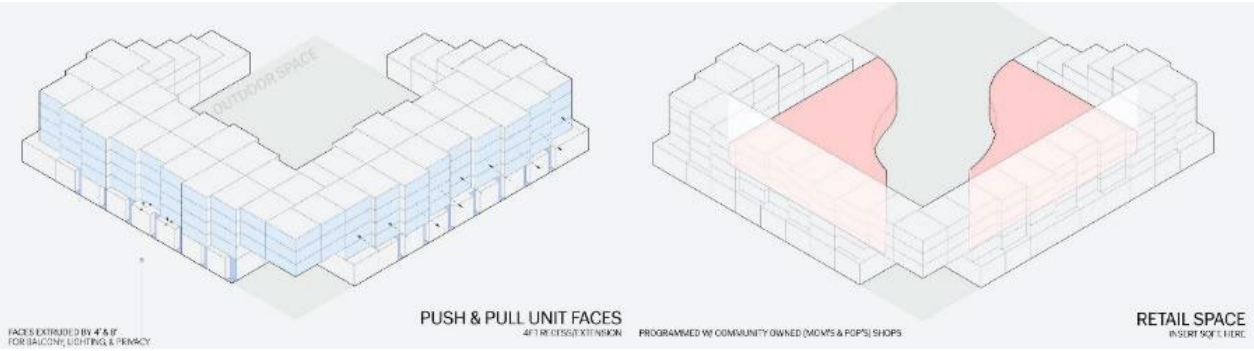

Figure 5. Modular design axonometric diagrams. Left: Modular units with push-and-pull unit face adjustments (4-foot and 8-foot extrusions) for improved balcony space, daylighting, and privacy. For-sale townhomes occupy the lower levels, with rental units above. Right: Two 17,000 SF retail wings (highlighted in red) connect directly to the back of owner units, supporting a community-owned “mom and pop shops” marketplace model. Drawn by students in the Morgan State University design studio.

The residential units are single-loaded on the first four levels to integrate retail (levels one and two), incubator spaces (level three), and community space (level four). Levels five and six are double-loaded residential units with expanded access to outdoor green roof and amenity spaces. Modular construction strategies underpin LUAM’s concept of flexibility with capacity for individual and/or shared enterprise, as well as expandability and sustainability. Three core housing types (owner townhomes, long-term rental, and short-term rental) allow for consistent stacked but varied unit function across the site. Sustainable systems are embedded, including green roofs, rainwater harvesting, and courtyard microclimate management.

OWNERSHIP, GOVERNANCE, AND RESILIENCE

LUAM’s governance structure is modeled after Community Land Trust (CLT) principles, enabling owner-occupants to share decision-making rights over retail stalls and shared services. Owners can lease their stalls or operate them directly, providing flexibility for passive income and intergenerational wealth-building. According to Purtill (2024), “The CLT model... originated in the Civil Rights Movement... ensures long-term affordability and stability.” The residential

and retail portions operate under a modified (CLT) framework by ensuring that the land is held collectively, and the improvements (units and retail stalls) are owned or leased by individuals. This approach stabilizes property values against speculative pressures, while resale formulas ensure affordability for future generations.

Retail governance is organized cooperatively, with all resident-owners holding voting shares in the management entity. This cooperative structure directs a portion of net retail revenues toward shared maintenance funds and neighborhood improvement initiatives, further embedding financial resilience into the project. The model allows for multiple participation pathways: owners can directly operate their retail spaces, lease them to other entrepreneurs, or collaborate in cooperative business ventures.

By localizing decision-making, LUAM directly addresses the displacement and loss of agency experienced in Lower Albina during mid-century urban renewal. This governance structure is not merely an operational framework; it is an intentional social infrastructure that promotes stability, fosters collective accountability, and ensures that the project evolves in alignment with community priorities.

REPLICABILITY AND POLICY IMPLICATIONS

LUAM is designed as a modular, scalable solution for disinvested urban neighborhoods. As Turner and Galvez (2024) note, “Fostering community stewardship... can ensure that all community members, particularly those belonging to disadvantaged... communities benefit” (p. 5).

Community Development Financial Institutions (CDFIs) and mission-driven lenders are critical in bridging financing gaps for low and moderate-income buyers. Partnerships with anchor institutions, such as hospitals or universities can provide both tenant pipelines for retail spaces and vocational programming, as in LUAM’s integration of a nurse training incubator. Modular and prefabricated building systems further strengthen replicability by reducing construction timelines and costs, making the model viable even in high-cost urban markets. This Albina pilot demonstrates that LUAM’s format can align with anti-displacement strategies nationwide.

CONCLUSION

The Live-Up Advancement Marketplace presents a compelling vision for a post-displacement, community-controlled urban future. By integrating modular housing, entrepreneurship, and self-governance within a single architectural framework, LUAM transforms the traditional “mom and pop” shop into a scalable “moms and pops shops” ecosystem, one that multiplies opportunity while safeguarding affordability.

This model offers more than physical revitalization; it is a form of spatial justice. It acknowledges and counters the structural forces that disinvested neighborhoods like Albina have

faced, using design as both a physical and political tool. The combination of ownership flexibility, cooperative governance, and embedded workforce development creates a platform for sustained economic resilience, cultural preservation, and social equity.

As cities grapple with the dual challenges of affordability and displacement, LUAM provides a replicable, construction-focused strategy that merges architectural innovation with intentional policy alignment. Its success in Albina would serve as both a precedent and a proof of concept for other communities seeking to transform redevelopment from an extractive process into one that is generative, inclusive, and rooted in local control.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the talented students from the Morgan State University School of Architecture + Planning design studio, whose creativity, dedication, and collaborative spirit were integral to the development of the Live-Up Advancement Marketplace project. Their design work, drawings, models, and visualizations formed the foundation of this study and exemplify the capacity of architectural education to address pressing community needs.

This project was initially conceived and advanced as part of the National Organization of Minority Architects (NOMA) Student Design Competition, which provided a platform for exploring innovative, community-driven solutions to urban design challenges. The author extends appreciation to NOMA for fostering opportunities that engage emerging designers in work that bridges design excellence and social impact.

The author also extends appreciation to the residents of Portland's Albina community, whose lived experiences, cultural heritage, and ongoing resilience in the face of displacement and disinvestment continue to inspire this work. Their voices and histories serve as an essential guide for shaping equitable, community-rooted design strategies.

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Role of Race, Socioeconomic Status, and Evacuation Orders in Hurricane Evacuation: A Systematic Literature Review

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ABSTRACT

Hurricanes pose significant risks to coastal populations, and evacuation remains one of the most effective ways to prevent loss of life. Yet, evacuation behavior varies widely across communities and is shaped by social, economic, and structural conditions. This systematic review analyzed 157 studies on hurricane evacuation in the United States, of which 44 met the inclusion criteria, to examine how racial identity, socioeconomic status, and evacuation orders influence evacuation decisions. Findings revealed that racial identity affects evacuation behavior primarily through underlying structural inequities. Individuals identifying as white are generally more likely to evacuate promptly, supported by greater access to transportation, financial resources, and trusted information. African American and Hispanic populations often face financial limitations, limited mobility, housing vulnerability, and lower institutional trust, which collectively hinder timely evacuation. Socioeconomic status emerges as the most consistent predictor across all studies, shaping households' ability to prepare for evacuation, absorb associated costs, and reach safe destinations. Evacuation orders, especially mandatory, clearly communicated ones, tend to increase compliance, but their effectiveness depends on residents' capacity to act. Households constrained by low income, caregiving responsibilities, or limited transportation may be unable to evacuate even when motivated. Overall, evacuation behavior reflects the intersection of social vulnerability and structural barriers. Enhancing evacuation outcomes requires equity-focused planning, improved communication strategies, and built-environment solutions that reduce resource and accessibility gaps.

Keywords: Natural Disasters, Hurricane, Evacuation, Economic Condition, Race, Evacuation Order.

INTRODUCTION AND BACKGROUND

Hurricane evacuation is a complex behavioral process shaped by a wide range of interconnected social, economic, perceptual, and structural factors. Although evacuation is one of the most effective protective actions during hurricane threats, the presence of risk alone is often

insufficient to motivate individuals to leave (Dash and Gladwin, 2007; Lindell et al., 2005a). The decision to evacuate typically unfolds across multiple stages, including hazard recognition, risk perception, and behavioral response to that risk (Dow and Cutter, 2000). Each stage is influenced by an individual's access to financial and physical resources, knowledge of evacuation routes, awareness of shelter locations, and the availability of safe and uncongested travel corridors. Limitations in any of these areas may hinder evacuation and increase individuals' risk during hurricane events (Riad et al., 1999; Whitehead et al., 2000).

Beyond these considerations, numerous demographic, socioeconomic, and experiential factors also shape evacuation intentions. Prior research has identified variables (gender, age, income level, educational attainment, hurricane-related knowledge, previous disaster experience, and others) as predictors of evacuation behavior (Huang et al., 2016; Smith and McCarty, 2009). Yet, findings across studies are highly inconsistent: factors that strongly predict evacuation in one context may have weak, neutral, or even opposite effects in another (Huang et al., 2016; Peacock et al., 2005). These conflicting results highlight the context-specific nature of evacuation decision-making and underscore the importance of examining how predictors operate across different geographic, cultural, and socioeconomic settings. Moreover, evacuation-related determinants may evolve due to changes in public awareness, communication technologies, infrastructure quality, population mobility, and prior disaster exposure (Meyer et al., 2018). Understanding how these influences shift across populations and time periods is essential for accurately interpreting evacuation behavior and for designing targeted, community-specific emergency management strategies.

A growing body of research suggests that evacuation intentions are non-uniform across populations. Instead, they vary significantly based on individuals' racial and ethnic backgrounds, socioeconomic conditions, and the characteristics of the evacuation orders issued by authorities (Cutter and Smith, 2009; Elliott and Pais, 2006). These factors influence how people interpret risk, access transportation or financial resources, trust official communication, and ultimately decide whether to evacuate. Importantly, race and socioeconomic status often function as markers of deeper structural conditions, such as historical residential segregation, unequal access to transportation, differences in housing quality, and disparities in income and wealth that constrain evacuation options (Gladwin and Peacock, 1997; Masozera et al., 2007). Likewise, the timing, clarity, and credibility of evacuation orders affect behavior, but household resources, past experiences, and levels of institutional trust mediate their influence (Dow and Cutter, 2000; Huang et al., 2012).

Despite the extensive literature on evacuation behavior, limited work synthesizes how three factors: a) racial identity; b) economic status; c) evacuation orders, intersect to influence hurricane evacuation decisions in the U.S. Existing reviews often emphasize risk perception, communication, or socioeconomic vulnerability individually, but few draw together the structural and logistical mechanisms that jointly explain disparities across communities (Thompson et al., 2017). Moreover, no prior review has addressed the implications of these intersecting factors for the Architecture, Engineering, and Construction (AEC) community,

despite the built environment's essential role in shaping evacuation feasibility, transportation access, and structural vulnerability.

By systematically reviewing the existing evidence, this study aims to clarify the roles of race, socioeconomic status, and evacuation orders in shaping evacuation behavior and to highlight the cross-cutting structural mechanisms that underpin these relationships. This synthesis offers insights to support more equitable disaster planning, improved risk communication, and design strategies that reduce vulnerability in hurricane-prone regions.

METHODOLOGY

This study employed a five-phased Systematic Literature Review (SLR) to examine factors influencing hurricane evacuation behavior in the United States (Figure 1). The first phase involved an initial scoping phase in which broad search terms ("evacuation," "hazards," "flood," "storm," and "United States") were used in Litmaps to identify 30 publications. Litmaps was purposively selected as a starting point because it helps researchers to determine the most relevant papers to their research domain, highlighting overall significance and connections among the research articles (Sulisworo, 2023). Seventeen out of 30 papers were retained after screening for relevance, language (English), and U.S. hurricane contexts. These papers helped refine the understanding of commonly recurring determinants, such as race, socioeconomic status, and evacuation orders, without predetermining the analytical focus of the review. In the second phase, the search was then expanded through backward snowballing of the 17 seed papers, where the reference list was used as the point of departure to identify additional studies (Wohlin, 2014) and supplemental keyword searches on Google Scholar (e.g., "race and evacuation," "socioeconomic status hurricane evacuation," "evacuation logistics," and "warning systems"), resulting in a total pool of 157 publications. In the third phase, publications were filtered and screened by title and abstract to exclude non-U.S., non-hurricane, and non-English-language studies. Full texts of the remaining papers were reviewed using three inclusion criteria: the study must

(1) examine evacuation related to hurricanes or tropical storms,

(2) be situated within the U.S., and

(3) have been published in 1990 or later.

This process yielded 44 studies eligible for synthesis.

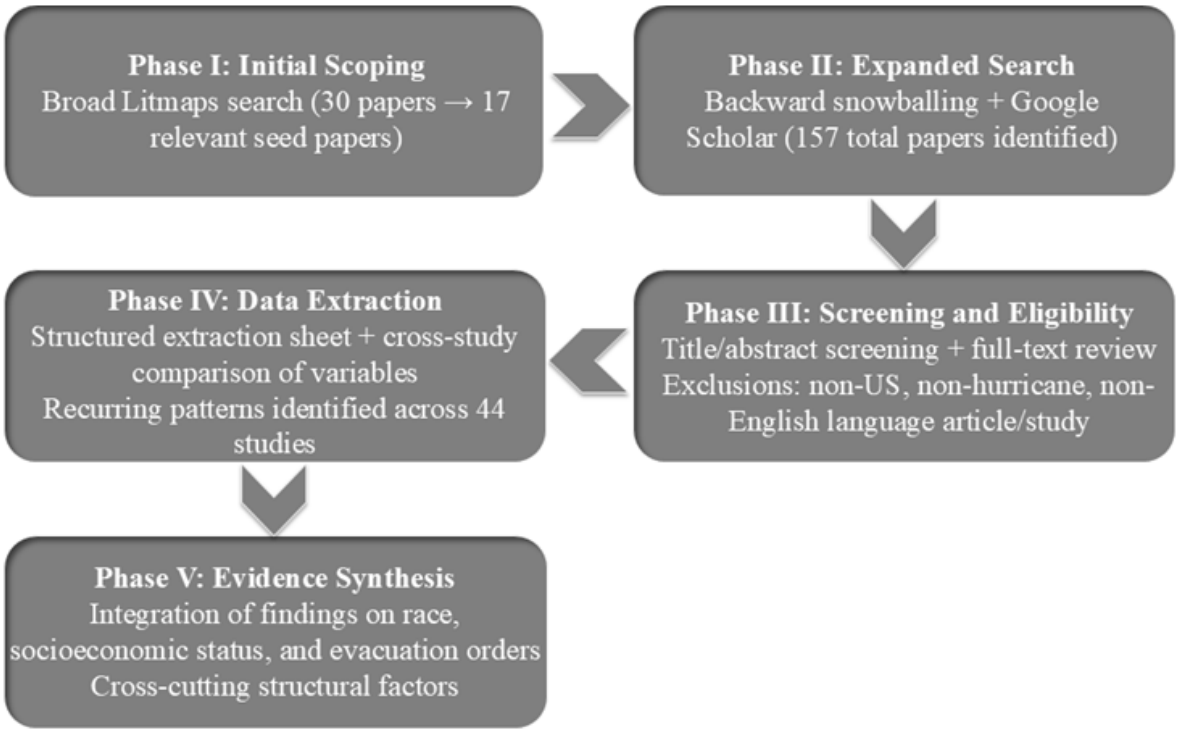

Figure 1. Research method (n=44).

The fourth phase of the study involved the data extraction from the selected articles. A structured data extraction sheet was used to document study characteristics: publication year, geographic area of study, community type, hurricane analyzed, study design, population studied, data source, timing, variables examined, and reported determinants of evacuation behavior. Rather than conducting line-by-line qualitative coding, the review employed a comparative evidence synthesis approach, a method for integrating findings from multiple studies to provide a comprehensive and balanced overview of evidence on a specific topic, in which findings from each study were systematically compared to identify recurring patterns across evacuation predictors (Gandhi et al., 2025). As data extraction progressed, certain factors, including racial identity, socioeconomic status, and evacuation orders, repeatedly appeared as influential determinants across multiple studies. Although the authors had prior exposure to research suggesting the importance of race, socioeconomic conditions, and evacuation orders, these factors emerged organically and consistently during coding as recurrent predictors across diverse study contexts, alongside additional variables such as transportation access, housing type, and risk perception. The selection of race, socioeconomic status, and evacuation orders as the focal themes of this review, therefore, reflects their frequency and prominence in the reviewed literature rather than predefined assumptions. The final phase of the study, analytical synthesis, examined how these three factors shaped evacuation behavior individually and in interaction with structural and logistical constraints documented across the studies.

RESULTS

Out of the total identified 44 articles analyzed, 41 were journal publications, two were book chapters, and one was a report. In addition, among the articles analyzed based on the initially identified parameters, the highest number (7) was published in 2007, followed by 5 published in 2016 (Figure 2). The dataset focused on multiple events, many of which modeled multiple storms or hypothetical scenarios. However, among event-specific studies, some hurricanes recurred. Among event-based studies, Hurricane Katrina (2005) accounted for the largest share (n=4) of research in our sample (Elder et al., 2007; Elliott and Pais, 2006; Masozera et al., 2007). Hurricanes Andrew (1992) (Gladwin and Peacock, 1997; Riad et al., 1999) and Bonnie (1998) (Bateman and Edwards, 2002; Whitehead et al., 2000) followed with multiple studies, while events such as Lili, Ike, Bret, Rita, Floyd, Sandy, and Irene appeared in only one or two cases each. Many studies also modeled multiple hurricanes together or examined hypothetical future scenarios rather than a single historical event (Baker, 1991; Bowser and Cutter, 2015; Lazo et al., 2015; Peacock et al., 2005). Geographically, the literature is concentrated in the U.S. hurricane-prone coastal regions, especially the Gulf Coast and Southeast Atlantic states, with additional studies from the Northeast and Mid-Atlantic after Hurricanes Sandy and Irene. Most research focused on residents of evacuation or surge zones, flood-prone neighborhoods, and coastal counties, including mobile-home communities and other structurally vulnerable areas (Gladwin and Peacock, 1997; Karaye et al., 2019; Lindell et al., 2005b; Solis et al., 2009; Van Willigen et al., 2005). While many studies surveyed the general adult population, a significant subset examines vulnerable groups, such as African American residents of New Orleans, low-income Mexican American communities in Texas, older adults, families caring for relatives with Alzheimer's disease, and mobile-home residents (Christensen et al., 2013; Elliott and Pais, 2006; Reininger et al., 2013; Rosenkoetter et al., 2007; Solis et al., 2009). These studies consistently showed greater structural barriers to evacuation among racial and ethnic minorities, low-income households, and medically or socially vulnerable populations.

In addition, out of 44 articles, 32 articles had keywords that generated 126 keywords. The top three most frequently repeated keywords were: Evacuation (17 times), Hurricane (15 times), and Disaster (7 times) (Figure 3). After the de-duplication of keywords, 72 keywords were identified as unique. Based on the analysis of the unique keywords, seven primary thematic areas were identified:

1) Disaster and Emergency Management;

2) Risk and Decision-Making Dynamics;

3) Social and Demographic Factors;

4) Environmental and Regional Contexts;

5) Health and Vulnerability;

6) Information and Communication; and

7) Modeling and Analysis Techniques.

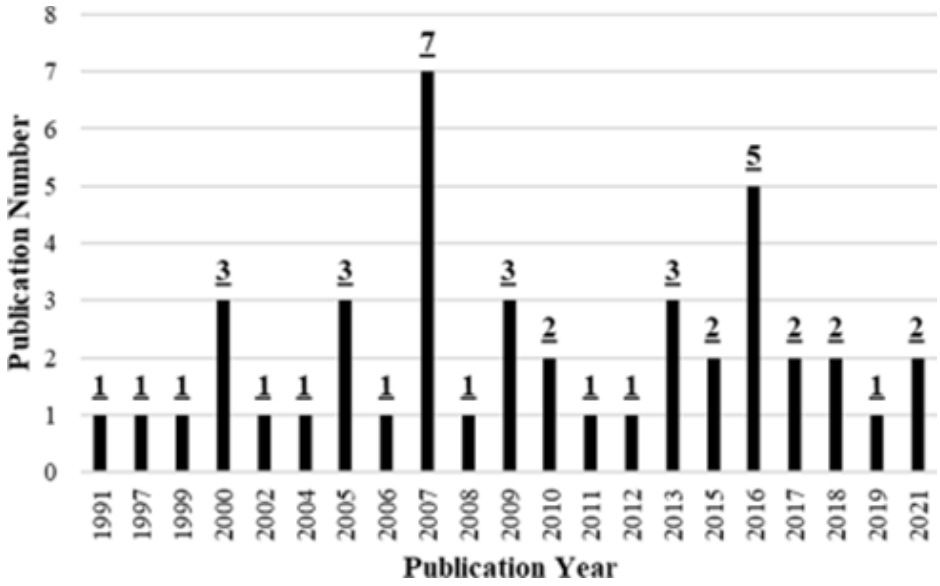

Figure 2: Publication of analyzed publications (n =44).

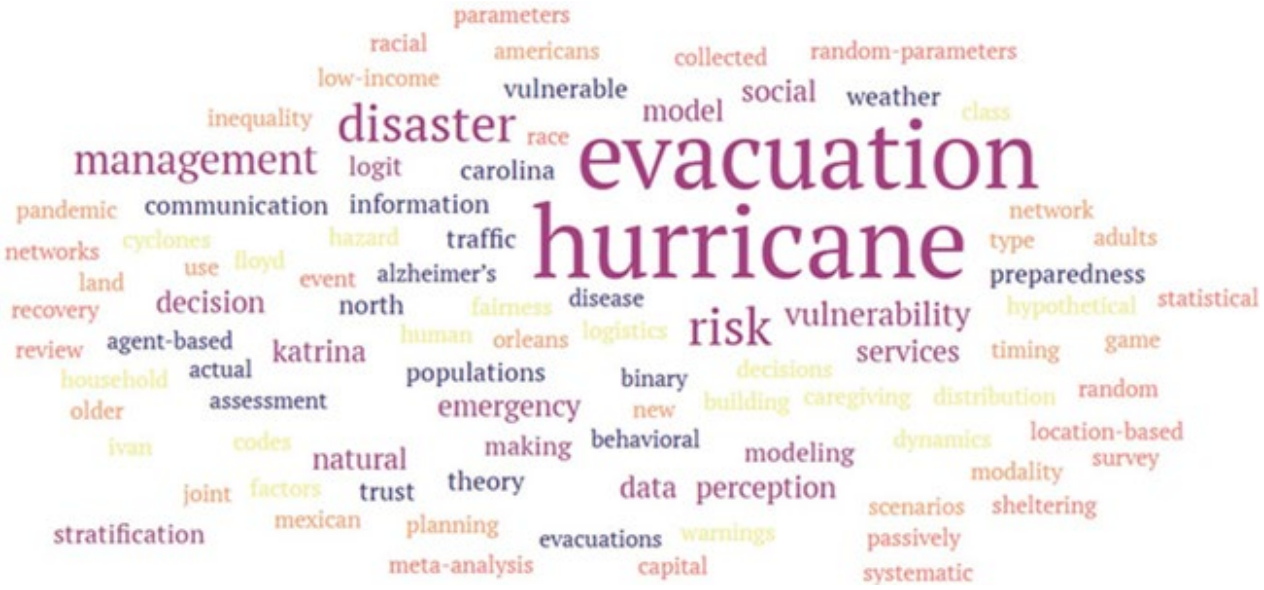

Figure 3: Keyword word cloud (n =44).

Role of Race in Evacuation

Race emerged as a measurable factor in evacuation behavior, though its effects were often indirect or mediated by socioeconomic and structural conditions. Among the 44 studies, nine (20.5%) identified race as a significant predictor, 18 (41%) reported mixed or context-dependent effects, nine (20.5%) found no significant effect, and eight (18%) either did not analyze race or included only a single racial group. Studies of Hurricane Katrina provide some of the clearest evidence that race can be associated with lower pre-storm evacuation and more constrained options. Analyses of Katrina survivors show that African Americans were less likely to evacuate before landfall and more likely to experience severe displacement and difficulty leaving, with race closely intertwined with neighborhood segregation, poverty, and limited car access than White residents (Cutter and Smith, 2009; Elder et al., 2007; Elliott and Pais, 2006; Masozera et al., 2007; Thiede and Brown, 2013). Similar patterns appeared in earlier hurricanes: studies on Hurricane Andrew and other events finds that African American and Hispanic households are often under-represented among evacuees and over-represented among those reporting serious constraints, particularly where they live in more exposed neighborhoods and have fewer resources (Dash and Gladwin, 2007; Gladwin and Peacock, 1997; Riad et al., 1999; Smith and McCarty, 2009).

At the same time, many studies reported mixed or limited racial effects once socioeconomic status, geography, and housing are controlled. For example, in some studies, African American households appear more likely to evacuate because they are concentrated in the most flood-prone areas (Peacock et al., 2005; Van Willigen et al., 2005), while large-sample or meta-analytic work finds that race is not a consistently significant predictor across models once income, car ownership, and risk zone are included (Huang et al., 2016; Karaye et al., 2019; Thompson et al., 2017). Several surveys and modeling studies include race, but either find no independent effect or treat it primarily as a control variable (Lazo et al., 2015; Lindell et al., 2005a; Meyer et al., 2018; Sarwar et al., 2018; Whitehead et al., 2000).

Qualitative and community-specific research reinforces the idea that race itself is not the mechanism but rather marks differential exposure to structural constraints. Studies focusing on African Americans who remained in New Orleans, and on low-income Mexican American communities in Texas, describe barriers such as lack of transportation, limited cash, health problems, and distrust of shelters and authorities, rather than a lack of concern about risk (Elder et al., 2007; Reininger et al., 2013). Taken together, these findings indicate that racial disparities in evacuation are real but primarily mediated by socioeconomic position, residential segregation, transportation access, and trust in institutions, rather than operating as a purely independent demographic effect.

Role of Socioeconomic Status (SES)

Across the dataset, Socioeconomic Status (SES) is the most consistently important factor. Measures such as income, education, car ownership, employment conditions, and housing type were analyzed, and most found that SES was significantly associated with evacuation behavior. Of the 44 papers, 25 (57%) identified SES as a significant factor, 14 (32%) reported mixed effects, only one study found SES non-significant, and four did not examine SES measures.

Households with higher income and more financial reserves were more likely to evacuate and to do so earlier, in part because they could afford transportation, lodging, and lost wages (Dash and Gladwin, 2007; Karaye et al., 2019; Masozera et al., 2007; Smith and McCarty, 2009). Car ownership repeatedly emerged as a critical determinant: studies of Hugo, Andrew, Floyd, Katrina, and other events show that not having access to a private vehicle severely constrained the ability to leave, even when residents understood the risk and evacuation orders (Cutter and Smith, 2009; Riad et al., 1999; Thiede and Brown, 2013). Research on older adults and medically fragile populations similarly notes that limited income and reliance on others for transport and care complicate evacuation plans (Christensen et al.. 2013; Rosenkoetter et al., 2007).

Housing characteristics are another SES-related mechanism. Several Florida and Gulf Coast regional studies found that mobile-home and manufactured-housing residents, often lower-income, were more likely to evacuate than owners of site-built homes, reflecting the high perceived vulnerability of their dwellings (Peacock et al., 2005; Solis et al., 2009). In contrast, higher-income homeowners in stronger structures sometimes chose to shelter in place, suggesting that SES can also support "staying" where physical protection is perceived to be adequate (Meyer et al., 2018; Whitehead et al., 2000). Studies on low-income Mexican American communities likewise emphasize that limited savings, insecure employment, and crowded housing reduce the feasibility of evacuation even when residents recognize the threat (Reininger et al., 2013).

A smaller group of studies reported mixed SES effects or found that storm characteristics and prior experience were more influential than income alone, especially in repeat-storm contexts or when evacuations had previously been perceived as unnecessary (Dixit et al. 2008; Huang et al. 2016; Lazo et al. 2010; Morss et al. 2016). However, across the corpus, SES consistently appears as a core constraint on capacity: it shapes whether households can pay for travel and shelter, take time off work, mobilize rapidly, and evacuate farther to safer locations.

Role of Evacuation Orders

Evacuation orders and warning messages were the most consistently positive triggers for evacuation behavior. Across the 44 studies, 26 (59%) reported a significant positive effect of mandatory or recommended orders on evacuation behavior, and 14 (32%) documented mixed effects related to message timing, clarity, or household constraints. None found evacuation orders to be non-significant, although four studies did not examine them directly. Many of the earliest and most cited evacuation analyses found that being under an official evacuation order substantially increases the probability of leaving, relative to no order or only a watch/warning (Baker, 1991; Dow and Cutter, 2000; Whitehead et al., 2000). More recent studies and modeling across multiple storms and regions confirm that mandatory orders are associated with higher evacuation rates and earlier departure, particularly when coupled with clear information about storm intensity and local risk (Dixon et al., 2017; Fu et al., 2007; Hasan et al., 2011; Huang et al., 2012; Lazo et al., 2010; Lindell et al., 2005a).

Studies focused on risk communication and forecast use underscored that the effectiveness of orders depends on timing, clarity, and trust. Work on public interpretation of forecasts shows that people respond more strongly when messages are consistent across sources, emphasize local impacts, and are issued with sufficient lead time (Lazo et al., 2015; Morss et al., 2016). Research on information channels indicates that demographic groups differ in their reliance on television, radio, social networks, mobile alerts, and weather radios. Therefore, orders may be less effective when communicated through channels that do not match preferences or access (DeYoung et al., 2016).

At the same time, qualitative Katrina studies and work with structurally disadvantaged populations demonstrate that orders alone are not sufficient. In New Orleans and other Gulf Coast communities, many low-income and minority residents reported that they heard and understood the mandatory evacuation orders but were unable to comply because they lacked a vehicle, could not afford transportation or lodging, had health or caregiving responsibilities, or feared leaving their homes and neighborhoods unprotected (Cutter and Smith, 2009; Elder et al., 2007; Elliott and Pais, 2006; Masozera et al., 2007; Thiede and Brown, 2013). Studies of older adults and caregivers likewise note that official orders may conflict with practical realities of moving frail relatives, medical equipment, or dependent family members (Christensen et al., 2013; Rosenkoetter et al., 2007). Overall, the literature shows that evacuation orders reliably increase evacuation likelihood, but their impact is mediated by communication quality, risk perception, and, critically, by residents' socioeconomic capacity and mobility.

Cross-Cutting Structural and Logistical Mechanisms Influencing Evacuation

Across all three focal factors, race, socioeconomic status, and evacuation orders, the same structural and logistical mechanisms consistently emerged as the drivers of evacuation disparities. Transportation access was one of the most frequently cited barriers, with low-income and minority households often lacking private vehicles or relying on limited public or informal transportation options, making timely evacuation difficult or impossible (Cutter and Smith, 2009; Riad et al., 1999; Thiede and Brown, 2013). Financial constraints also played a central role: many residents who wished to evacuate reported being unable to afford fuel, lodging, or food, or to make up for lost wages, even when they perceived evacuation as the safer option (Dash and Gladwin, 2007; Elder et al., 2007; Reininger et al., 2013). Housing vulnerability and residential location further contributed to disparities. Individuals living in mobile homes, floodplains, or low-lying areas, where low-income and racialized communities are often overrepresented, tend to have higher evacuation rates due to heightened perceived risk, while those in sturdier homes often choose to shelter in place (Gladwin and Peacock, 1997; Masozera et al., 2007; Solis et al., 2009; Van Willigen et al., 2005). Additional obstacles arose from health limitations and caregiving responsibilities, as older adults, individuals with disabilities, and families caring for chronically ill relatives frequently faced logistical difficulties that hindered evacuation, especially when coupled with low income or weak support networks (Christensen et al., 2013; Rosenkoetter et al., 2007). Finally, trust and prior experience strongly influenced evacuation behavior: previous false alarms, negative shelter conditions, or severe traffic delays decreased subsequent compliance, whereas direct experience with damaging storms increased the likelihood of evacuation (Dow and Cutter, 2000; Meyer et al., 2018; Whitehead et al., 2000).

Collectively, these mechanisms demonstrate that racial disparities in evacuation behavior largely stem from structural inequities, economic disadvantages, vulnerable housing, limited transportation, and lower institutional trust, rather than race alone, while socioeconomic status directly shapes both the ability to act on evacuation orders and the likelihood of living in the highest-risk areas.

Interactions Among Race, SES, and Evacuation Orders

Although race, SES, and evacuation orders are often examined separately, research indicates that they are tightly interconnected. Racial differences in evacuation frequently disappear once SES is controlled, indicating that disparities stem from unequal access to transportation, financial resources, and stable housing (Huang et al., 2016; Lindell et al., 2005a; Peacock et al., 2005; Solis et al., 2009). Lower-income African American and Hispanic households are especially likely to lack vehicles, savings, or external support networks, limiting their ability to evacuate even when they perceive high risk (Elder et al., 2007; Elliott and Pais, 2006).

SES strongly influenced whether households complied with mandatory or voluntary orders. Many residents want to evacuate but cannot because of financial constraints, caregiving responsibilities, or mobility barriers (Christensen et al., 2013; Dash and Gladwin, 2007). Thus, orders tend to be most effective for higher-SES households with the resources to act quickly (Meyer et al., 2018; Whitehead et al., 2000). Racial disparities emerge not because groups interpret orders differently, but because the ability to act on those orders is unevenly distributed. Overall, the evidence indicates a three-way interaction: race shapes SES, SES shapes the capacity to respond to orders, and the impact of orders depends on structural conditions. As a result, evacuation behavior reflects not just personal choice but broader systemic inequities.

Geographic Variation in Evacuation Predictors

Evacuation behavior differs across U.S. regions because of variations in housing, transportation, governance, and risk cultures. Gulf Coast studies, especially from Texas and Louisiana, identify vehicle ownership, income, and trust in government as key predictors, with sharp racial and economic disparities shaping who can evacuate (Cutter and Smith, 2009; Elliott and Pais, 2006; Karaye et al., 2019; Masozera et al., 2007). In Florida, evacuation patterns are strongly tied to housing type and storm characteristics. Mobile-home residents consistently show high evacuation rates due to perceived vulnerability, while those in sturdier homes often stay, even at similar SES levels (Gladwin and Peacock, 1997; Whitehead et al., 2000). Florida also exhibits relatively high compliance with official orders, reflecting long-standing hurricane experience. Studies from the Mid-Atlantic and Northeast highlight different influences, including language barriers, limited hurricane experience, and recent in-migration, factors that particularly affect Hispanic households and contribute to lower baseline evacuation intentions (Morss et al., 2016; Vásquez et al., 2016). Overall, evacuation determinants vary regionally, reflecting differences in vulnerability, built environments, and population characteristics.

Temporal Shifts in Evacuation Determinants

Patterns of evacuation behavior have evolved as communication technologies, population characteristics, and disaster experiences have changed. Early studies from the 1990s and early

2000s emphasize risk perception, housing vulnerability, and storm track uncertainty as major predictors of evacuation (Baker, 1991; Whitehead et al., 2000). After Hurricane Katrina (2005), research increasingly focused on the roles of race, SES, transportation access, and institutional trust, reflecting heightened awareness of structural inequities exposed by that disaster (Cutter and Smith, 2009; Elder et al., 2007; Elliott and Pais, 2006). Since the 2010s, studies have highlighted new dynamics, such as the influence of social media, forecast improvements, and repeated storm exposure. Improved communication systems have increased early awareness, but past negative evacuation experiences, such as long traffic delays or unnecessary evacuations, have contributed to declining compliance in some areas (Meyer et al., 2018; Morss et al., 2016). Additionally, rising housing costs, demographic shifts, and growing coastal populations have intensified disparities in who can afford to evacuate (Karaye et al., 2019). Meta-analytic evidence further shows that factors once considered strongly predictive (e.g., gender, prior experience) now produce more inconsistent results as populations and infrastructure evolve (Huang et al., 2016). These temporal trends illustrate that evacuation behavior is dynamic rather than static and must be interpreted considering broader social change, technological advancement, and cumulative disaster experience.

CONCLUSION

This systematic review of 44 studies (41 articles, two book chapters, and a report) demonstrates that a complex interaction among racial identity, SES, and the nature of evacuation orders shapes hurricane evacuation behavior in the U.S. Race influences evacuation primarily through structural inequities, such as disparities in transportation access, income, housing quality, and institutional trust, rather than through race itself. SES is the most consistent predictor of evacuation, indicating whether households have the resources to act on official guidance. Evacuation orders, particularly mandatory directives, generally increase compliance, but their effectiveness depends on households' material capacity to respond, the clarity of communication, and prior disaster experience. Across regions and time periods, the same cross-cutting mechanisms emerge: transportation limitations, financial constraints, housing vulnerability, health and caregiving responsibilities, and trust in authorities. These factors explain why racial and economic disparities persist and why evacuation decisions vary across populations and storms. Together, these findings underscore that evacuation behavior is not solely an individual choice but is embedded in broader social, economic, and infrastructural systems.

For emergency managers and policymakers, these results highlight the need for targeted communication strategies, resource support for vulnerable populations, and investments in transportation and shelter infrastructure. For the AEC community, the findings emphasize the importance of designing resilient housing, strengthening evacuation routes, and addressing long-standing inequities in the built environment. Improving these structural conditions is essential for reducing disparities in evacuation behavior and enhancing community safety in hurricane-prone regions.

RESEARCH LIMITATIONS

There is significant literature exploring how social systems respond to an incoming natural disaster (including a hurricane). Given that the study is based on a review of 44 articles, some aspects of the evacuation parameters may have been missed.

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Building Science

Balancing Energy Efficiency and Thermal Resilience of Baltimore City's Rowhouses

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ABSTRACT

This study evaluates energy efficiency and thermal resilience in Baltimore row houses, addressing the critical gap between standard energy codes and indoor overheating risks in non-air-conditioned rowhomes. Utilizing calibrated energy models and NSGA-II optimization, the research assesses code-compliant retrofits against optimized solutions under current and future weather scenarios. Results indicate that while standard retrofits offer energy savings, they may fail to mitigate fatal indoor heat in future climates (2080-2099). However, optimizing retrofit parameters relative to the IECC 2021 baseline can reduce overheating risks by 13.5-16.8% without compromising heating demand. Despite these gains, future scenarios project a severe increase in overheating hours, ranging from 140% to 421%. The study highlights that modest code customization and targeted zonal strategies help balance energy performance with indoor thermal safety needs in a warming world.

Durability Assessment of Retrofitted VIP Insulated Cladding System in a Hot-Humid Climate

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ABSTRACT

This study presents the results of a long-term durability performance assessment of a vacuum insulated panel (VIP) retrofit insulated cladding system installed side by side with a baseline wall in ASHRAE's Climate Zone 3A. The primary objective was to evaluate the moisture and thermal behavior of retrofit prefabricated cladding solutions in a warm-humid environment through continuous in-situ monitoring. The system evaluated includes a VIP encapsulated within expanded polystyrene (EPS) foam. The wall assembly was instrumented with sensors to monitor temperature, relative humidity (RH), and heat flux at multiple layers, including the oriented strand board (OSB) sheathing and interior drywall. The retrofit cladding system maintained relative humidity levels in all layers below critical thresholds (typically 80-85%) throughout the monitoring period. In contrast, the baseline wall consistently exhibited higher RH values at the sheathing layer. However, during the summer months, the baseline wall's drywall layer recorded slightly lower RH levels than those observed in the retrofitted assemblies.

INTRODUCTION

Building envelopes in the United States represent a significant share of 28% of national building energy use (EIA, 2021; Harris, 2021) with a substantial portion attributed to heat loss and moisture-related challenges in exterior wall systems (DOE, 2014; Palani, 2025).

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Much of the existing building stock predates the widespread adoption of modern energy codes, leaving many structures with limited insulation, high air leakage, and reduced resilience, and reduced occupant thermal comfort (Antonopoulos et al., 2019). These conditions are particularly pronounced in older residential buildings, where over four decades of aging infrastructure has often led to vulnerability to moisture intrusion.

Efforts to retrofit existing wall assemblies are increasingly recognized as a cost-effective strategy to reduce energy consumption, improve indoor comfort, and extend building lifespan (Harris, 2021). Wall retrofits typically involve the addition of insulation, either on the exterior to form a continuous thermal envelope or on the interior to accommodate urban or site limitations (Laustsen, 2008). Exterior insulation solutions are generally preferred for minimizing thermal bridging and reducing occupant disruption, and for saving interior space. (Kelley and Blanford, 2023; NYSERDA, 2010). Interior retrofits can be advantageous in causing less destruction to constrained sites and historical preservation, but they may introduce unique hygrothermal risks, including condensation within wall cavities, occupant disruption, and reduced indoor floor space (Rodrigues et al., 2018). These risks are amplified in climates characterized by high humidity and significant seasonal temperature variations, where moisture durability becomes a critical design consideration.

A variety of retrofit materials and techniques have been explored, ranging from traditional cavity fills and rigid boards to advanced solutions, such as vacuum insulation panels (VIPs) (Kolaitis et al., 2013; Johansson et al., 2014) and hybrid insulation-coating systems (Moradias et al. 2012). While laboratory testing and numerical simulations have provided valuable insights into the thermal resistance and transient moisture transport of building materials and exterior wall systems (Johansson et al., 2014; Moradias, 2012; Tariku et al., 2015), real-world hygrothermal performance data remains limited, particularly for retrofitted wall systems exposed to mild-humid coastal climates over extended periods. These climates subject building envelopes to frequent wetting and drying cycles, increasing the likelihood of long-term hygrothermal performance degradation and occupant thermal comfort.

This study addresses these challenges by focusing on the in-situ hygrothermal performance of a selected retrofit wall system installed in a warm-humid coastal region (Climate Zone 3A). The findings contribute to developing retrofit strategies that balance improved thermal efficiency with moisture durability, ultimately supporting energy savings, enhanced occupant comfort, and building resilience in climates where temperature fluctuations and high humidity levels present unique retrofit challenges.

METHODOLOGY

This section is divided into four main steps: (1) test location, (2) wall systems and construction materials, (3) sensor installation design and layout, and (4) data collection. Detailed explanations for each step are provided below.

Test Location

The testing was conducted in Hollywood, South Carolina, near Charleston, a representative warm-humid coastal Climate Zone 3A location. The facility has been used to evaluate the moisture durability of different wall configurations. Figures 1A and 1B illustrate the facility's exterior and interior views, respectively.

Wall Systems and Construction Materials

Two wall assemblies were designed, constructed, and tested side by side in the testing facility.

- **Baseline wall** (reference sample): The assembly, representing a typical uninsulated wall, consisted of vinyl siding, a weather-resistive barrier (WRB), oriented strand board (OSB) sheathing, an uninsulated 0.05 m × 0.10 m (2 in. × 4 in.) stud cavity, and an interior painted gypsum board (Figures 2A and 2B).

- **VIP retrofit wall system**: This assembly was developed by modifying the baseline wall and consists of (from exterior to interior): vinyl siding, WRB, a VIP panel (see Figure 3, composed of an OSB layer, an EPS foam lid, VIP insulation, and an EPS foam tray), the baseline wall's OSB sheathing, an uninsulated 0.05 m × 0.10 m (2 in. × 4 in.) stud cavity, and an interior painted gypsum board. The VIP panel consists of eight VIPs placed within a 1.2 m × 2.4 m (4 ft × 8 ft) EPS foam tray (see Figure 3). The tray incorporated four wells (cavities) separated by 0.025 m (1-inch) EPS ribs. Each VIP is 0.03 m (1.18 in.) thick, while the EPS tray and EPS lid are 0.06 m (2.25 in.) and 0.035 m (1.375 in.) thick, respectively. The OSB sheet adds an additional 0.01 m (7/16 in.). The combined thickness of the VIP panel assembly is approximately 0.10 m (4 in.). This wall system incorporates two OSB layers: an interior OSB sheet housing the VIP panel (VIP_OSB) and an exterior OSB sheet enclosing the combined VIP and EPS components (VIP_Cover).

(a) (b)

Figure 1. Testing facility: (A) exterior side and (B) interior side.

(a) (b)

Figure 2. Baseline wall: (A) interior side (before the wall is closed with drywall) and (B) exterior side.

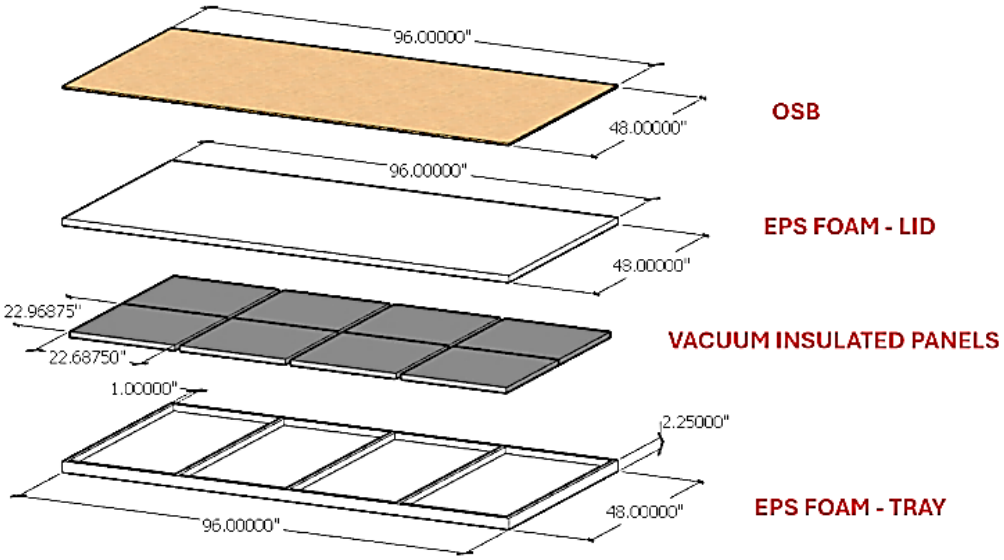


Figure 3. VIP retrofit panel system layout.

- **Sensor installation design and layout**
  To evaluate the hygrothermal behavior of the wall assemblies, temperature (Honeywell 192-103LET-A01), RH (Honeywell HIH-4000-003), and heat flux transducers (Concept Engineering HFT F-002-4) were embedded within the wall assemblies.

  In the baseline wall panel (Figure 4), RH sensors were installed on both the exterior surface of the OSB sheathing and the interior surface of the drywall. For the VIP retrofit wall panel (Figure 5), an additional RH/T sensor was placed on the exterior surface of the OSB layer that enclosed the VIP panels.

  Sensors were placed at three vertical levels within each wall, 0.41 m (16 in.) below the top plate, 0.41 m (16 in.) above the bottom plate, and at the vertical midpoint. Heat flux transducers were installed on the interior surface of the drywall for both wall types and on the exterior surface of the sheathing for the VIP retrofit wall panel.

- **Data Collection**
  Following the construction, installation, and instrumentation of both wall systems, continuous monitoring and field data collection was carried out for over 15 months. A data collection period exceeding one year was found necessary to capture the hygrothermal response of the wall systems under all four seasonal weather cycles, including the effects of temperature extremes, humidity variations, and seasonal moisture loading. This extended monitoring ensured that both short-term weather events and long-term seasonal patterns were represented in the performance assessment.

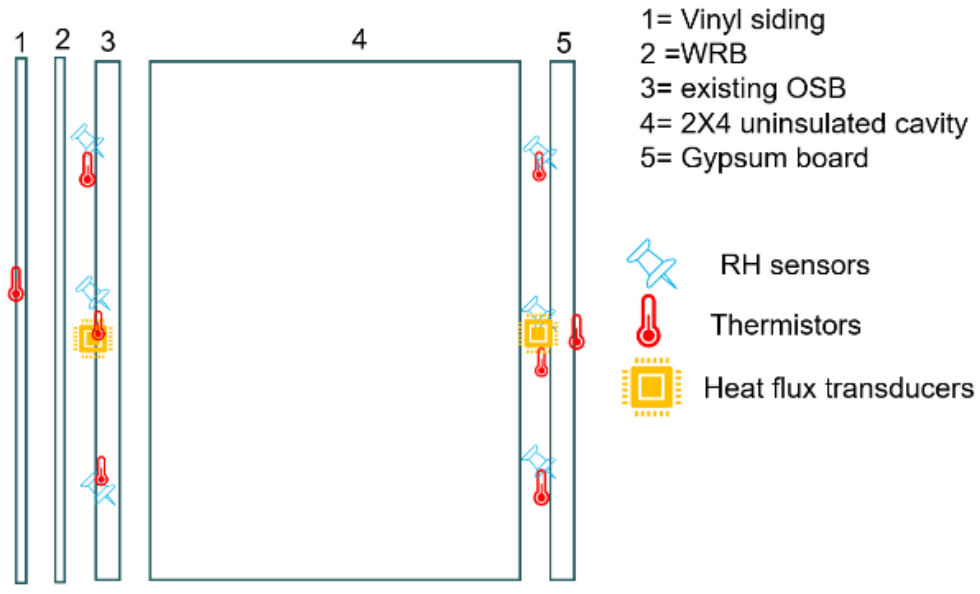


Figure 4. Baseline wall panel Sensor installation design and layout.

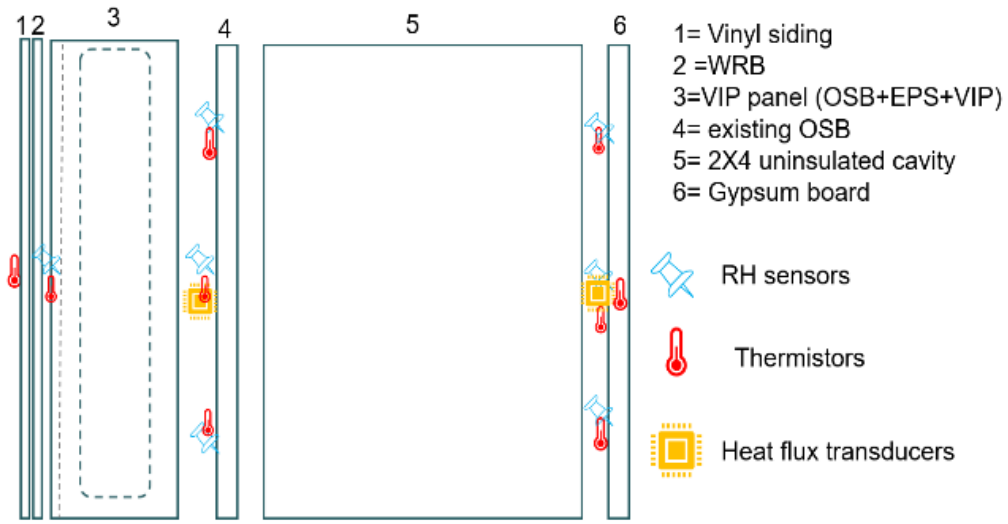


Figure 5. VIP retrofit wall panel Sensor installation design and layout.

RESULTS AND DISCUSSION

Measured Hygrothermal Performance

The long-term hygrothermal performance of the VIP-retrofitted wall system was compared with that of the baseline uninsulated wall. RH measurements were recorded at the OSB and drywall layers at three vertical locations, top, middle, and bottom, and averaged to facilitate direct comparison between the two wall types. Spatial uniformity of relative humidity measurement across the OSB and gypsum board layers were quantified using the coefficient of variation of top, middle, and bottom sensor readings and remained below 5%.

Figure 6 shows that from mid-May to mid-September, the drywall RH in the VIP-retrofitted wall panel remained higher than that in the baseline wall. For reference, the figure also includes the indoor and outdoor RH values Despite this seasonal difference, the OSB behind the VIP panels demonstrated more stable RH behavior than both the exterior OSB and drywall layers, indicating that the VIP retrofit effectively moderated internal moisture fluctuations. Maximum recorded RH (percent of moisture content) levels were 67% (9.1%) at the exterior OSB, 50% (6.8%) at the interior OSB, and 61% (4.2%) at the drywall. These findings suggest that the VIP retrofit contributed to improved moisture regulation within the wall assembly compared to the baseline wall panel and maintained those levels below critical threshold values.

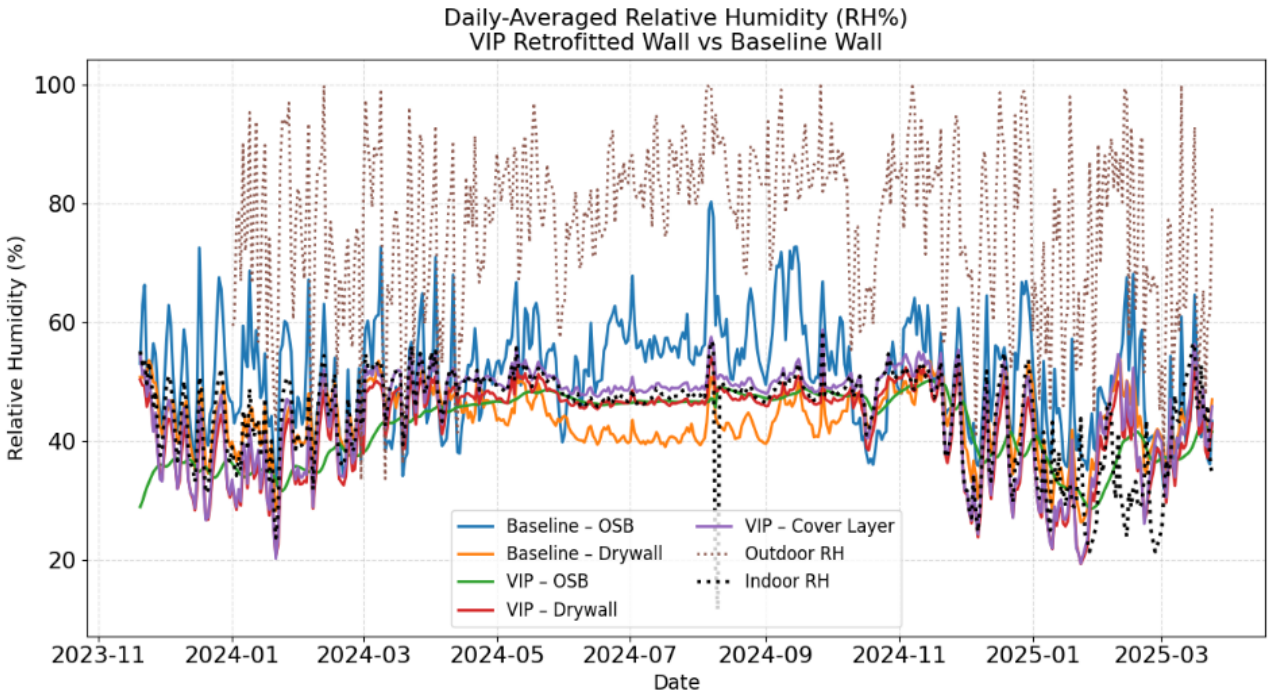


Figure 6. The daily average RH of the wall system with VIP cladding panel.

Measured Thermal Performance

Temperature measurements further highlighted the insulation benefits of the VIP retrofit wall panel system. The exterior OSB covering the VIP+EPS panel recorded temperatures ranging from 43.1 °C to −8.26 °C (109.6 °F to 17.1 °F), demonstrating strong thermal separation from interior spaces. In contrast, the interior OSB of the VIP-retrofitted wall maintained a narrower temperature range of 18.2 °C to 24.7 °C (64.8 °F to 76.5 °F) (Figure 7).

Additionally, for the drywall layer, the VIP-retrofitted wall exhibited temperatures between 18.5 °C (65.3 °F) and 24.5 °C (76.1 °F), whereas the baseline wall drywall experienced wider fluctuations, ranging from 12.2 °C to 28.8 °C (54 °F to 83.8 °F) (Figure 7). This clear difference in thermal stability confirms that the VIP retrofit panel substantially improved the overall temperature regulation of the wall system, reducing heat transfer and contributing to more stable interior conditions thus enhancing the thermal comfort of the occupants.

The overall R-values of both the VIP-retrofitted wall system and the baseline wall system were calculated using the procedure outlined in ASTM C1155-95 (2021).

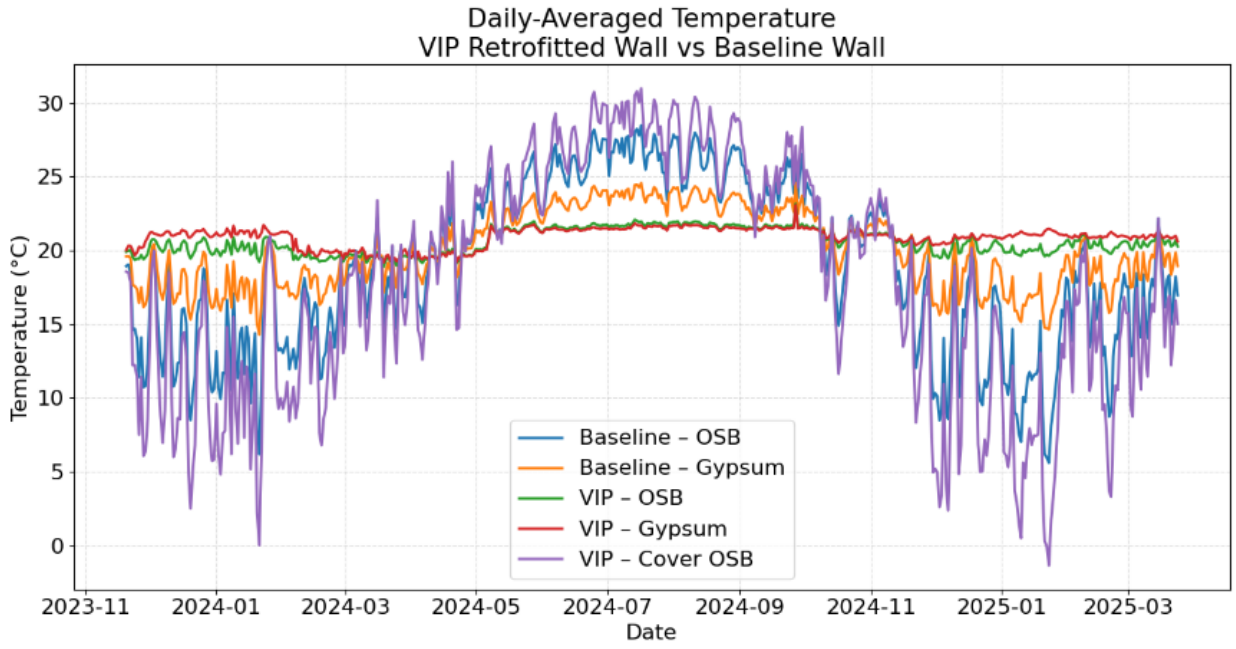


Figure 7. Daily average sheathing and drywall temperatures for wall system with VIP cladding panel.

Thermally, the retrofit delivered substantial improvements in wall insulation performance. Post-retrofit measurements indicate that the derived wall R-value increased to approximately R-39.2°F·ft²·h/BTU (6.9 m²·K/W), compared to the initially uninsulated baseline wall with an R-value of about R-2.3°F·ft²·h/BTU (0.4 m²·K/W) (Table 1). These results demonstrate that the retrofit measures—particularly the added insulation and cladding system—performed as intended and significantly enhanced the thermal resistance of the wall assembly in both orientations.

Table 1. Computed R-Value of the Wall System.

Measurement Segment	Layers (Figure5)	Computed R-Value (°F·ft²·h/BTU)	Computed R-Value (m²·K/W)
Exterior VIP panel → drywall	3–6	39.2	6.9
Baseline OSB → drywall	4–6	2.3	0.4
Added VIP R-value (difference)	(3–6) – (4–6)	36.9	6.5

Simulation Findings

To complement the experimental measurements, a hygrothermal analysis was performed using WUFI Pro 6.7 for the VIP-retrofitted wall assembly after model calibration using the measured data. Simulations were conducted for representative locations in three ASHRAE climate zones: Climate Zone 4A (Baltimore, MD), Climate Zone 4C (Seattle, WA), and Climate Zone 6A (Minneapolis, MN). Each simulation was run for a three-year period to capture long-term moisture and temperature behavior under varying climatic loads.

The assembly includes vinyl siding, a 10-mm (0.4 in.) ventilated air gap, and a multi-layer insulation system consisting of 0.04 m (1.5 in.) EPS, a 0.025 m (1 in.) vacuum insulation panel (VIP), and an additional 0.025 m (1-in.) EPS layer, positioned over the existing sheathing and fiberglass-insulated 0.05 m × 0.10 m (2 in. × 4 in.) wall. The interior side incorporates a vapor retarder and gypsum board. The full list of baseline and retrofitted wall components is summarized in Table 2.

Table 2. Wall Components of Post Retrofit Walls.

		Baseline	**Retrofitted Wall**
Cladding		Vinyl siding	Vinyl siding
		10-mm (0.4 in.) airgap	10-mm (0.4 in.) airgap
Retrofit			Spun bonded polyolefin
			VIP Cover OSB
			0.04 m (1.5 in.) EPS
			0.025 m (1 in.) VIP
			0.025 m (1 in.) EPS
Existing Wall	**Sheathing Board**	**OSB**	**OSB**
	Wood frame	0.05 m × 0.10 m (2 in. × 4 in.) wood frame	0.05 m × 0.10 m (2 in. × 4 in.) wood frame
	Cavity insulation	R-13 Fiberglass	R-13 Fiberglass
	Vapor retarder	57.2 ng·s-1·m-2·Pa-1 (0.05perm) vapor retarder	57.2 ng·s-1·m-2·Pa-1 (0.05perm) vapor retarder
	Drywall	Gypsum board	Gypsum board

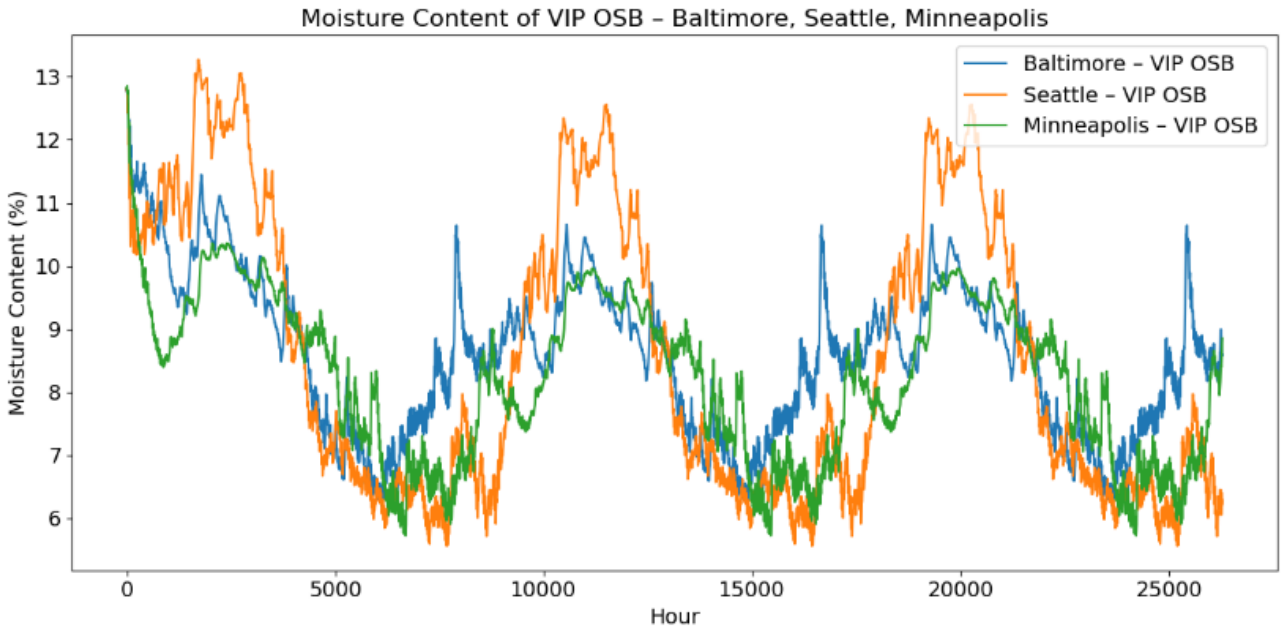
Moisture performance was evaluated by tracking the moisture content (MC) at two critical layers:

- the OSB supporting the VIP panel (VIP_Cover), and
- the existing wall OSB, representing the primary structural sheathing.

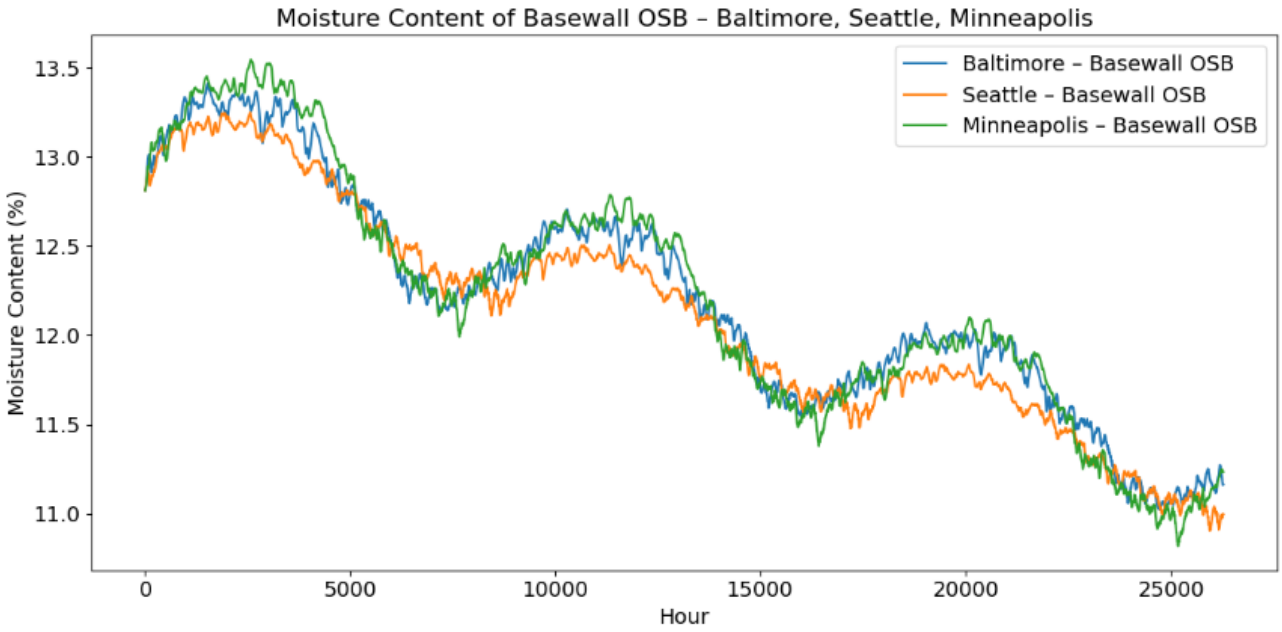
Figures 8(A) and 8(B) show the simulated moisture content trends at the monitored OSB layers across all climate zones. In every climate, both OSB layers remain below 13.5% moisture content, well under levels associated with material degradation or durability concerns. Seasonal fluctuations are observed on the exterior-side OSB (VIP-side OSB, VIP_Cover in Table 2), with the Seattle wall assembly exhibiting the highest peak value of approximately 13.5%. In contrast, the interior-side OSB (VIP_OSB) continues to dry over time, with moisture levels gradually decreasing throughout the simulation. Both moisture profiles remain within the acceptable moisture-safety thresholds for OSB.

Mold index values were calculated for all moisture-sensitive layers, including the VIP-side OSB and the existing OSB sheathing. Across all climates and all three simulation years, mold index values remained negligible.

Overall, the WUFI analysis demonstrates that moisture content remains within safe limits, and mold growth potential is minimal, confirming that the retrofit assembly can be durable with proper moisture control strategy.



(A)



(B)

Figure 8. The moisture content values of the (A) exterior side OSB supporting the VIP and (B) the OSB of the existing wall (base wall).

CONCLUSION

The VIP retrofit wall system exhibited superior thermal resistance compared to the baseline uninsulated wall, resulting in more stable interior temperatures and reduced heat transfer. Moisture monitoring indicated no evidence of elevated moisture risk or hygrothermal failure within the retrofitted assembly, even during peak seasonal humidity conditions.

These findings highlight the value of integrating high-performance insulation materials such as VIPs into panelized retrofit solutions. By improving thermal stability and maintaining moisture durability, VIP retrofits offer a viable pathway to extend building envelope life, reduce energy consumption, and enhance occupant comfort.

ACKNOWLEDGMENTS

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Framework to Simulate the Delamination Failure of Air Barrier Systems Installed in Building Envelopes

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ABSTRACT

The use of air barrier systems in building envelopes has been steadily increasing over the past few decades, primarily due to the increasingly stringent air leakage requirements that were introduced by local building codes, and by building standards like the Passive House Standard. Applying an air barrier seal at the seams of the external sheathing is considered common practice in the building industry to reduce the air infiltration through the building envelope. Popular sealing products may be divided into two categories based on their method of installation, the first are mechanically attached membranes and the second are adhesively attached tapes and liquid membranes. The scope of this paper is limited to the second category of the sealing products, the adhesively attached tapes and liquid applied membranes. Immediately after installation, the adhesive component of the tapes and the liquid applied membranes form an adhesive bond to the exterior sheathing boards. When fully bonded, the tapes and liquid applied membranes are effective at preventing air infiltration or air leakage through the building envelope. However, throughout the service life of the building, inter-story drift caused by seismic or storm related events may potentially lead to debonding of the adhesive from the sheathing boards and compromise the overall performance of the air barrier system. This paper presents a framework to simulate the debonding behavior of adhesively attached tapes and liquid applied membranes using the cohesive zone technique. The framework presented in this paper was applied to a liquid applied membrane and may be applied to the acrylic adhesives used in the adhesively attached air barrier tapes as well. The simulations carried out were able to capture the failure mode observed in the experimental tests. The findings show that the cohesive zone technique may be used to simulate the failure of the adhesively attached air barrier systems used in building envelopes when subjected to external displacements.

INTRODUCTION

The process of sealing the gaps and seams between external sheathing boards using air barrier tapes and liquid applied sealants has been proven to be an effective and economical approach to preventing air transfer through the building envelope as discussed by Hutchinson et al. (1996) and Hun et al. (2014). The published literature pertaining to pressure sensitive air barrier tapes

and liquid applied sealants investigates the long-term durability of the air barrier products in terms of their resistance to weathering and environmental degradation (Mamo Fufa et al., 2018, and Dobilaitė et al., 2023). However, the published literature (e.g., Sun and Jin, 2012) has not addressed the structural integrity of air barrier tapes and liquid applied sealants used in building envelopes when subjected to seismic or wind induced displacements. Abdelwahab et al. (2024) and Abdelwahab et al. (2022) experimentally investigated the performance of commercially available air barrier tapes and sealants when subjected to monotonic and cyclic displacements, which simulated a seismic event. The authors concluded that the sealing performance of the air barrier products may become fully compromised if subjected to seismic induced displacements, noting that different air barrier products perform differently when loaded. The authors also noted that delamination of the air barrier tapes and tears along the liquid applied elastomeric sealant were common failure modes, emphasizing the importance of developing failure prediction and simulation models to determine the performance of the air barrier systems along their useful service life. This agrees with the findings of the literature review conducted by Prignon and Van Moeseke (2017) stating that the current prediction models for air barrier systems do not meet the requirements of various stakeholders and recommending the need to develop failure prediction models that would better predict the behavior of air barrier systems used in building envelopes. This paper presents a framework to model and simulate the failure behavior of air barrier tapes and liquid applied sealants that are adhered to external sheathing boards. The proposed framework is based on the Cohesive Zone Model (CZM), which is presented in detail by Sun and Jin (2012), describing the CZM as a fracture mechanics-based technique that investigates the ability of a material to resist crack propagation. The CZM technique assumes the presence of a cohesive zone in front of the propagating crack resisting crack propagation. By accurately characterizing the fracture properties of the adhesive material, the ability of the adhesive to resist failure can be quantified.

The study by Yun et al. (2019) has shown the simulation of the interlaminar failure of composite materials using the CZM technique. Used also by Zaeri and Googarchin (2019), the authors have simulated the behavior of various bonded joints in automotive related applications. However, the use of the CZM technique in the field of non-structural adhesives that incorporate air barrier tapes and liquid applied membranes has been limited. 3M (2020a, 2020b) has discussed the possibility of using the technique to model the delamination failure of adhesive tapes; however, limited guidance has been provided by the authors on how to implement the CZM technique on air barrier tapes and liquid applied sealants.

The framework provided in this paper aims to provide some guidelines for developing a unified approach to simulate the failure of air barrier tapes and liquid applied sealants used in building envelopes.

PROPOSED FRAMEWORK

The objective of the proposed framework is to provide a procedure to accurately simulate the failure of air barrier systems used to seal the gaps between external sheathing boards in a building envelope. The proposed framework is applicable to liquid applied membrane products

and pressure sensitive air barrier tapes having an adhesive material that can be obtained in liquid form. The proposed framework assumes an unsealing or delamination failure mode for the air barrier products when subjected to seismic induced inter-story drifts, this assumption was confirmed by Abdelwahab et al. (2024). Figure 1 presents a flowchart of the framework. The details of the framework are discussed in this section.

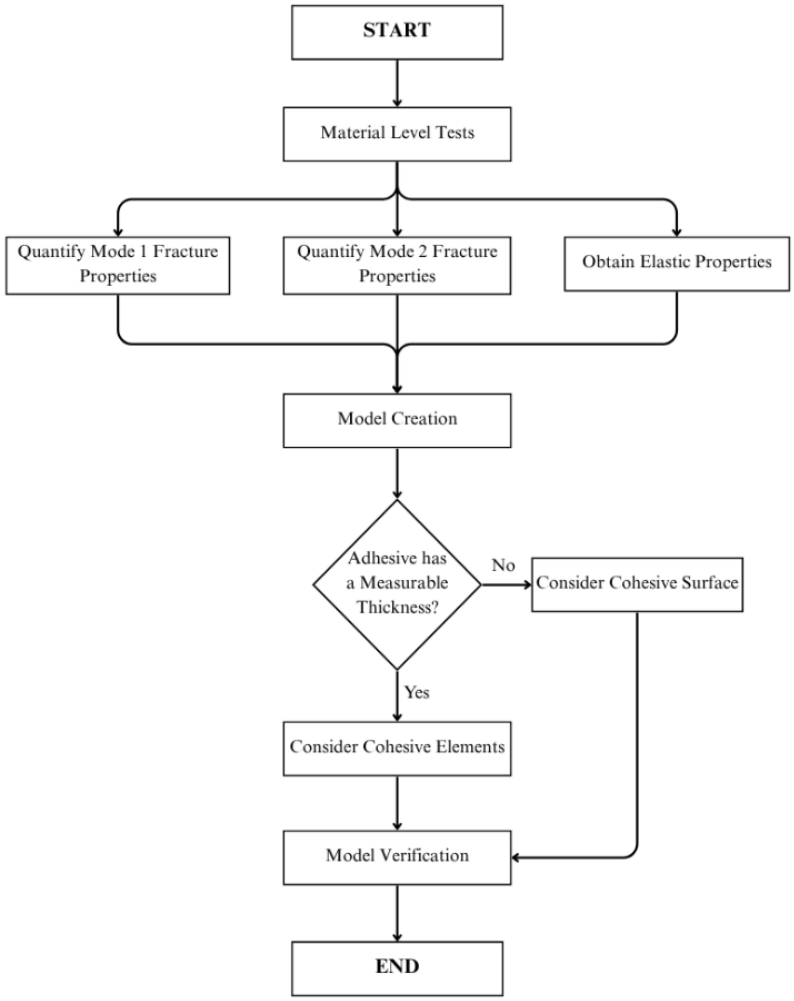


Figure 1. Proposed framework to simulate the failure of air barrier tapes using the cohesive zone method.

MATERIAL LEVEL TESTS

Accurate determination of key elastic and fracture material properties for the air barrier system is a crucial step towards the development of a precise finite element model able to simulate the failure of the air barrier system. Therefore, the initial step in the proposed procedure is aimed towards obtaining the properties of the adhesive material incorporated in the construction of air

barrier systems, which in the case of air barrier tapes would be the adhesive film and in the case of elastomeric liquid applied sealants, would be the sealant material itself. If available, the material properties may be obtained from the published literature, however obtaining the material properties experimentally is highly recommended. Table 1 presents the material properties of interests in addition to presenting the applicable standards to obtain each property.

Table 1. Required Material Properties and Applicable Test Standards.

Property	Symbol	Test
Elastic Modulus	E	Tensile Test
Mode 1 fracture energy	G_{Ic}	DCB*
Mode 2 fracture energy	G_{IIc}	ENF**
Mode 1 failure stress	σ_{11}	DCB*
Mode 2 failure stress	σ_{22}	ENF**
Elongation at failure	ε_u	Tensile test

Notes: *Double Cantilever Beam Test (DCB).
** End Notched Flexure Test (ENF)

Model Creation

Different commercially available finite element software such as ABAQUS/CAE (ABAQUS 2024) and Ansys LS-DYNA® (Livermore Software Technology Corporation (LSTC) 2024) are able to incorporate cohesive elements in their solvers. Open-source code-based solvers such as FreeFEM (Hecht, 2012) are also available but require knowledge of programming languages such as C++ and the ability to formulate the problem using the finite element method. The software incorporated in this work and used to develop the framework is ABAQUS/CAE. However, the modeling principles are the same regardless of software used.

The finite element software enables the user to present the adhesive material either as cohesive elements or as a cohesive surface. In the case of cohesive elements, a layer having a negligible thickness is introduced to the model to simulate the adhesive substrate. The in-plane dimensions of the cohesive elements should represent the actual dimensions of the adhesive material on the air barrier system. The traction properties are assigned to the cohesive elements to include either in terms of stress or strain limits. Furthermore, a damage initiation criterion must be set for the cohesive elements either in terms of failure energy or failure displacement. It is recommended to experimentally obtain the traction and damage initiation properties in order to accurately represent the air barrier product. In the case of a cohesive surface, no element is assigned to the adhesive substrate; instead, the behavior between the adhered surfaces is enforced at the boundary through specifying the traction conditions between the two surfaces. Specifying the interaction at the boundary will allow the user to incorporate the traction-separation behavior of

the adhesive material at the boundary. In the case of cohesive elements, without including the cohesive elements, this eliminates the requirement of adding tie constraints between the cohesive elements and the adhered components. However, the use of a cohesive surface will not provide in-depth information regarding the status of the adhesive material after loading.

Model Verification

The finite element model should be calibrated to produce the results obtained experimentally. After successfully replicating the experimental results, model verification becomes necessary to verify that the material properties and model assumptions are able to simulate the failure of the air barrier material under different loading cases. Model verification can be done by constructing a separate model for an independent test using the calibrated material properties and comparing the results to the experimental results obtained from carrying out the test. Examples for possible model verification tests include the lap joint test, blister test, butt joint test, and the 90-degree peel test. The verification test is said to be independent as the output of the simulation does not depend on the verification test. The lap (or butt) joint test that is the recommended candidate test for the independent test is relatively simple to conduct and simulate. The model is considered validated when the load-displacement behavior obtained through the model is identical to the load-displacement behavior measured experimentally or is within an acceptable margin of error. The results of the independent test reproduce the behavior observed experimentally for the independent test.

Experimental Application

The developed framework was implemented on a commercially available liquid applied membrane used to seal the gaps between the external sheathing boards, thus creating an air barrier system. After application, the product hardens to create an elastomeric membrane that prevents air movement through the external sheathing boards. The elastomeric sealant was used for experimental application due to its availability in liquid format, which allows for the construction of test specimens.

Specimens and Test Setup

Six specimens were constructed by adhering from two 25mm (0.98inch) wide plywood boards together using the liquid applied membrane. Three specimens were tested using the End Notched Flexure (ENF) test (ASTM, 2019), and three other specimens were tested using the Double Cantilever Beam (DCB) test (ASTM, 2021). Figure 2 presents the dimensions of the specimens and direction of applied loading for each test.

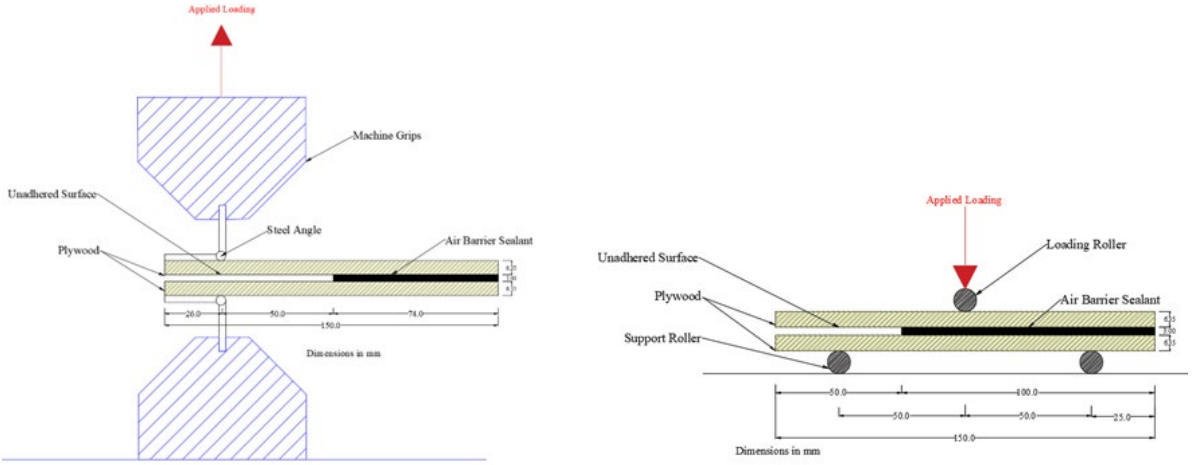


Figure 2: (A) Double cantilever beam test setup. (B) End notched flexure test setup.

Testing Procedure and Data Collection

The DCB test was conducted according to ASTM D5528/D5528M "Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites" (ASTM, 2021), while the ENF test was conducted according to ASTM D7905/d7905m "Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites" (ASTM, 2019). Additionally, the tests require measuring the propagated crack through the adhesive material corresponding to the changes in the applied load. This requirement can be achieved by incorporating an optical measurement device to capture the initiation of fracture cracks in the adhesive material in addition to the propagation of the crack with respect to loading and unloading of the specimen. It is worth noting that the test standard developed by the International Organization for Standardization (International Organization for Standardization, 2009) provides both width and height tapered Mode 1 specimens, which eliminates the need to include an optical measurement device.

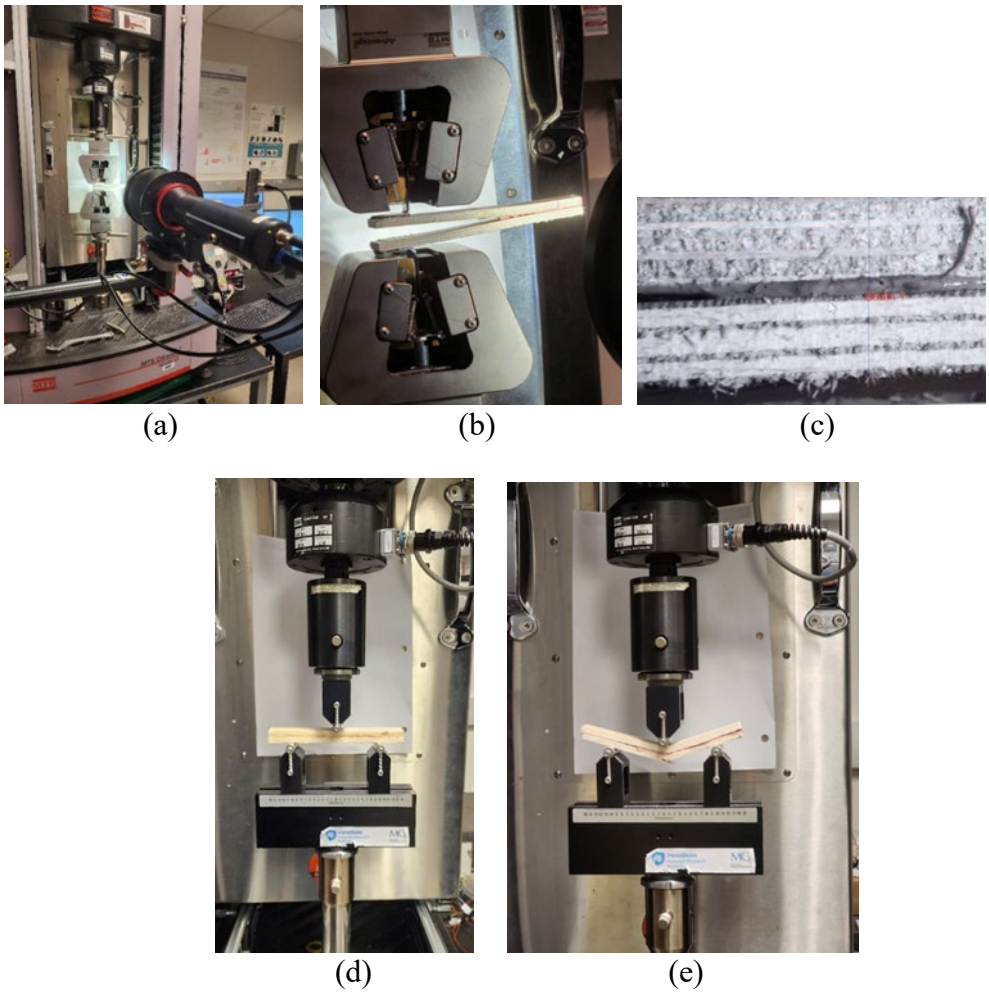
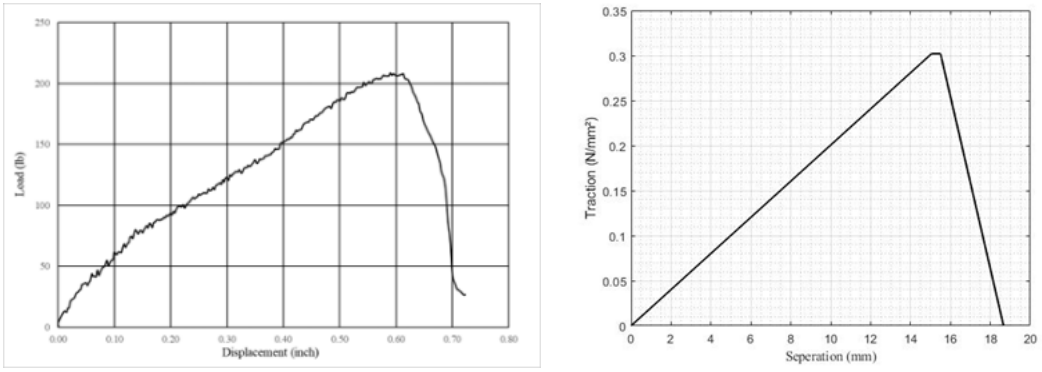


Figure 3. (A) DCB Specimen before testing inside the testing rig. (B) DCB after testing. (C) Image from the optical measurement camera. (D) ENF prior to testing. (E) ENF after testing.

Failure Simulation using CZM

The DCB and ENF tests were modeled using the finite element software ABAQUS/CAE (ABAQUS, 2024). The finite element models simulated the air barrier system by using a cohesive zone model framework. Based on the previous experiments, the traction separation behavior was produced and introduced to the model. From the load-displacement diagram obtained from the DCB test shown in Figure 4 (A), the Mode 1 traction-separation curve for the air barrier material was produced and is shown in Figure 4 (B). The trilinear traction-separation diagram presents the behavior of the adhesive material by three regions consisting of an elastic region defined until a separation of approximately 14.6 mm, then followed by a brief plastic region until a separation of 15.7mm, after which a softening region ends at a separation of 19mm.

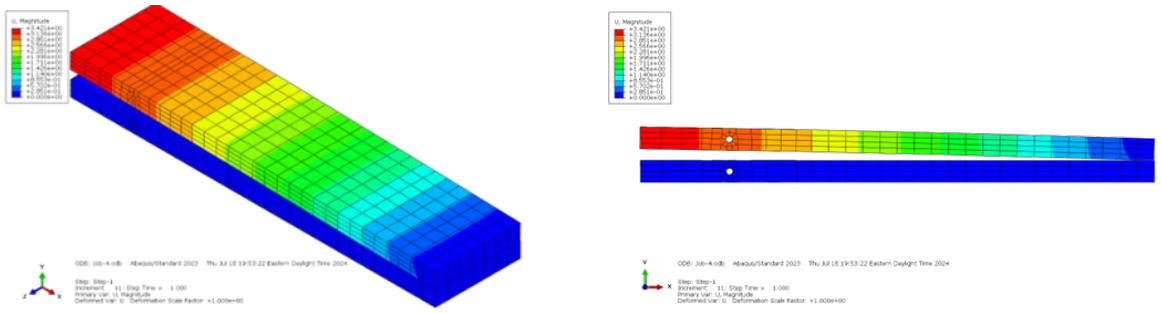


(a) (b)

Figure 4. (A) Load-displacement diagram of the air barrier material obtained from the DCB tests. (B) Traction separation diagram of the air barrier material.

DCB Model

The three-dimensional DCB model shown in Figure 5 incorporated the air barrier material as a cohesive surface (SFM3D4). The behavior of the cohesive surface was dictated by the traction-separation diagram presented in Figure 4 (B). The use of a cohesive surface to represent the adhesive material eliminates the need to define and mesh the adhesive part. However, obtaining damage progression and degradation behavior of the adhesive becomes unfeasible.



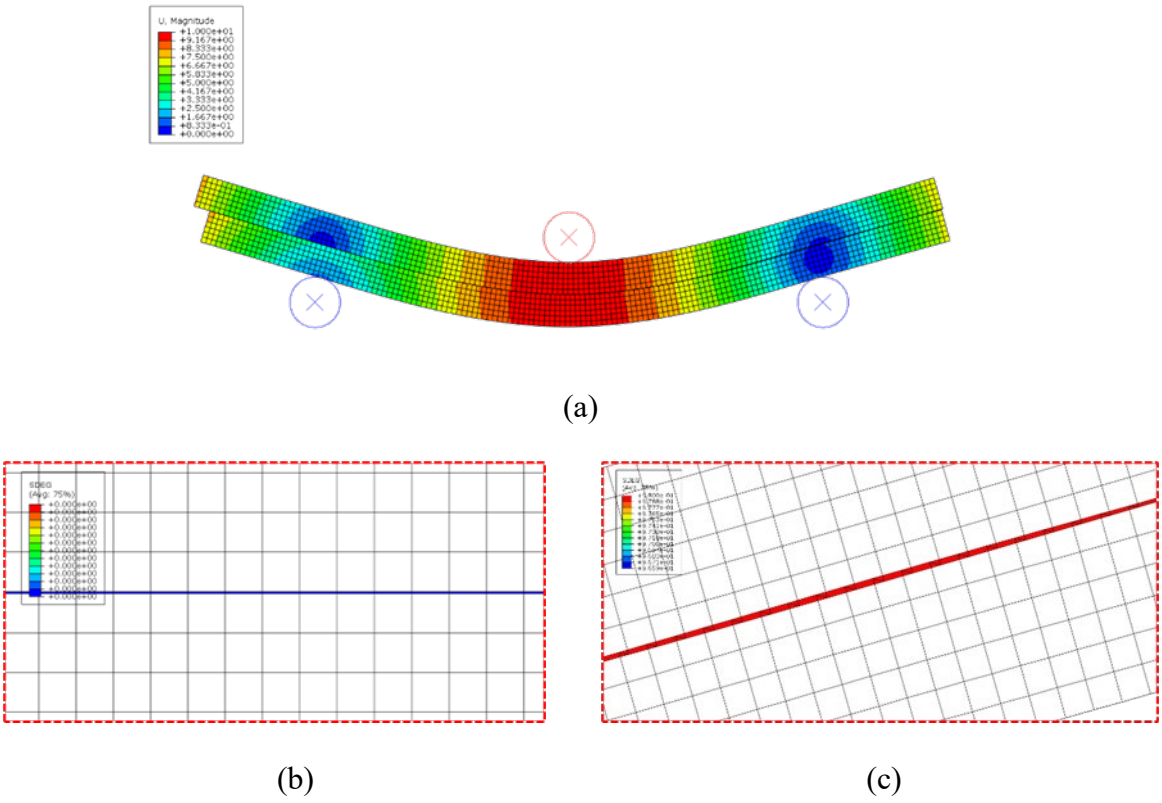
(a) (b)

Figure 5. (A) Isometric view of the DCB model. (B) Elevation view of the DCB model showing the model at maximum applied displacement.

ENF Model

A 2-dimensional model shown in Figure 6 (A) was created in ABAQUS/CAE (ABAQUS, 2024) to simulate the ENF test. The adhesive material was modeled as cohesive elements (COH2D4), which allowed for the extraction of the damage behavior and failure propagation through the air

barrier material. Figure 6 (B) and (C) show the same location on the air barrier material corresponding to varying levels of damage. The level of damage is quantified by the stiffness degradation factor (SDEG), which is a scalar damage indicator for the cohesive elements which can range from zero for an undamaged element to 1.0 for a completely damaged element. Further discussion regarding the SDEG parameter is presented by Correia et al. (2023). Figure 6 (B) shows the adhesive material in blue prior to loading and having a SDEG value of 0 indicating the absence of damage, while Figure 6 (C) shows the adhesive material in red after loading with cohesive elements having a SDEG value of 0.98 indicating complete failure of the adhesive material. The ENF model discussed further subsequently was successful at simulating the failure mechanism observed experimentally for the adhesive material.



(a)

(b) (c)

Figure 6. Model output showing: (A) Deformed shape including displacement contours. (B) Closer view showing stiffness degradation (SDEG) of the cohesive elements (adhesive material) prior to loading, SDEG = 0. (C) Closer view showing stiffness degradation (SDEG) of the cohesive elements (adhesive material) at Failure, SDEG = 0.98.

DISCUSSION

A comparison between the experimental observations and the finite element simulations is presented in Figure 7 (A) and (B), showing the opening of the DCB specimen and the

delamination of the air barrier material. The ENF finite element model was successful at replicating the failure mode of the deformed shape observed experimentally. Figure 7 (C) presents the slip occurring between the plywood boards at the left support. This was reproduced by the DCB model and is presented in Figure 7 (D) for the same location.

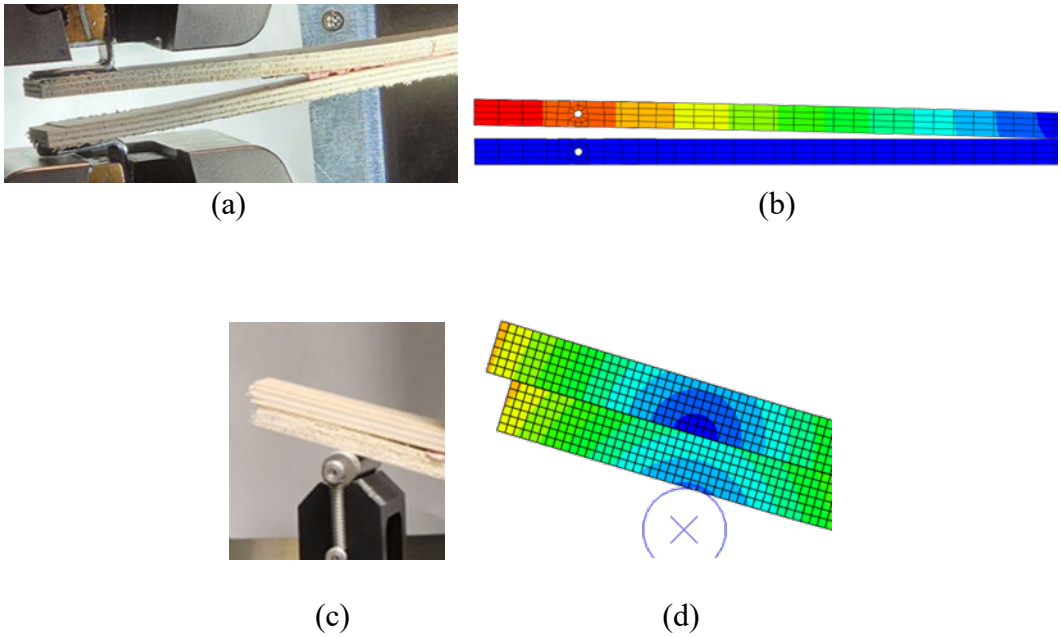


Figure 7. (A) Experimental failure mode of DCB. (B) Simulated failure mode of DCB. (C) Experimental failure mode for ENF. (D) Simulated failure mode for ENF.

The framework presented in this paper provides a viable approach to model air barrier systems, which require an adhesive component for their functionality. While the framework was applied to a self-adhered elastomeric liquid applied membrane, it may also be applied to pressure sensitive air barrier tapes having an adhesive film. However, it must be noted that it is unfeasible to construct ENF and DCB specimens directly using air barrier tapes that have a single sided adhesive film. Therefore, the adhesive component of the air barrier tape must be available in liquid form to allow for specimen creation to determine the fracture properties of the adhesive. Depending on the air barrier tape, the finite element model for air barrier tapes may include the membrane portion of the air barrier tape, which may be modeled as a membrane element. However, in some cases neglecting the effect of the membrane may be a valid approximation.

CONCLUSION

Building envelope air barrier systems are one of many non-structural components installed in a building. However, their failure or malfunction may lead to significant energy loss. Their ability

to prevent air leakage may become compromised due to physical strains caused by seismic or wind loads. Therefore, it is necessary to characterize and predict the response of air barrier systems due to external loads, particularly those caused by earthquakes or windstorms. This paper presented a framework that may be used to design and assess the structural integrity of air barrier systems after sustaining applied loads. The key findings and recommendations are as follows:

1. The fracture properties of adhesive dependent air barrier systems may be obtained using the ENF and DCB tests. However, the adhesive must be obtained in liquid form to allow for specimen construction.

2. The use of cohesive elements over a cohesive surface in finite element simulations will provide more insight into the behavior of the adhesive material under applied loading.

3. Model verification is required and can be done by comparing the results of independent tests such as lap joint or butt joint tests, along with corresponding simulations of the used tests.

4. The mixed mode blister test may be beneficial in determining the fracture properties of single-sided adhesive tapes. However, this has not been investigated by this study and is recommended for future research.

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Proposed Zone-Specific Methodology for Thermal Comfort Analysis in Traditional Courtyard Houses in Pune, India

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ABSTRACT

Droughts are a major concern for every country, especially India, where the states in the central region are the ones which are worst affected. Given the current climatic conditions worsening due to global warming and historically having faced multiple times over the past few centuries, India must be well-prepared to deal with the life-threatening effects of droughts. This calls for strong reasons to investigate drought conditions, accurately forecast and assess their potential impacts for a better future. The vernacular architecture of India exemplifies a complex thermal adaptation that has developed over many centuries in reaction to the country's varied climate, economic conditions, social mores, and cultural demands. Traditional courtyard houses, also known as Wada architecture of Maharashtra, with their central courtyards, represent a vernacular response to the region's hot and dry climate. This research aims to investigate how extreme drought conditions affect thermal comfort and air flow velocity within the three spatial zones (central courtyard, surrounding verandahs, and adjacent rooms) of traditional Wada houses in Pune, by developing a comprehensive methodology that proposes a detailed, zone-specific approach that combines environmental monitoring, material diagnostics, and digital simulation.

INTRODUCTION

The scientific community now acknowledges that droughts, together with other extreme weather events, represent major obstacles that extend from global climate change. The Intergovernmental Panel on Climate Change indicates that anthropogenic global warming causes compound events such as heatwaves and droughts to occur more frequently and severely, and South Asia stands as a region most at risk from these dangers. Environmental and social resilience face enduring consequences due to these climatic changes (Calvin et al., 2023). The state of Maharashtra, India, including its urban center Pune, has historically experienced significant water-related stress. Throughout the last hundred years, Maharashtra has endured multiple intense drought periods, and different areas throughout the state qualify as drought-prone areas. Scientific studies demonstrate that Indian droughts occur with increasing frequency and severity while lasting longer periods, and climate change, together with poor groundwater management practices contribute to this pattern (Chuphal et al., 2024). These stressors create significant threats to building environments and community well-being because they impact both food security and water availability (Pawar et al., 2025). Wada architecture in Maharashtra exists as traditional courtyard houses that have developed through centuries of local adaptation to hot, dry environments. The passive thermal system of these residences includes a central open courtyard,

which is surrounded by semi-open corridors (verandahs) and clusters of adjacent rooms. The architectural design of such configurations enables natural ventilation while controlling indoor temperatures through courtyard-based stack-driven airflow and shading systems (Salameh, 2024). Research on the microclimatic performance of courtyards during prolonged extreme drought periods remains scarce, although thermal benefits in hot-dry climates are already established, making it difficult to assess heritage forms' vulnerabilities and adaptive capabilities (Intergovernmental Panel on Climate Change (IPCC), 2023). This research aims to investigate how extreme drought conditions affect thermal comfort and air flow velocity within the three spatial zones (central courtyard, surrounding verandahs, and adjacent rooms) of traditional Wada houses in Pune, by developing a comprehensive methodology that proposes a detailed, zone-specific approach that combines environmental monitoring, material diagnostics, and digital simulation.

OVERVIEW OF CLIMATE

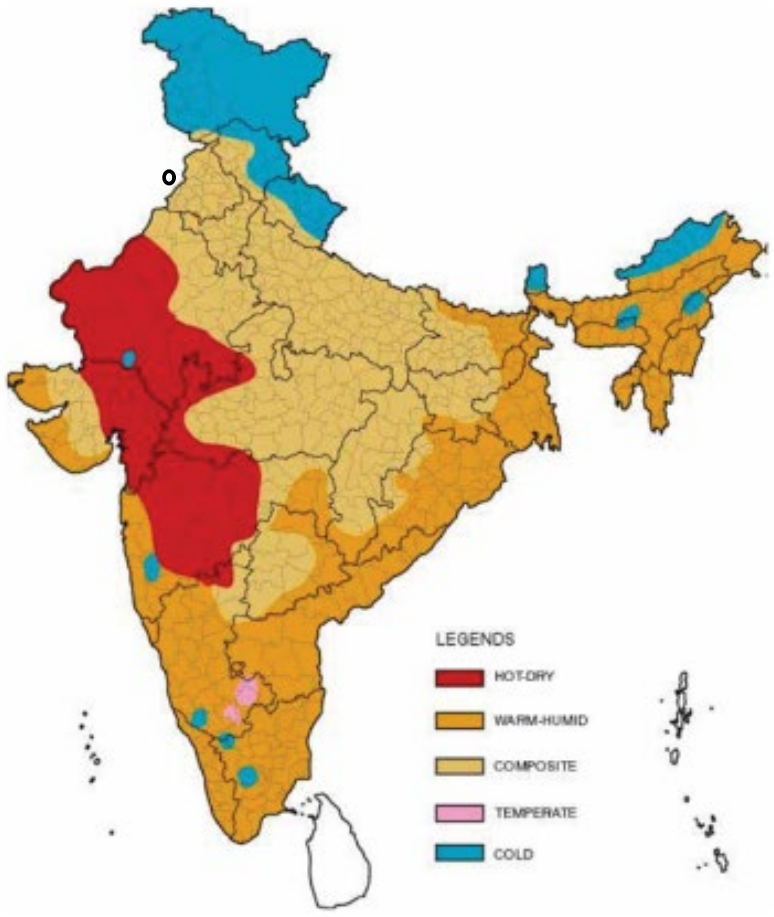

Figure 1. Map showing climatic zones in India Pune (Vakharia and Joshi, 2024). Image Adopted from Paper Titled "Climate-Responsive Wada Architecture: A Bioclimatic Design for Climate Change Resilience," 2024.

The Energy Conservation Building Code (ECBC) 2017 from the Bureau of Energy Efficiency (BEE) divides India into five main climatic zones for climate-responsive building design: Hot and Dry, Warm and Humid, Composite, Temperate (Moderate), and Cold (see figure 1). The classification system relies on long-term weather data to guide architects and engineers toward developing energy-efficient buildings that match local climate conditions. The Hot and Dry zone in red (figure 1) requires thick walls and shaded courtyards and limited window openings because it experiences hot temperatures with low humidity and minimal rainfall. Pune in western Maharashtra belongs to the hot and dry zone with three main seasons: summer, monsoon, and winter. The summer season in Pune lasts from March to June, with its peak temperatures occurring in late April or May. The average maximum temperatures during this period reached between 36°C to 38°C, and in some years, experienced daily highs above 40°C, while the highest recorded temperature was 43.3°C. The summer minimum temperatures stay in the low 20s°C range, which provides better nighttime relief from daytime heat (Vhatkar et al., n.d.) (Tiwari et al., 2025). Pune's annual temperature records show that the city experiences a mean yearly temperature of 24.7°C, with May being the hottest month at 36–38°C and December and January being the coolest months at 11–13°C, and sometimes reaching lower temperatures in exceptional years (Vhatkar et al., n.d.) (Tiwari et al., 2025). The daytime temperatures in Pune range between 29°C and 38°C throughout the year, but nighttime temperatures can reach as low as 10–12°C during winter (Tiwari et al., 2025). Pune has experienced rising temperature extremes throughout the last few decades because of fast urbanization and changes in land cover, and climate change effects. The urban heat island effect causes localized temperature rises between 2°C to 8°C above non-urban areas, while summer months show a significant increase in both maximum and minimum daily temperatures (Tiwari et al., 2025). The temperatures in Pune rise dramatically throughout drought periods, which creates severe heat stress for both urban and rural populations. (Tiwari et al., 2025). The combination of urban growth and drought-related low rainfall and dry soil conditions strengthens the Urban Heat Island (UHI) effect, which produces elevated maximum and minimum temperatures throughout the city (Tiwari et al., 2025). Drought emerges as a gradual process that lasts for months or years before it becomes challenging to predict and control. The condition develops from substantial precipitation deficits that exceed typical regional amounts to create dry soil conditions and depleted water reservoirs and strain both human settlements and environmental systems (Pawar et al., 2025). The research indicates that Tmax values increase by 0.13°C to 1.63°C annually at different locations in Pune, while Tmin values rise by 0.06°C to 0.23°C annually throughout the night (Tiwari et al., 2025). The temperature increases become most noticeable during dry spells and drought years because precipitation shortages and vegetation loss create additional heat retention that leads to daytime temperatures exceeding 35°C under dry conditions. (Tiwari et al., 2025). The twentieth century shows that Pune experiences significant temperature fluctuations throughout the year, with drought years causing major temperature spikes in both normal and extreme readings. The rise in temperatures becomes more extreme because of meteorological drought combined with decreased green spaces and expanded built-up areas, which results in more frequent and intense heat waves during drought periods (Tiwari et al., 2025).

ARCHITECTURAL FEATURES OF WADAS IN PUNE

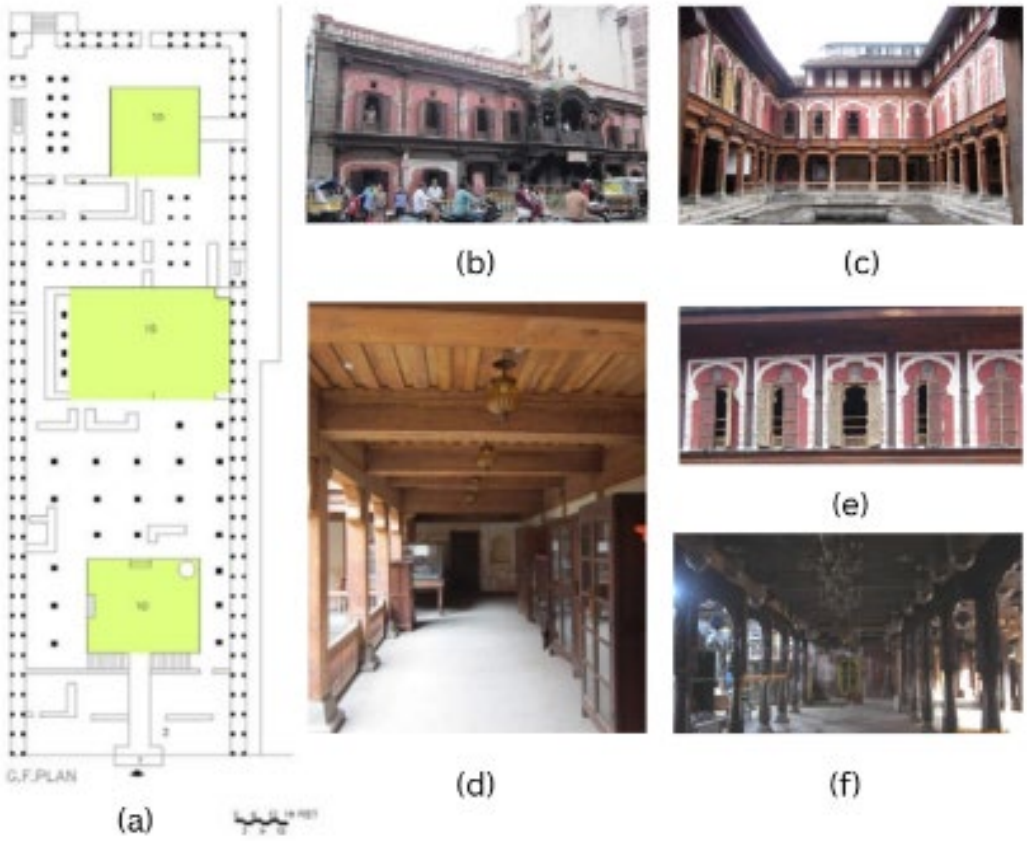

Figure 2. (A) Plan of Vishrambag Wada in Pune. (B) Eastern façade of Vishrambaug Wada. (C) Courtyard (third court) in Vishrambaug Wada. (D) Verandah in Vishrambaug Wada. (E) Windows in Vishrambaug Wada. (F) Hall (internal rooms) (Diwankhana) in Vishrambaug Wada. (Dhepe, 2017). Image taken from paper titled "Traditional Approach towards Contemporary Design: A Case Study," 2017.

The traditional courtyard mansions of Pune in Maharahtra, known as Wadas, have maintained their deep connection to the city's historical background as well as social and architectural traditions. The spatial layout, together with their collective use and symbolic significance, has secured their position as enduring cultural infrastructure and community institutions in the old city structure (Dhepe, 2017). In Maharashtra, the Sanskrit word "Vata" or "Vastu" evolved into "Wada" to represent a large house built around one or multiple internal courtyards (Shivani et al., 2025). The main architectural element of Wadas in Pune includes a chowk, which functions as the central point that controls spatial arrangement and social interaction. The standard layout of Wadas includes one or several chowks arranged in a square or rectangular pattern, with Vishrambaug Wada representing the largest example that uses multiple chowks (refer to figure 2). The courtyard receives its boundaries from verandahs, which act as transitional areas between public and private domains, while protecting from the sun and scattered natural light and

providing environmental protection (Dhepe, 2017; Nagapurkar et al., 2020). The rooms behind these verandahs are distributed across two to three floors, with public areas facing forward and semi-public and service zones positioned near the courtyard, before private family quarters reach deeper levels of the building (Alapure et al., 2015). Construction techniques in Wadas rely on a robust timber–masonry hybrid system. The structural foundation consists of basalt stone blocks that local quarries produce, which are set in lime mortar for durability and moisture resistance (Nagapurkar et al., 2020). Load-bearing walls are made from sun-dried or kiln-fired bricks or rubble masonry with dimensions that support both stability and insulation needs. The substantial hardwood beams and pillars, which make up the grid of columns and floors, rely on teak and neem wood and advanced carpentry techniques such as mortise-and-tenon joints and horizontal tie beams (Patli), and interlocking brackets (Dhepe, 2017). These assemblies have demonstrated resilience against seismic forces due to their flexibility and ability to dissipate energy, providing a form of earthquake resistance that is well documented in timber–masonry hybrid research (Nagapurkar et al., 2020). The roof structure consists of sloping timber trusses that carry Mangalore (clay) or country tiles as roofing materials, which provide both water-shedding properties and thermal effectiveness (Dhepe, 2017). Materials used are locally sourced and well-adapted to the regional environment. The foundation consists of large basalt blocks, which combine with walls that use bricks and stones sealed by a specialized lime plaster containing organic additives, including jaggery and egg white, hemp fiber, and plant extracts for better workability and durability, and breathability (Alapure et al., 2015) (Dhepe, 2017). Carpentry relies on mature hardwoods, mainly using teak and neem, because these woods exhibit resistance to decay and carry weight well, and allow detailed carving. Roofing consists of timber trusses combined with clay tiles to achieve optimal monsoon water shedding and solar insulation, while floor finishes range from stone slabs to lime-plastered earthen floors. The climatic responsiveness of Wadas is a core attribute, with passive cooling and ventilation intrinsic to their form. The courtyard design allows cool air to enter through its semi-open verandahs while hot air rises upward through space (Alapure et al., 2015). The combination of thick masonry walls and shaded verandahs, together with the high reflectivity and breathability of lime plaster work to regulate temperature swings. The roof extends beyond the walls to protect both external surfaces and indoor areas from solar heat during the summer months and monsoon precipitation. Thermal comfort can be achieved throughout the day through the designed spatial and material configurations, which also reduce indoor temperature peaks and stabilize humidity (Vakharia and Joshi, 2024).

OVERVIEW OF THERMAL COMFORT STUDIES OF WADA HOUSES IN PUNE

The investigation into climate-responsive Wada architecture by (Vakharia and Joshi, 2024) utilizes a methodology that includes literature review, on-site case studies. In addition to that, quantitative environmental data are recorded over a full year using calibrated data loggers, documenting air temperature and humidity at regular intervals in selected indoor and outdoor spaces to capture the building's performance across seasonal extremes. This dataset is further contextualized with three decades of regional meteorological data, highlighting significant recent warming trends in Pune (Vakharia and Joshi, 2024). Then the study proceeds with the construction of a digital simulation of the Ranade Wada using Design-Builder (EnergyPlus),

informed by precise measurements of building envelope thermal properties. The model is rigorously calibrated using empirical field data and validated against ASHRAE standards to ensure reliability. Future climatic scenarios for the years 2050 and 2080 are simulated using weather files generated from the IPCC HADCM3 model, allowing projections of indoor thermal comfort under altered climate conditions. Results reveal that Wada architecture, through passive features such as thick walls, courtyards, and natural ventilation, currently ensures significant indoor comfort even during extreme weather. However, simulations indicate that climate change will substantially reduce comfort hours, with projections showing declines from 50% currently to 22% by 2050 and 11% by 2080, especially in upper and less ventilated spaces (Vakharia and Joshi, 2024).

Another study conducted by (Bangad and Joshi, 2022) involves a post-occupancy comparison of human comfort in a traditional Wada house and a newly designed modern house in Pune, India. Both residences, located about a kilometer apart in Kasba Peth in a Pune serve as case studies reflecting two architectural eras and climatic adaptation strategies. Environmental comfort parameters, mainly air temperature, humidity, wind velocity, and sound, were measured over three days in key spaces of both houses at morning and afternoon intervals. In addition to objective readings, questionnaires were administered to residents to capture subjective perceptions of comfort, adaptability, and spatial association across daily cycles. The architectural characteristics, materials, spatial organization, and microclimatic context of each dwelling were documented, with the traditional house characterized by a courtyard-centric layout, thick masonry walls, and natural materials, and the modern house representing a typical 2BHK modular plan from 2010 with contemporary construction materials and mechanical conditioning systems. The results reveal marked contrasts between the two built forms. The traditional house consistently maintained lower indoor temperatures and higher relative humidity throughout the day compared to the modern house, demonstrating the effectiveness of passive strategies such as courtyard planning, shading, and the use of high thermal mass materials in mitigating external climatic variations. Occupants of the traditional house reported higher comfort, particularly in spaces adjacent to the courtyard, attributable to natural air movement, thermal inertia, and strategic spatial flexibility. In the modern house, indoor temperatures and wind velocities were generally higher, with comfort increasingly reliant on mechanical intervention for cooling and ventilation (Bangad and Joshi, 2022).

Above discussed studies showed that traditional courtyard houses ensures significant thermal comfort; however, the studies do not isolate the microclimatic effects of major acute drought and increasing risk in semi-arid regions like Pune. In both studies, Monitoring and simulation are generally aggregated at the building or household level, not resolving variations between highly differentiated spaces such as sun-exposed courtyards, shaded verandahs, and insulated rooms. Also, (Bangad and Joshi, 2022) use three-day snapshots, which are insufficient for capturing atypical, stress-period phenomena.

PROPOSED METHODOLOGICAL FRAMEWORK

The proposed methodology (see figure 3) aims to conduct an in-depth investigation of the impact of extreme drought conditions on internal thermal comfort and air velocity within the spatially distinct zones of traditional Wada houses in Pune. The research aims to overcome the limitations of previous works that have glossed over spatial heterogeneity and the ways occupants adapt to acute climatic challenges. Rather than looking at the building in aggregate, this study measures and analyzes each distinct spatial zone, such as the courtyard, verandah, and individual rooms, using detailed environmental (temperature, humidity, air velocity) data. The initial phase involves selecting a sample of three to four representative Wada houses in a hot and dry zone of Pune, chosen for their traditional courtyard layouts and diversity in age, size, orientation, and urban siting. Each property will be documented, capturing the detailed dimensions and arrangement of principal spaces; courtyards, verandahs, and rooms, alongside crucial envelope factors such as wall construction, openings, materials, and interior circulation routes. In addition to geometric documentation, baseline assessment will be established for the thermal and airflow characteristics inherent in various architectural surfaces, spatial connections, and material choices. The next phase involves understanding the interior environment. The study deploys a microclimate monitoring system comprising temperature and humidity loggers, globe thermometers for radiant heat measurement, and high-precision anemometers to capture air velocity. Sensors will be positioned from floor to near-ceiling height within each spatial zone, with additional lateral placements to map microclimatic gradients and capture localized differences caused by shading, ventilation, and occupancy. Rigorous calibration routines will be enforced before and throughout deployment to assure the accuracy and reliability of recorded data. This multi-tier measurement approach enables the precise mapping of heat, humidity, and airflow profiles that can otherwise be lost in conventional, low-resolution building analysis.

Uninterrupted environmental monitoring will span a minimum of one complete pre-monsoon to summer cycle, typically three to four months, with a strong preference for extending coverage across additional drought-prone months to maximize the capture of stress-period dynamics. During standard conditions, core environmental variables such as temperature, humidity, and air velocity will be logged every 15 minutes, creating richly detailed time series data. The protocol will intensify to five-minute intervals during periods deemed an acute drought by the Indian Meteorological Department, defined by extended rainless phases and/or consistently low humidity. Contextual outdoor data will be secured via dedicated on-site weather stations, facilitating robust indoor-outdoor comparisons and ensuring that the monitoring campaign reflects both typical and extreme climatic regimes.

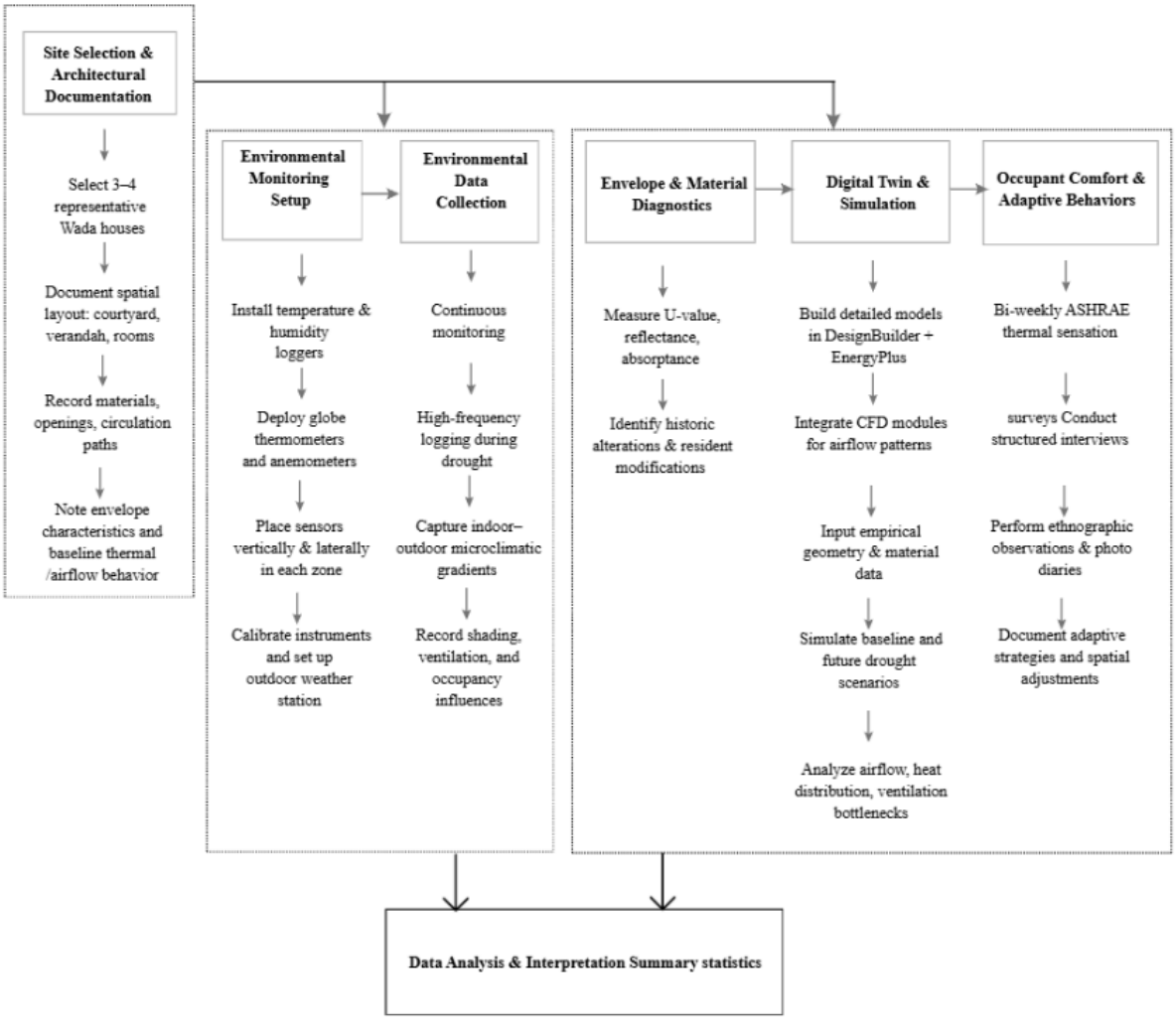

Figure 3 Proposed methodology flowchart (source: author).

The next phase involves a comprehensive regimen of envelopes and material diagnostics. Using specialized tools, on-site field measurements will ascertain key thermal properties of each building's envelope, such as U-value, surface reflectance, and absorptance, to reveal their role in heat transfer and retention. Additional documentation will record historic interventions and resident-led modifications, such as secondary insulation, wetted flooring strategies, or temporary shading, that may influence the real-world performance of each spatial zone during heat stress. This nuanced attention to materials supports a deeper integration of architectural factors into the environmental analysis. The next phase involves a highly detailed digital twin of each Wada will be developed using Design Builder and Energy Plus, incorporating computational fluid dynamics (CFD) modules. These models will be precisely informed by the empirical diagnostic data, ensuring an accurate reproduction of spatial geometry and material performance. Simulation scenarios will examine both baseline thermal behavior and stress-response under projected future

drought conditions, using regionally downscaled climate data. The models will offer powerful visualization and analysis of airflow, temperature distribution, ventilation bottlenecks, and heat accumulation across the courtyard, verandah, and room sequence, illuminating intervention points for optimal comfort maintenance. In the next phase, occupant thermal comfort and adaptive behavior will be systematically documented through bi-weekly surveys using established ASHRAE thermal sensation scales, paired with structured interviews exploring perceptions of heat, airflow, and comfort-seeking strategies. Ethnographic observation supported by participatory mapping, photographic diaries, and direct engagement with occupants will chronicle evolving behaviors and spatial modifications in response to acute climate stress, such as altering room usage patterns, installing temporary shading, or employing water-based cooling rituals. This human-centered layer is crucial for linking quantitative environmental data to practical adaptation measures and for understanding the social relevance of spatial resilience.

For analysis, basic statistical techniques will be used to compare how temperature, humidity, and air movement vary between the courtyard, verandahs, and rooms, as well as before, during, and after drought periods. Simple comparative tools such as summary statistics (mean, median, range) and visualizations (box plots, line graphs, heat maps) will be applied to make it easy to spot which areas and times experience the greatest stress. Correlations between environmental data, building features (like wall thickness, window placement), and occupant comfort (from surveys) will be identified using straightforward correlation measures (like Pearson or Spearman coefficients). Simulation outputs will further diagnose the risks and opportunities for improvement, guiding recommendations for zone- and scenario-specific enhancements to thermal comfort and airflow management.

CONCLUSION

It can be concluded that climate change is causing the risk of droughts in the hot and dry regions of India, including Pune, and hence, there is a need to study the thermal performance of traditional courtyard houses in Pune. However, the current studies lack detailed investigation into microclimatic variations and occupant adaptation within different spatial zones, such as courtyards, verandahs, and rooms, especially during acute drought events. Current research aggregates findings at the whole-building level and does not address specific vulnerabilities, adaptive behaviors, or resilience strategies required to maintain comfort and airflow under prolonged climate stress. Hence, there is a need to study this courtyard typology in detail to assess thermal comfort and resilience during extreme drought conditions.

FUTURE SCOPE OF WORK

The future scope of this work is to extend zone-specific thermal monitoring and analysis to a larger and more diverse sample of Wada houses, test innovative passive cooling and adaptive design interventions, and collaborate with architects and policymakers to implement these findings for heritage preservation and climate-resilient urban housing solutions in Pune and similar regions.

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Residential Design Strategies for High-Exposure Environments

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ABSTRACT

Extreme weather events, many directly linked to a warming planet, are increasingly affecting communities all over the United States. More homes are being built in high-risk and high-exposure locations, and conventional residential design approaches are often inadequate, leading to increased and more severe enclosure failures in these worsening conditions.

This paper examines our investigation of a home located near California's central coast that suffered through exposure to high-intensity weather events, resulting in sustained damage. We discuss the designer's evolving role and strategies to design robust and resilient repairs to protect the growing number of homes in exposed and at-risk environments by exploring the California Building Code and California Residential Code requirements and enhancements related to air and water-resistive barriers, wind design, and ignition resistance.

These code requirements, while tailored to the subject home's climate risks, offer guidance that can be extrapolated to other regions facing similar threats. As extreme weather becomes more frequent and severe, designers must prioritize durability, risk mitigation, and occupant safety.

INTRODUCTION

Extreme weather events and environmental hazards, many of which are directly linked to a warming planet, are increasingly top of mind. In just over the first half of this year alone, California faced its second- and third-most destructive wildfires in its history (California Department of Forestry and Fire Protection, 2025), Texas experienced one of its deadliest floods on record, and a dangerous and record-breaking heat wave swept across the eastern and central United States.

Not only are extreme weather events and environmental hazards becoming more frequent and intense, but Americans are also building more homes in areas that are highly vulnerable to wildfire, flooding, drought, and other climate-related risks (Redfin, 2022). In many cases, conventional home designs are proving inadequate in these worsening environmental conditions.

This paper examines our investigation of a home located near California's central coast that suffered exposure to high-intensity weather events, resulting in sustained damage. It then examines a designer's responsibility and strategies for providing robust and resilient designs for new and existing homes, aiming to protect the growing number of homes in exposed and at-risk environments.

Building code requirements vary by jurisdiction. This paper will generally refer to the 2022 California Building Code (CBC) and the 2022 California Residential Code (CRC).

CASE STUDY HOME BACKGROUND

The subject home is located in Templeton, California, approximately fifteen miles inland from the coast of California. According to the CBC, this places the home in California's Climate Zone 4 (Figure 1), which is characterized by hot, dry summers and mild winters with a rainy season typically between November and March. California's central coast has topography that includes mountains, valleys, and a rugged coastline. The subject home is located at the top of an escarpment at an elevation of 1,095 ft.

Figure 1. California Climate Zone 4 (adopted from CBC).

The two-story home's cladding is a cement plaster assembly with areas of thinset-bonded stone veneer at the base of the plaster-clad walls and aluminum-clad wood windows in punched openings. Precast concrete trim surrounds the windows and doors and at the edge of the south elevation balcony. The roof is covered with clay tile.

It was built in approximately 2008, and the current owner moved into the home in 2016. Over the past two winters (2022-2023 and 2023-2024), the residence has experienced several heavy rain events during the wet season. During rain events, the owner observed strong western winds. One rain event in December of 2022 resulted in flooding into the first level along the west elevation. No leakage is reported through other enclosure systems, including the roof. In the summer of 2024, the owner engaged Simpson Gumpertz and Heger Inc. to perform an investigation and diagnose the cause of water intrusion on the west elevation.

INVESTIGATION

We performed our investigation in general accordance with ASTM E2128, Standard Guide for Evaluating Water Leakage of Building Walls. We began with a visual survey of the exterior of the home and representative locations in the interior. Prior to our arrival, the repair contractor removed interior finishes; we observed oriented strand board (OSB) sheathing and wood framing with black apparent biological growth at floor lines and at the bottom corners of several windows on the west elevation (Figure 2). We observed no damage in openings around a representative selection of windows on the other elevations.

Figure 2. Water-damaged oriented strand board sheathing below a west elevation window (left) and water intrusion during testing (right).

The next step in our investigation included recreating leakage pathways and diagnosing the source of water intrusion. We did this by applying water using a water spray grid calibrated per ASTM E1105 and an AAMA 501.2-type nozzle. We applied water to two windows located above the reported water intrusion on the west elevation during the heavy storms. Within less than one minute of water application, we observed multiple locations of water leakage around the window framing of one window. Twenty minutes later, we observed additional water leakage

around the second window's frame. We observed water penetration both above and below the windows.

The contractor removed cement plaster around the perimeter of one of the windows. From interior to exterior, the wall assembly is as follows: interior drywall and insulation (removed prior to our arrival), structural framing, OSB sheathing, perimeter flexible flashing (non-self-adhered plastic membrane at the head and jambs, and self-adhered asphalt flashing at the sill), two layers of building paper, metal lath, and the cement plaster assembly.

We observed damaged existing construction, including deteriorated building paper, stained and deteriorated OSB sheathing above the window, and corroded fasteners and window flanges. The OSB sheathing was damp from our testing. We also observed workmanship issues, notably where the flashing membrane lapped and was sealed inboard of the window flange at the head of the window. The jamb and sill flanges had some sealant squeeze-out between the flange and the air/water barrier membrane, and multiple nail penetrations through the flanges were unsealed (Figure 3). The membrane sill flashing had several holes at the corners. We observed immediate water intrusion when we applied water to these unsealed penetrations and holes in the membrane.

Figure 3. Window head with flashing lapped and sealed inboard of the flange (left) and deteriorated and damp OSB sheathing above the window (right).

We concluded that water intrusion and damage to the building structure are due to a combination of the following conditions:

- Incorrectly installed window perimeter flashing (membrane lap behind the head flange, which directs water behind the flange and sealed sill flange blocking water from draining).

- Unsealed penetrations window perimeter nailing flanges.
- Torn and deteriorated building paper water-resistive barrier.
- Unsealed fastener holes in the nail flanges and through the perimeter flashings.

Further, the omission of through-wall flashings at window heads allow water entering above windows to travel around the perimeter of the windows, increasing leakage at the incorrectly installed flexible flashings at the recessed windows. The surcharging water also contributes to building paper deterioration due to the increased water migrating downward under the cement plaster. The lack of sheet metal sill pan flashings also results in less protection at the vulnerable recessed sill conditions.

Similarly, the doors lack head flashings and proper threshold pan flashings, thereby increasing the chances of leakage at the doors and the surfaces below them, including at the north and south balconies and at grade to the interior floors.

REPAIRS

Based on the extent of reported leakage, we limited the repair design to the building facades and did not include roofing. After understanding the current enclosure's shortcomings, we reviewed the environmental factors at play at this geographical location and incorporated them into a robust repair design. We summarize these environmental factors—precipitation, wind, and fire—below.

Given the pervasive nature of the water intrusion and extensive damage, we recommended removing the existing cladding and replacing framing as required on the entirety of the west elevation. Because the other elevations had limited damage, and to limit the scope of the project, we recommended replacing windows and window perimeter flashing due to the limited remaining service life of the windows and the workmanship issues we observed at window flashings on the west elevation. We assumed that all of the windows are likely prone to the same issues, though leakage has not yet manifested at these locations.

PRECIPITATION

Templeton, California, generally experiences mild winters and dry summers. The rainy season is typically between November and March. According to neighboring Paso Robles's records, the yearly total rainfall between the fall of 2000 and the spring of 2022 was, on average, 13.7 inches (Paso Robles Daily News, 2025). Between the fall of 2022 and the spring of 2024, the yearly total rainfall averaged 25.1 inches.

According to the National Oceanic and Atmospheric Administration (NOAA), the increased rainfall volume was largely driven by multiple atmospheric rivers over the central coast. An atmospheric river is a flowing column of condensed water vapor in the atmosphere. While these

systems can vary significantly in size and intensity, the average atmospheric river transports a volume of water vapor roughly equal to the flow of the mouth of the Mississippi River (NOAA, 2025). According to research by the U.S. Geological Survey (USGS), while the frequency of atmospheric river events is not expected to increase, due to warming temperatures, their intensity is (USGS, 2021). As a result, it is imperative that designers develop enclosure systems capable of withstanding more severe rainstorms. We addressed this by specifying the following air/water-resistive barrier and drainage plane, and head and sill pan flashings.

Air- and Water-Resistive Barrier and Drainage Plane

The CBC requires a water-resistive barrier; Section 2510.6.1 Dry (B) describes an acceptable compliance path for a water-resistive barrier as being two layers of Grade D paper. However, under prolonged exposure to severe weather, as experienced on this site, building paper deteriorates, compromising its effectiveness and increasing the risk of leakage over time. Given the heavy rain exposure anticipated at this project, we determined that it was imperative to specify a more robust air- and water-resistive barrier (A/WRB) membrane to improve long-term performance. To accomplish this, we specified an enhancement to the CBC: a self-adhering, vapor-permeable A/WRB membrane.

The 2022 editions of the CBC and CRC include a new requirement to incorporate a drainage plane under cement plaster for Marine Climate Zones, which includes Climate Zone 4, where this house is located. Based on the building's significant damage on the west elevation, we incorporated a drainage plane for that elevation (Figure 4). For the other elevations, due to the comparatively minor damage, we incorporated only local repairs at windows, doors, and transitions using the same A/WRB membrane. To keep the adjacent cement plaster assembly in plane, the installation of a drainage layer is not feasible.

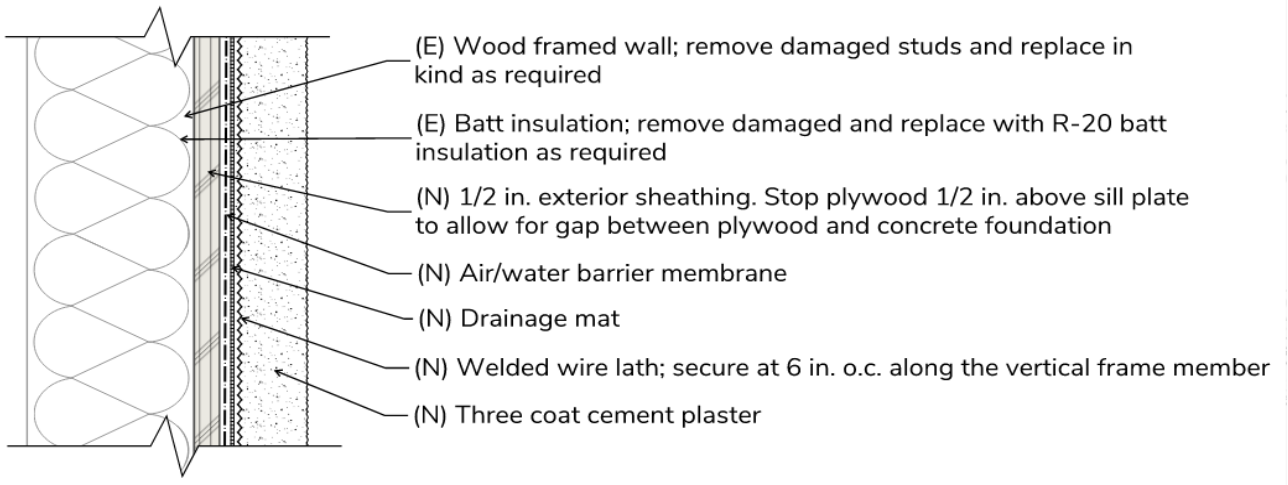

Figure 4. Typical cement plaster wall assembly with drainage.

Head and Sill Pan Flashings

A key omission in the original installation, as noted above, is the lack of sheet metal flashings at windows and doors. Section 1404.4 of the CBC requires that flashing be installed at the perimeters of exterior door and window assemblies to prevent moisture from entering the wall or to redirect that moisture to the surface of the exterior wall finish or to a water-resistive barrier. The CRC has similar requirements in Section R703.4.

To meet CBC and CRC requirements, we designed through-wall sheet metal head flashings integrated as drip edges above the windows (Figure 5) and doors, soldered sheet metal sill pans (Figure 6), and threshold flashings at the windowsills and door thresholds.

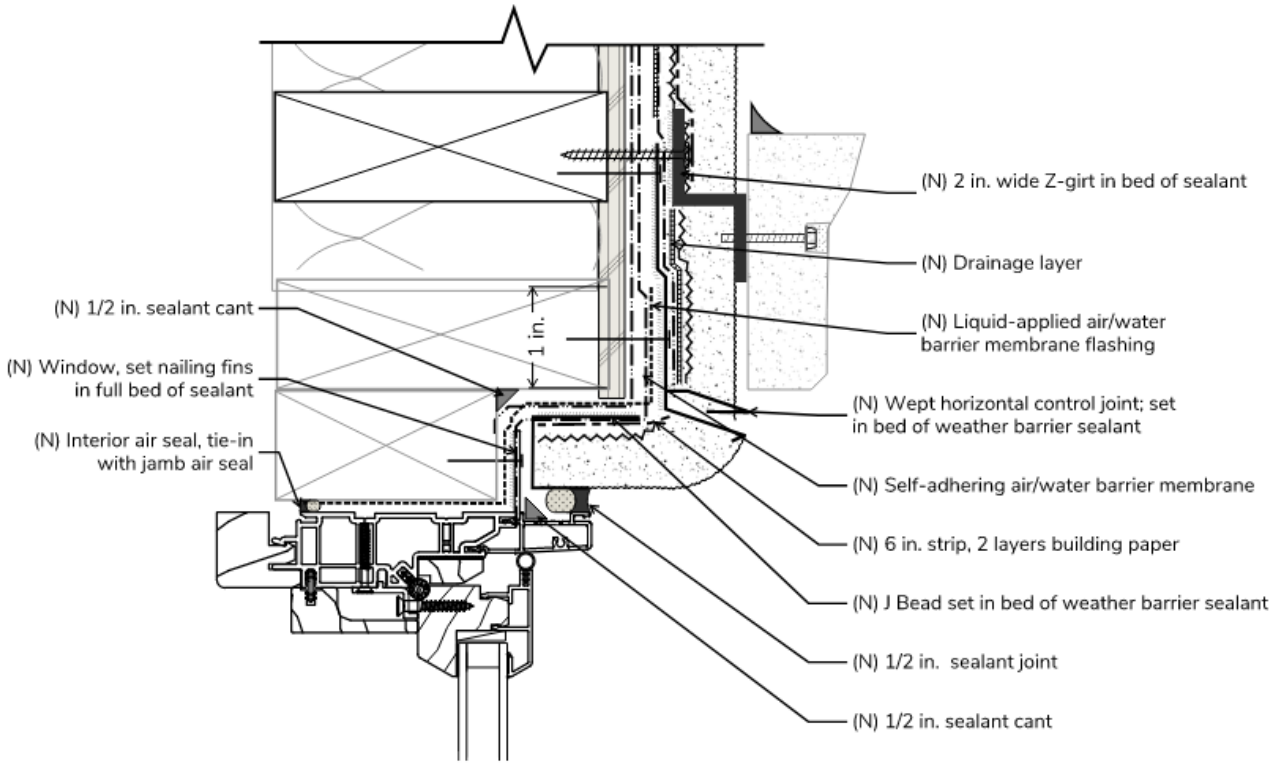

Figure 5. Typical window with head flashing.

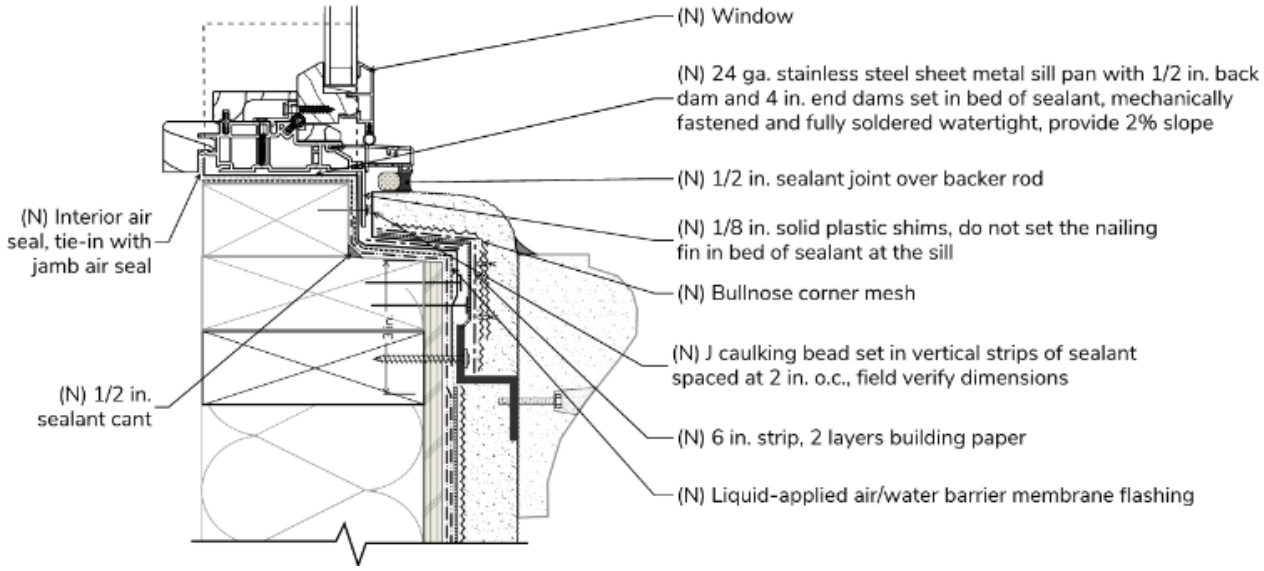

Figure 6. Typical window with sill pan flashing.

WIND

While the city of Templeton generally experiences moderate wind speeds, the homeowner reported significant winds at the property, likely due to localized speed-up effects from the home's position on an escarpment.

Our wind design calculations support the homeowner's account. The CRC describes the wind design calculation process, which draws heavily from the Components and Cladding method described in ASCE 7-16, Minimum Design Loads for Buildings and Other Structures. These calculations inform designers of the wind uplift pressure at which a non-structural building component and its attachment can withstand without failure.

The calculations consider several provisions, including, but not limited to, wind speed, exposure category, and topographic wind effects. As described in the CBC, topographic features, such as hills and escarpments, can increase the basic wind speed depending on their height, slope, and any obstructions.

Given that the subject home is located at the top of an escarpment (Figure 7), the code requires that a modified (increased) ultimate design wind speed be used in the calculations. This resulted in the calculation of higher net design pressures.

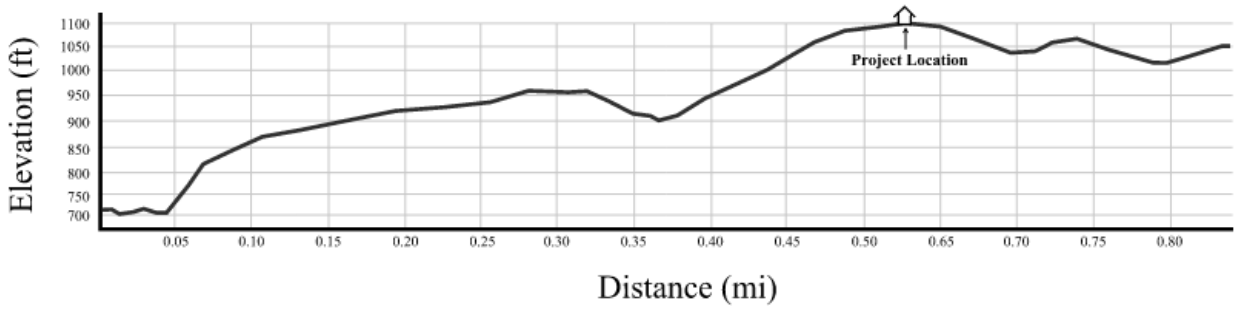

Figure 7. Topographic feature elevation graph (adopted from Google Earth).

The net design pressures are used to determine the rating for fenestration or the Performance Grade (PG) using FGIA/WDMA/CSA 101/I.S.2/A440:22, North American Fenestration Standard/Specification for Windows, Doors, and Skylights. The PG rating indicates the fenestration's ability to resist weather conditions, specifically wind and water. Therefore, elevated design pressures due to the location on the escarpment increased the PG requirements for the specified windows and doors on the project. We specified windows to have a PG of 50 PSF to meet these requirements.

FIRE

While the building enclosure failures for this project were not fire-related, it is imperative to address the severe and growing risks fires pose to homes. According to the National Aeronautics and Space Administration (NASA), wildfires could increase in frequency and intensity as global temperatures continue to rise (NASA, 2024). While wildfires have been particularly devastating to California homes in 2025, this is far from being just a problem for Californians. The Federal Emergency Management Agency (FEMA) reports that over 60,000 communities in the United States are located in Wildland-Urban Interface (WUI) Fire Areas.

The subject house is in a WUI zone. The CRC defines WUI as a geographical area identified by the state as a "Fire Hazard Severity Zone" or other areas designated by the enforcing agency to be at a significant risk from wildfires. California is followed by Texas, Florida, North Carolina, and Pennsylvania for the greatest number of homes in WUI zones (FEMA, 2022).

The CRC establishes minimum standards for buildings located in WUI Fire Areas to resist flame or burning ember intrusion during vegetation fires and to reduce conflagration losses, including but not limited to the following glazing and vent requirements, which are applicable to this project.

Glazing
Section R337.8.2.1 of the CRC requires that exterior glazing

> (1) be constructed of multi-pane glazing with a minimum of one tempered pane meeting the requirements of Section R308, Safety Glazing,
>
> (2) be constructed of glass block units,
>
> (3) have a fire resistance rating of not less than twenty minutes when tested according to NFPA 257, or
>
> (4) be tested to meet the performance requirements of SFM Standard 12-7A-2. For this project, we specified that the exterior glazing be fully tempered.

Vents
Section R337.6 of the CRC describes guidelines for vents, including requiring vents to resist building ignition from the intrusion of burning embers and flames. Vents are considered fire resistant when tested in accordance with ASTM E2886, Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement. Such vents are readily available and necessary for projects located in areas vulnerable to wildfires.

CONCLUSION

Extreme weather events are becoming more frequent and severe, and North Americans are building homes in increasingly vulnerable areas, resulting in increased environmental loads on residential building enclosures. As a result, designers must be informed of evolving code requirements and necessary enhancements to the code requirements to improve enclosure performance. Code and prudent design considerations for this project required including the following:

- Dedicated A/WRB
- Drainage layer
- Head and sill pan flashing
- Fully tempered windows that can meet the net design pressures
- Fire-resistant vents

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Scaling Deep Energy Retrofits: A Strategic Path to U.S. Housing Energy Affordability

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ABSTRACT

The energy affordability of new housing has increased dramatically over the past decades. This is evident observing the latest residential energy code enclosure requirements are equivalent to those specified by voluntary high-performance home certification programs administered by the federal government. These include ENERGY STAR Certified Home, DOE Efficient New Homes and Indoor airPLUS. Beyond energy efficiency, the 350,000-plus homes certified to these programs in 2024 also include comprehensive building science control layers, quality-installed comfort systems and whole-house ventilation. While significant innovation is still needed to enhance energy affordability, disaster resistance and productivity, new housing in America has made impressive strides reducing the energy burden and enhancing wellness. But as they say, "existing homes are different" (whoever they are). In fact, progress has been glacial scaling deep energy retrofits. This lack of market adoption is often attributed to significantly greater challenges related to high costs, complexity, market fragmentation, and quantifying value for existing homes energy upgrades compared to new construction. Meanwhile, our ageing housing stock is woefully substandard with 85% of all existing homes constructed before 2000 when the energy codes were about 60% less rigorous than today. The Oak Ridge National Laboratory has engaged an outstanding and diverse group of high-performance housing experts to identify an optimized investment plan for scaling deep energy retrofits historically defined as an energy efficiency upgrade level at least 50 percent better than a home's, or similar home's, historic energy consumption. The unique process utilized was to strictly focus the expert group on critical barriers to scaling innovation and key fundamentals for leading change. This paper will present the project methodology and initial recommendations for scaling deep energy retrofits by 2035. The prize from transforming the U.S. housing stock in terms of economic growth, creating a vibrant new American industry, and greater energy security are too big not to get this right.

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WHY SCALE DEEP ENERGY RETROFITS

Our nation has approximately 85 million single-family attached and detached homes out of a total 133 million occupied units in 2023. However, they are significantly substandard compared to the latest energy codes. This is based on recent data showing approximately 85% of the U.S. housing stock was constructed before the year 2000 including 60% built before 1980 and 35% built before 1970. As a result, there is a profound performance gap with new homes constructed to the latest versions of the International Energy Conservation Code (IECC) and the vast majority of our nation's housing stock. This is based on the approximate 60% gap in normalized energy use between homes constructed to the 1983 Model Energy Code (MEC) and 2021 IECC shown in Figure 1. Normalized energy is determined by modeling annual energy consumption of a prototype building and dividing by its floor area with a home constructed per 1975 code requirements set as a reference of 100.

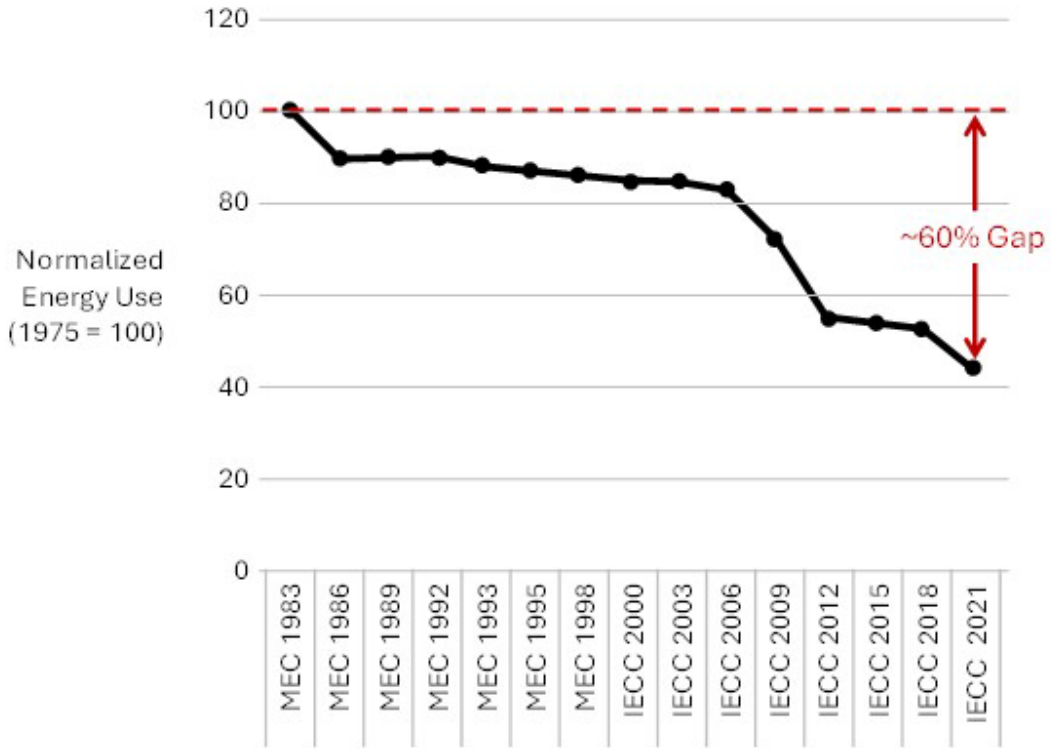

Figure 1. Energy use for residential model energy codes (1983 – 2021).

Simplified analyses reveal that transforming energy affordability for the 85% of single-family attached and detached homes constructed before the year 2000, approximately 73 million homes, would provide impressive benefits including:

• **~$35+ billion annual utility bill savings**
(73 million single-family homes x $1,884 energy bill/yr. x 52% energy for heating and cooling x 50% estimated reduction in heating and cooling loads)

• **~$60+ billion/year home energy upgrade industry added to U.S. economy**
(3 million upgrades/yr. mature retrofit market x $20K average retrofit cost)

• **~360,000 - 900,000 jobs with low risk of outsourcing and AI replacement**
(3 million retrofits/yr. x $20K/avg. retrofit cost /6-15 jobs per $1M invested)

• **~20% electric peak demand reduction increasing grid reliability**
(73 million single-family homes represent 55% of total housing units accounting for 50% peak demand)

PROBLEM SCALING DEEP ENERGY RETROFITS

Progress scaling deep energy retrofits has been glacial, including one study documenting rates of whole-building deep retrofits in the U.S. well below one percent. The inability of past programmatic efforts to achieve meaningful market adoption has been attributed to several key barriers including:

• High costs

• Complex projects

• Perceived risks

• Extensive disruption

• Unfamiliar work scopes.

If the substantial economic, affordability and grid security benefits from scaling deep energy retrofits are to be captured, a new path is needed.

SOLUTION TO SCALING DEEP ENERGY RETROFITS

In contrast to the substandard existing housing stock, there has been an impressive market transformation to high-performance new homes over the past 30 years. This is evidenced by the IECC 2021 serving as the baseline enclosure requirement for the primary federal government voluntary high-performance home certification programs: U.S. Environmental Protection Agency (EPA) ENERGY STAR Certified Home and Indoor airPLUS, and U.S. Department of Energy (DOE) Efficient New Homes (formerly Zero Energy Ready Home). Beyond energy efficient performance, the 350,000-plus homes certified to these programs in 2024 included

comprehensive building science control layers, quality-installed comfort systems and whole-house ventilation.

This high-performance new home market transformation can be attributed in large part to the impact of the voluntary ENERGY STAR Certified Home program. This is evident from the strong correlation between increasing requirements from Version 1 introduced in 1995 to Version 2 in 2006 and Version 3 in 2011 with the significantly increased rigor of the IECC codes starting in 2006 as shown in Figure 1. Currently, the latest versions of the IECC are being adopted or in the process of being adopted nationwide. This includes all states with a statewide residential energy code and major municipalities in the few states without one. Thus, a high-performance enclosure is rapidly becoming standard for new housing.

As a result of ENERGY STAR Certified Home's transformational impact on high-performance new homes, it is considered an impressive example of what is working and worth emulating for scaling housing innovation. However, this requires clarity about the implementation strategies that enabled the program's exponential growth. This is the subject of a prior research paper by the author during his tenure as National Director of the program. A key finding was an observation that ENERGY STAR Certified Home program effectively addressed critical factors to scaling innovation identified in a seminal work on moving new technology beyond early adopters and into the lucrative mainstream market. These factors were based on the finding that the smooth curve commonly used to depict market diffusion of innovation is a myth. Instead, the curve has a deep chasm in the transition between early adopters and mainstream users, attributed to profound differences in their behavior profiles shown in Figure 2. Where innovations do not cross this chasm, growth tends to flatline as shown by the dotted line.

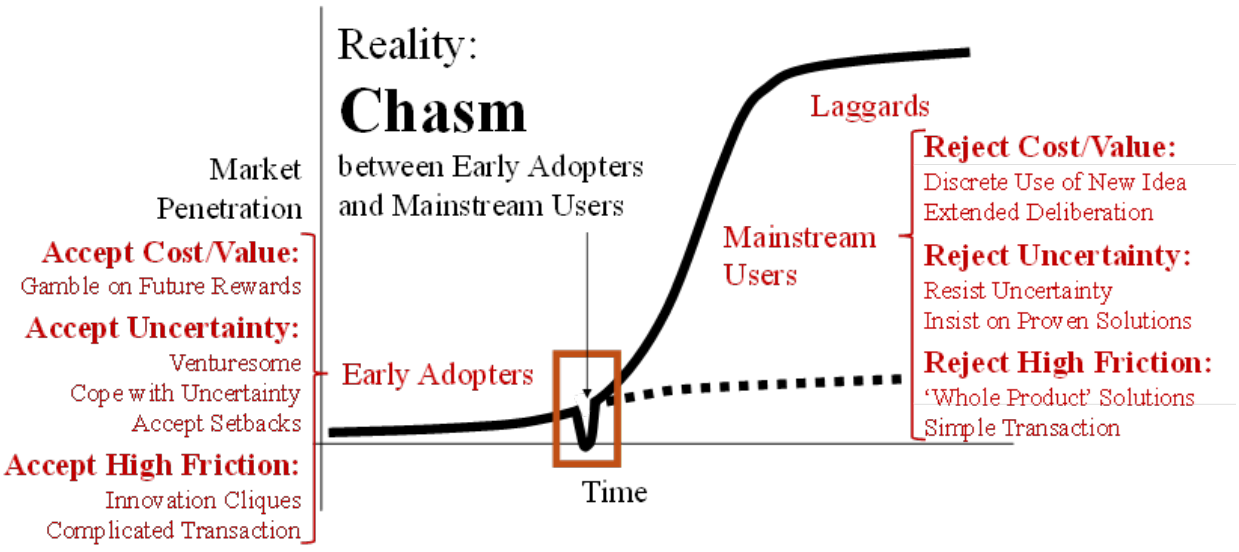

Figure 2. Market diffusion curve for innovation. Source: Moore, G. (1995). *Inside the Tornado*, Harper Collins. New York.

The author has curated the behavior differences between early adopters and mainstream users into the three critical scaling factors shown in Figure 2:

- **Cost/Value**: user willingness to accept the cost based on perceived value,
- **Friction**: user willingness to accept any real or perceived extra burden, and
- **Uncertainty**: user willingness to accept any real or perceived additional risks.

An assessment of the key implementation strategies leading to the success of ENERGY STAR Certified Home suggested all three scaling factors were effectively addressed, although more by instinct and constant iterative changes than awareness of the market diffusion chasm concept. Two leading change fundamentals were also instinctively applied and had a substantial impact on ENERGY STAR Certified Home's success. They were identified from additional research as "shrink the change" and "build on what's working" (a.k.a. "bright spots").

The key principle behind "shrink the change" is to avoid overwhelming mainstream users with too big a change and risk never start scaling. Instead, the goal is to strategically shrink the change to a level that provides a runway to reaching the larger goal. Applying this strategy, ENERGY STAR Certified Home assessed the level of home performance upgrades compatible with mainstream builders and used the findings to set the initial program requirements. As the program gained traction, it would incrementally build to the much more comprehensive high-performance home target being advocated at its inception by leading building science experts. The resulting Version 1 program requirements introduced in 1995 provided a strong foundation for growth including building a critical infrastructure for verification with Home Energy Rating System (HERS) ratings and introducing the housing industry to the impressive business case applying low-hanging fruit innovations (e.g., duct sealing, low-E windows). Over 15 years there was steady progress to a much more comprehensive house building science market transformation with Version 3. This success may never have been realized or would have taken much longer without shrinking the change.

The key principle to "build on what's working" is to identify and leverage proven solutions rather than getting overwhelmed attempting to identify and fix all problems. The entire ENERGY STAR program applied this strategy by building on the huge success of its precedent voluntary partnership program at EPA called Green Lights. This program effectively motivated commercial and institutional building owners to voluntarily upgrade their lighting systems with a two-step process. First, staff rigorously researched building owners' financial criteria for making investments. Second, a compelling business case for lighting upgrades was effectively translated in terms building owners understood. Specifically, Green Lights asked building owners to assess their lighting systems and voluntarily commit to making upgrades that provided a 20 percent pre-tax return on investment. EPA's front-end research showed that lighting upgrades routinely met or exceeded this return on investment which far exceeded the financial threshold for mainstream building owners to invest in improvements. This example of what was working was invaluable to the success of the ENERGY STAR program across all product categories.

In the case of ENERGY STAR Certified Home, extensive customer discovery meetings revealed enhanced differentiation was the most compelling value proposition for prospective builder partners. As a result, program communication focused on the ability for builder partners to distinguish themselves as industry leaders able to meet the federal government's highest standards for home performance excellence. This differentiation was much more motivating than the energy bill savings they could promise potential buyers and met the threshold for getting initial builders to join this new program. That said, there was slow initial growth because of significant friction with the verification requirement from the nascent HERS industry at the time. However, after successfully nurturing a HERS supply chain, the differentiation benefit proved highly effective putting increasing pressure on builders to join the program to be competitive. The important lesson-learned is that ENERGY STAR Certified Home existed to reduce energy consumption in new homes, but its partners were engaged on their terms.

The solution chosen to develop a path for scaling deep energy retrofits was to assemble an effective mix of home energy upgrade experts and then extract their wisdom following a script based on these lessons-learned leading change. This led to three key desired outcomes:

- Solution for shrinking the change that doesn't overwhelm program implementers and homeowners

- Assessment of what is working that could be applied to scaling deep energy retrofits

- Prioritized list of cost-effective investments with the greatest impact and least risk mitigating scaling barriers (e.g., cost/value, friction and uncertainty) including both research projects and mutually reinforcing stakeholder activities critical to social change

SCALING DEEP ENERGY RETROFITS ROADMAP PROCESS

The first task was to assemble highly experienced experts representing a diverse array of home energy upgrade stakeholders. This follows the "getting the right people on the bus" concept identified as an essential practice with the most successful companies. The resulting distribution of participating experts includes representatives from research organizations, energy retrofit programs, advanced manufacturing, low-income housing, financing and insurance. With the working group of experts on board, the project moved forward in three phases (see Figure 3).

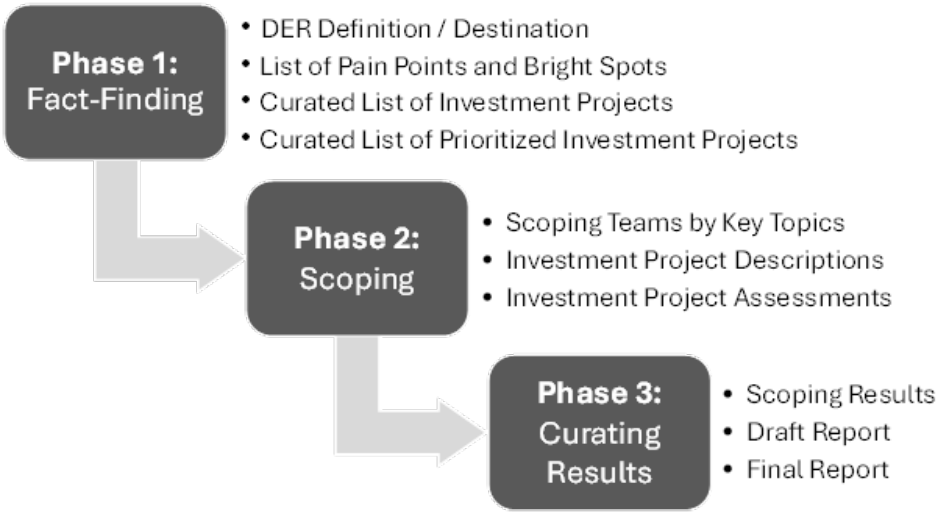

Figure 3. Scaling deep energy retrofit project phases and outcomes.

Each of these phases focused on extracting the wisdom of the expert working group with a Delphi Method type of process that strictly targeted the key factors for scaling innovation and fundamentals for leading change. The key objectives for each of these phases are as follows:

• **Phase 1**: Fact-Finding: Identify and prioritize investments that could contribute to scaling deep energy retrofits based on key pain points, critical scaling factors, and examples of what's working.

• **Phase 2**: Scoping Assessments: Organize the expert working group into teams to develop project descriptions for high-priority investments identified in Phase 1 and then assess them relative to their impact scaling, risk achieving specified deliverables, and cost.

• **Phase 3**: Curating Scoping Results: Curate the results of the scoping assessments from Phase 2 into a report identifying optimized investments to scale deep energy retrofits including research projects and mutually reinforcing stakeholder activities.

SCALING DEEP ENERGY RETROFITS RESULTS

A kick-off meeting established critical foundational elements for the project. This began by recognizing the term "Deep Energy Retrofit" is foreign to homeowners and needs to be much more user-friendly. Building on a strong homeowner interest in home renovations, the alternative term with the highest group approval was Home Energy Renovation.

Next the group collaborated on an equally user-friendly definition for this term. The current housing affordability crisis provided important context for this task. This is because the impact

of home energy renovation utility bill savings has shrunk substantially as homeowners struggle with exponentially greater expenses for mortgages, property taxes, and insurance. As a result, there was general agreement that a much more compelling value proposition would be the opportunity for homeowners to transform their existing homes, so they were no longer substandard. Secondly, the group acknowledged that a deep energy retrofit upgrade was too great a burden for a large majority of households and chose to shrink the change from one large intervention to an incremental path of upgrades. Thus, the definition of home energy renovation with the highest group approval is, a sequence of upgrades to the latest national energy code optimized for cost and related risks.

Then the group focused on a compelling destination (a.k.a., goal) for the path to scaling deep energy retrofit project that would inspire the greatest stakeholder interest. Home energy retrofit initiatives have historically focused on a percentage energy savings target (e.g., recent DOE Affordable Home Energy Shot goal of 20% energy savings) which were not considered adequately emotional as exponentially increasing housing costs continues to shrink the impact on total household expenditures. To meet the challenge, the group identified other highly successful project destinations that were worth emulating because they captured the public's imagination with much greater clarity and emotion. These included:

- **NASA Apollo Program**: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth." -John F. Kennedy, 1961.

- **DOE SunShot Initiative**: "Reduce the total costs of solar energy by 75 percent, making it cost competitive at large scale with other forms of energy without subsidies by the end of the decade. This cost reduction corresponds to utility-scale solar costing approximately $1 per watt or $0.06 per kilowatt-hour, making solar energy a possibility for millions of Americans." -DOE Official Initiative Launch, February 4, 2011.

The expert working group also recognized it needed to shrink the change to only focus on low-rise single-family homes to avoid substantial program complexity coordinating very different energy upgrade solutions and supply chains for single- and multi-family housing. The resulting project destination is millions of low-rise residences are on an optimized path of upgrades to the latest energy code each year by 2035.

With the change shrunk and critical foundational elements established, the process shifted to one-on-one interviews. These detailed discussions were used to identify pain points blocking the scaling of deep energy retrofits, what was working that could be applied to scaling deep energy retrofits, and investments that could mitigate these pain points and leveraging what was working. All the results of the interview findings were curated according to the three critical scaling factors: cost/value, friction, and uncertainty. A summary of the interview results include:

- 40 pain points,

- 34 examples of what's working for consideration,
- 17 off-the-shelf resources that might be useful, and
- 46 recommended investments.

The initial list of investments was then used as a basis for the group to reconvene for a second meeting to identify a prioritized list of investments that were most worthy of investment. That resulted in 26 high-priority investments ready for more detailed scoping assessments and the "Fact Finding" phase was now complete.

At the time of writing this paper, the 26 prioritized investments have been curated into four topics, and the full expert group has been divided into four teams to collaborate on scoping assessments. This entails writing descriptions for each investment project per an agreed upon one page template and then meeting in groups to assess each project relative to its impact scaling deep energy retrofits and risk of success achieving identified deliverables. A "1 to 10" scoring systems was used where a "1" denotes no impact or extremely high risk and "10" denotes very high impact or minimal risk. In addition, the groups will agree on an estimated cost for each investment. The results will be graphically laid out on a four-quadrant diagram as shown conceptually in Figure 4.

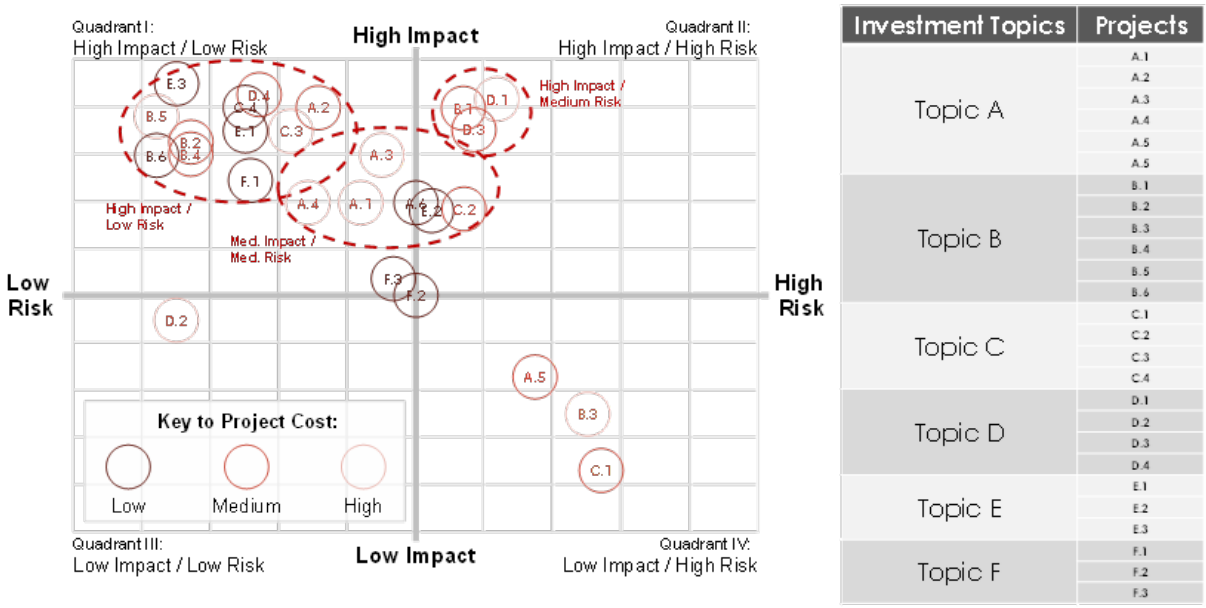

Figure 4. Four-quadrant diagram concept for displaying scoping assessment results.

Each project is numbered and located on the diagram based on its impact and risk assessment score. The cost for each investment will be depicted with dark, medium and light color circles

that denote high, medium and low cost respectively. The four-quadrant diagram is intended to make it easy to identify the most affordable projects with the greatest impact and least risk that will be highlighted in the final report.

CONCLUSION

Work is in progress to identify specific investments for scaling deep energy retrofits with the highest impact and least risk. Initial findings worth highlighting from the progress to date organized by key scaling factors and leading change fundamentals include:

- Scaling Factors:

  Mitigating cost/value barriers will require innovations that reduce the cost of home assessments, develop cost-effective paths for incremental upgrades to the latest energy code, reduce regulatory burden, improve cost-effectiveness of key energy measures, and leverage industrialized manufacturing for housing typologies conducive to larger interventions.

  Mitigating friction barriers will require investments in mutually reinforcing activities related to financing, messaging, programs, and transaction solutions.

  Mitigating uncertainty barriers will require investments ensuring home energy renovations deliver value understood by all stakeholders, provide consistent performance, and are accessible from a reliable supply chain.

- Leading Change Fundamentals:

  Shrinking the change will require alternatives to complex and costly single deep energy retrofit interventions by developing regionally specific paths of incremental upgrades to the latest energy codes.

  Building on what's working will entail addressing four key observations:

- There are no examples of successful deep energy retrofit programs that can be directly emulated. This includes the Energiesprong program that has met significant challenges maintaining funding even with over 10,000 homes retrofitted across Europe and North America.

- Significant lessons learned from ENERGY STAR Certified Home's impact transforming the new housing industry are worth emulating.

- There is a vast home improvement infrastructure performing millions of upgrades each year related to energy efficiency that should be leveraged (e.g., windows, siding, insulation, HVAC, plumbing, electric).

• There are elements of what is working with existing energy retrofit programs and tools possibly useful to scaling deep energy retrofits.

Investing in this strategic path to transforming the U.S. housing stock represents a huge opportunity to improve the lives of Americans, the economy, and grid security. This has been the dream of many past initiatives. The hope is that leveraging proven strategies for crossing the market diffusion chasm and leading change fundamentals will ensure success where past efforts have not gained meaningful traction. This paper lays out a process and initial results for how that can be done. However, it can succeed only if it effectively informs a common agenda embraced by a broad array of stakeholders vested in home energy upgrades.

If this effort is successful, a lot of attention should be paid to the Delphi Method type process that was utilized. The insights gained by listening and collaborating with outstanding experts to harness the synergy of their collective wisdom is an invaluable resource that could be applied to a wide range of other vital challenges. And there is no shortage of them.

ACKNOWLEDGMENT

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Social Housing Refurbishment in Italy: Identification of Targeted Interventions Based on a Multiscale Approach for Improving Sustainability and Energy Efficiency

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ABSTRACT

The paper is based on the experience developed in the field of the environmental design course at the Department of Architecture, University of Ferrara, with the cooperation of ACER, a public body that owns and manages social housing in the Emilia Romagna Region, Italy. Social housing built in the second post war period (1960-80) is a very poor building stock: no or very little insulating materials and single-paned deal window frames were used in buildings without paying any attention to saving energy, especially because of the deficiency of technical standards and building regulations. Moreover, a lack of identity, marginalization, and low architecture profile characterize this building segment. The objective of this paper is to propose a multiscale approach for the refurbishment of post-war social housing stock, based on a list of indicators derived from the most common environmental protocols (e.g. LEED), emphasizing the importance of a sustainable approach in renewal actions.

Three case studies have been examined with the main aim of improving architectural quality, social life, and energy performance, following the new European Energy Standards for energy savings.

A multiscale approach is starting from the urban area (improving water permeability, reducing heat island, collecting water from rain) then, as the energy failures in existing buildings are mainly due to low efficiency of the envelope, a list of intervention techniques to upgrade existing envelopes in the direction of passive solar gain, natural cooling, and other relevant sustainable technologies for building envelopes.

INTRODUCTION

In the European Union (EU) the building sector accounts for almost 40% of the total global energy-related carbon dioxide emissions (CO2), among which 17% is caused by the existing residential stock, also responsible for around a quarter of the final energy consumed (Ma et al., 2012). Social housing is a very extended segment of post war building stock, that is characterized by very poor architectural and technical quality: dwellings often lacking natural lighting and ventilation, poor insulating materials, and single paned deal window frames were used in buildings without paying any attention to saving energy especially because of the deficiency of technical standards and building regulations (ENEA, 2021). Moreover, a lack of

identity, marginalization and low architecture profile characterizes this building segment.

The renovation of public housing is one of the main activities of ACER (Azienda Casa Emilia Romagna), a company that manages a portfolio of public housing owned by municipalities, which in many cases requires upgrading interventions in which the overall quality and energy efficiency of existing buildings is evaluated though large-scale intervention instead of single-building approaches.

The 2010/31/EU Directive (IEA, 2010), for the first time, included the need to look for high-performance design and technological solutions to direct the building sector towards "balanced" construction solutions and options. For this purpose, the EPBD recast principles and minimum requirements for the energy performance of buildings, which member states are asked to re-define with a view to achieving cost-optimal levels.

Recently, as the renovation of existing buildings represents a major challenge towards the transition to sustainable cities, the EU Directive 24 04 2024 Green Houses Directive, addressed the importance of upgrading existing building stock, improving limits for energy performance and promoting incentives, especially in those urban areas where the poor quality of structures often determines social conditions of hardship and unlivable spaces (European Commission, 2024).

In this paper, the analysis concerning the renovation of a current segment of Italian social housing stock, in the Emilia Romagna region, have been carried out to identify targeted routes addressed to the development of suitable refurbishment planning for designers and stakeholders.

The main objectives at the center of the study are:

- The definition of refurbishment actions based on the architectural, typological, and technological characteristics of the buildings.

- The definition of KPIs and description of a catalog of design actions (social, architectural, technological) to be undertaken on existing buildings for sustainable and resilient buildings.

- The definition of a multiscale check list of design actions for evaluating the impact of the aforementioned project actions through the assignment of a summary score aimed at improving overall building sustainability and quality (architectural features, sustainably reducing consumption and increasing efficiency).

- The testing of the above-mentioned actions on three case studies selected from the ACER real estate portfolio.

The study aims to propose a multiscale approach based on a list of indicators that can guide a refurbishment action: starting from the urban area (improving water permeability, reducing heat

island, collecting water from rain), to architectural features (dwelling compatibility, orientation, natural cooling), intervention techniques (passive solar gain, insulation), and active measures (renewable energy) to reduce energy consumption and improve the global quality of the site.

METHODOLOGY AND CASE STUDY SELECTION

The cooperation between ACER and the department of architecture of Ferrara began at the beginning of 2025, promoted the analysis of three case studies in the province of Ferrara and proposed a package of actions to improve the overall quality of the buildings.

For refurbishment planning, suitable tools are required for the choice of more recommended interventions in the direction of a deep renovation. A multiscale model, derived from the most popular environmental protocols literature review (European Commission, EPBD; Green Building Council; BREEAM) has been developed, by selecting a list of indicators grouped by families of intervention (Ma, 2012).

The novel objective of the present research project is to develop an open-access repertoire of strategies, solutions, and best practices for assessing sustainable and energy retrofit strategies, to help obtain valuable information for addressing the urgently needed renovation of existing social housing buildings in Italy and, in particular, in the Emilia Romagna Region.

The methodology proposed aims to find multiscale social housing retrofit strategies by addressing literature on environmental protocols on existing social housing block typologies. The research helps regional decision-making, allowing users, technicians and public entities such as ACER to choose the most suitable options for their specific needs.

The purposed building sustainability rating system is a voluntary system to assess the proposal of sustainable action, starting from site improvement to the overall environmental performance of buildings, through a comprehensive reference score that defines numerically the incidence of a determinate action to go toward a sustainable building.

The rating system is organized into four environmental categories: Site Sustainability, Energy and Atmosphere, Indoor Environmental Quality, and Materials and Resources. The achieved score level defines the sustainability optimization of the design strategies: from a basic score (minimum level of 40-49 points), to a medium level (silver score of 50-59 points), to a good level (gold score of 60-79 points), and finally to the maximum platinum level (80-100 points).

Following the checklist and the assigned score (Figure 1), a multiscale analysis was conducted on three reference building blocks representative of a typical Italian social housing building, widespread in disadvantaged areas, which are strongly energy-inefficient and require urgent renovation. After conducting a preliminary analysis of the building stock, the influence of different measures was considered by grouping in different scales of intervention that correspond to the following thematic areas:

- **Site scale**: requirements regarding promoting green mobility, green and common spaces to improve socialization and site, improving water storage and recycling, reducing heat island by using reflective and cool materials for roofs and flooring.

- **Architectural scale**: requirements regarding the enhancement of the architectural features by dwellings modifies according to orientation, solar shading, ventilation, spaces and other architectural inputs that can improve the quality of the apartments.

- **Technical and energy efficiency scale**: the enhancement of the building value with new materials, methods, and techniques, the use of passive strategies (to optimize the thermal behavior of the envelope, improve solar gain, avoid overheating, improve thermal inertia), and active strategies (renewable energies, highly efficient artificial lighting).

The methodology workflow is represented in Figure 2.

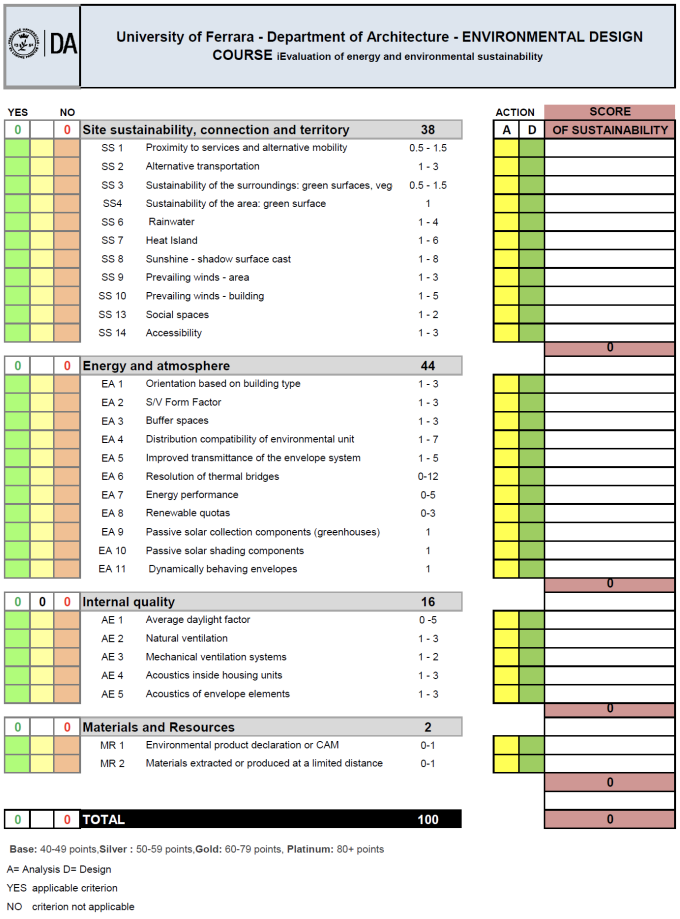


Figure 1. Checklist of indicators grouped by family for the evaluation of a sustainable affordable and efficient intervention on social housing stock.

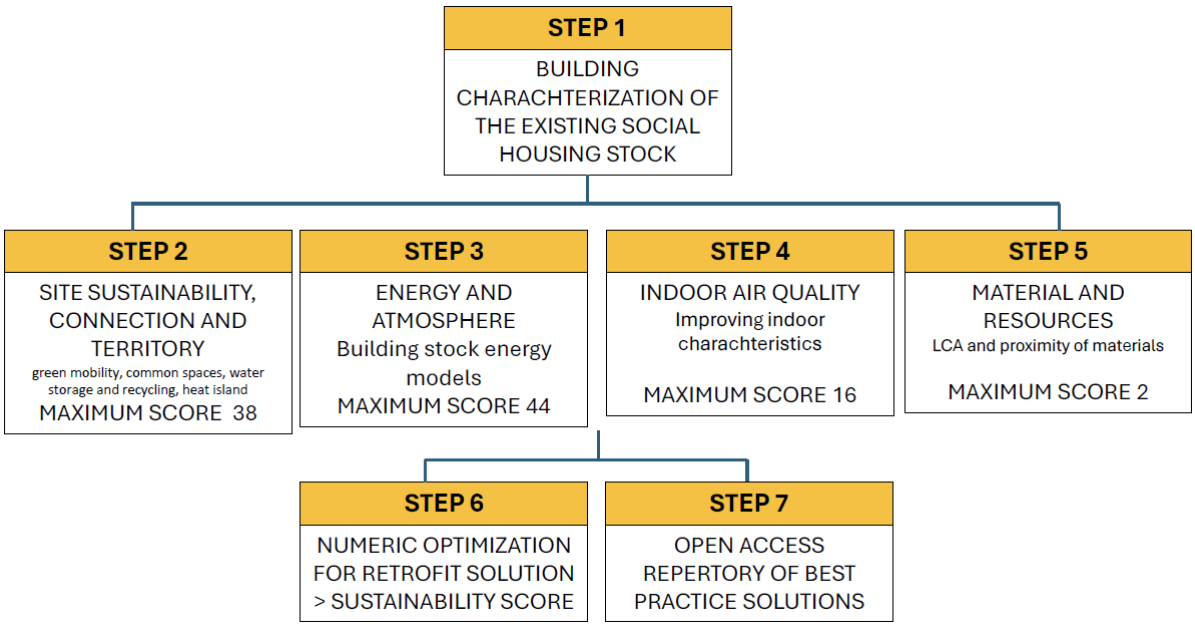


Figure 2: Work strategy of the methodology followed.

Case studies have been selected as representative of Italian building stock built between the 1950s and 1980s: low-rise and medium-rise apartment buildings, usually built in line and situated within densely populated surroundings. They are S. Giovanni, 1 Maggio, and via Fabbri, located in Ferrara, a small city in the north-centre of Italy. Italy is divided into six climatic zones, from north to south, from F (North) to A (south), and Ferrara is in the E zone, with the following climatic data: winter temperature -5 °C; summer temperature 32.2 °C; relative humidity in summer 45%; horizontal irradiance in the month of maximum sunshine 299 W/m2 (Brunoro, 2007). All are residential courtyards characterized by poor public and common space, mostly covered by asphalt, and minimal green areas with no place for green mobility (e.g. bike parking or electric vehicles). Building blocks are multifamily dwellings that have two or three apartments per floor, in total between 20 and 70 apartments. Heights range from two to four floors. The bearing structure is made of load-bearing brick walls, with plaster finishing or nude. No insulation is present either on the walls or on the roof. Windows are generally single-pane glass. Thus, an energy retrofit represents the most sustainable green option.

CASE STUDIES		
S. Giovanni building block. It is a complex of three linear building blocks disposed as an open courtyard.		
1 Maggio building block. It is a complex of three linear building blocks disposed as an open courtyard.		
Via Fabbri building block. It is a complex formed by diffused small buildings with 2-4 apartments and a central service space.		

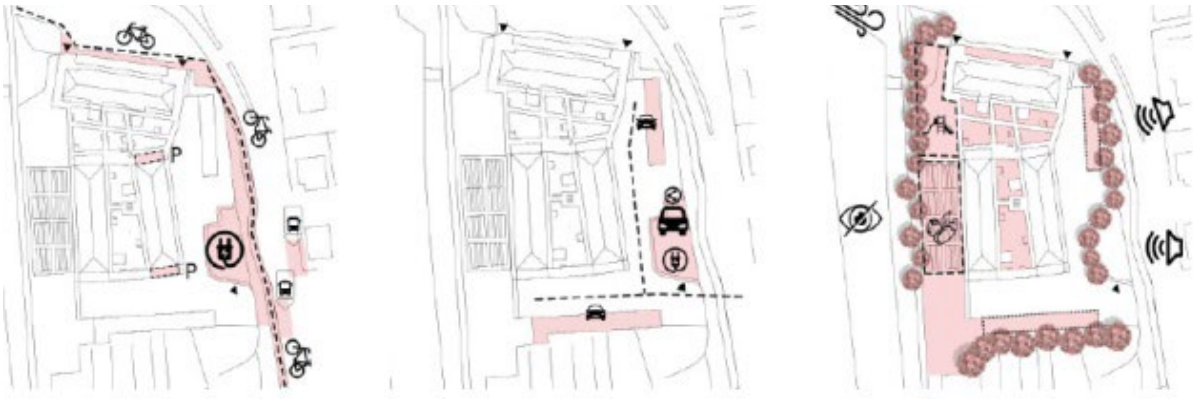
Figure 3. Social housing case studies in the province of Ferrara.

STRATEGIES OF INTERVENTIONS: FROM LANDSCAPE TO TECHNOLOGICAL SCALE

A multiscale approach for sustainability involves analyzing and planning for sustainability across different levels of detail, such as urban, architectural, and technical scale. To fulfill the objectives of sustainability, this methodology recognizes that environmental, social, and economic issues are interconnected across various levels, making it essential to consider integrated strategies to address challenges like urban development, resource management, and social life of inhabitants (Carbonari, 2012).

Landscape and architectural scale

The building's redevelopment is based on a careful analysis of the existing situation (Figure 4), identifying the specific requirements of intervention where the project would be most appropriate to address. Regarding the site's sustainability, connectivity, and landscape, interventions were promoted to improve sustainable mobility, increase soil permeability, and provide shared green spaces. Particular attention was paid to the creation of social and collective spaces, both internal and external, where residents can meet and socialize.



1. 2. 3.

Figure 4. S. Giovanni case study. Landscape analysis related to the sustainability indicators at the site scale. 1. Public transport 2. Green mobility 3. Green areas.

A new planimetric drawing summarizes the choices made in relation to the site analysis and the redevelopment criteria derived from the checklist. For S. Giovanni social housing complex, the choices made to improve site sustainability are summarized in Figure 5. By considering the proposed actions summarized in the overall score for the category Sustainable Site and territory is 32.

- Conversion of existing garages into covered bike storage.
- Extension of the bike path.
- Conversion of the existing driveway into green spaces and a cycle/pedestrian entrance.
- Two car-sharing stations = 5% for 40 parking spaces (one for each residential unit). Four electric car charging stations = 10% residential units with parking for electric scooters and bike sharing.
- Rainwater collection and treatment in underground tanks (two for each building) is planned in the large garden.

The permeability of the outdoor pavements will be improved through:

- Reducing the driveway space and consequently the use of waterproof or semi-permeable coatings.
- Application of semi-permeable materials for common areas and play areas. Adding green areas for lawns, flowerbeds, trees, and vegetable gardens.

- Rainwater collection and treatment in underground tanks (two for each building) in the garden. The collected and treated water will then be pumped and used to irrigate green areas and for reuse in toilets.

- Identification and design of common space both inside and outside the building for recreational, meeting and socializing activities.

Figure 5. S. Giovanni case study, new landscape design according to site sustainability, territory and connections indicators.

At the architectural level, interventions have been designed to reorganize the interior spaces and the building units to improve the optimal distribution of the various services and rooms. This package of intervention belongs to two different families: energy and atmosphere (requirement EA Ma 2012, International Energy Agency 2010, European Commission 2024) and indoor air quality (requirement AE Ma 2012, International Energy Agency 2010, European Commission 2024).

The redevelopment of the interior spaces considered comfort requirements related to the building's orientation, maximizing solar gain in certain areas and passively controlling heat loss (Figure 6). To improve the indoor quality, particular attention was paid to optimizing the natural lighting and ventilation of the individual residential units. This also included the placement of buffer spaces on the most unfavorable views. Bedrooms, bathrooms, and restrooms facing north, as these areas do not require a significant amount of daylight; also this allows for uniform lighting, avoiding the problem of overheating in summer. Living areas and kitchens facing south, maximizing solar gain during the day. These spaces enjoy ample sunlight in the winter months and overheat sun in the summer months (Figures 7, 8).

1

2

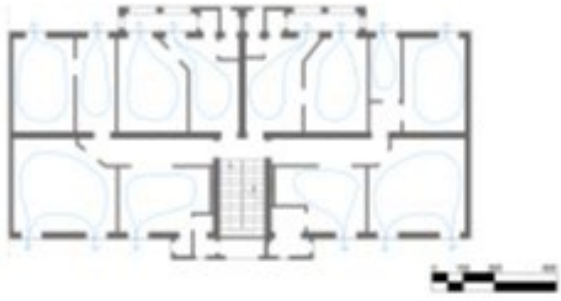


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Figure 6. 1 Maggio case study: sun path (1) and natural ventilation analysis (2, 3).

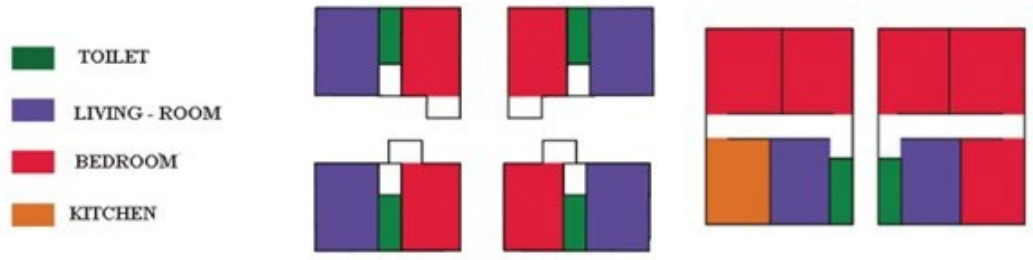


Figure 7. Via Fabbri case study: studies for the new architectural assets of the dwellings, to improve natural lighting and ventilation.

Figure 8. S. Giovanni case study: studies for the new architectural assets (1. current situation; 2. design). To optimize the dwellings orientation, the stairs have been moved on the north side. A new elevator has been added for accessibility.

Maximizing natural ventilation is obtained by ensuring views on opposite sides of the residential units, to promote cross-ventilation. The external residential units, positioned at the edges of the residential block, also have views on three sides, further promoting natural ventilation. Some two-room apartments feature movable panels instead of fixed partitions to further enhance ventilation inside. These modifications help the building control relative humidity and mitigate the effects of condensation. This package of intervention has been evaluated as follows: S. Giovanni 26, 1 Maggio 22, and via Fabbri 26.

Technological aspects and energy efficiency

Significant interventions have been designed to reduce existing thermal bridges and significantly improve the energy performance of the building envelope, including improvement of the overall U-value of the building using the ETICS system and the installation of a photovoltaic system on the roof, contributing to reducing primary energy requirements.

Passive Retrofit Actions
Main passive retrofit actions designed on envelope, are:

- Efficiency enhancement of existing envelope with external insulation solutions /ETICS) or internal, in the case of historical constraints on brickwork facades and insulation of roofs or attics and ground-floor slabs.

- Replacement of windows and doors with new frames with heat-insulating PVC profiles and double low-E glass.

- Installation, where possible, of a system for forced ventilation of homes with heat recovery and installation of solar thermal panels to produce domestic hot water where appropriate.

- Solar greenhouse design for terraces, designed to create a buffer space on the south side. In winter, when the solar greenhouse is closed, solar gain is maximized, thus reducing energy requirements. In summer, however, the greenhouse remains open to promote ventilation and shades the south side, protected by the horizontal overhangs of the solar greenhouse.

- Solar shadings have been designed to control the diffusion of the light through a glazing surface and to reduce the heat gain through an opaque wall system, allowing the incidence of the rays of sun during the winter, and this fact corresponds to a benefit for the overall thermal balance of the building. External solar shadings, windows elements (e.g. venetian blinds) and solar shadings for façade (e.g. lamellas or panels) are included. In south facades, where the sun is high on the horizon, horizontal shadings are more suitable. Particularly indicated in summer season, horizontal shading can hamper the rays of light in winter, therefore the use of adjustable or mobile systems is more suitable. Vertical solar shadings are more adapted for East and West oriented façades, where the sun is low.

Active Retrofit Actions
Main active retrofit actions, regarding plants and renewable energy, are:

- Replacement of the existing heating system: only the heat generator if a centralized system is present, all independent systems if not; new centralized heating system with independent metering; central heating system for each group of buildings; modular condensing boilers are used, allowing low operating temperatures and high efficiency at all operating modes.

- Addition of photovoltaic panels on the south and west facing slopes, for the partial compensation of energy consumption through renewable energy sources. The renewable sources included in the building cover 25% of the total requirement; the percentage is

lower than the 55% threshold established by the Italian decree of 08 11 2021 n.199, but it is admitted in a refurbishment intervention.

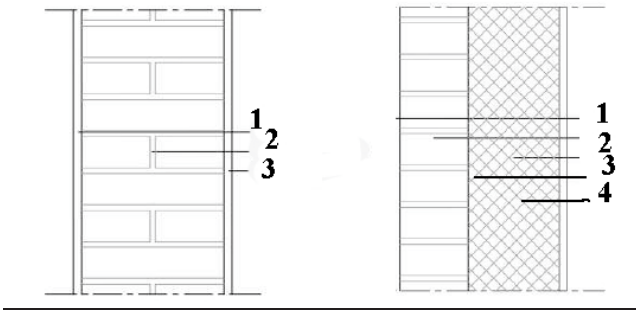
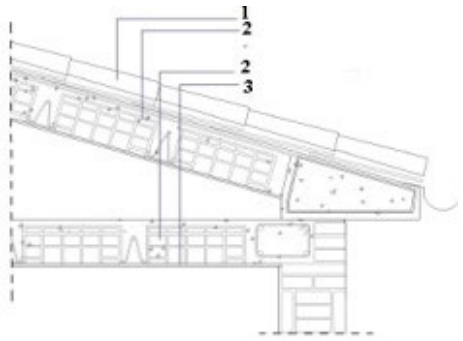
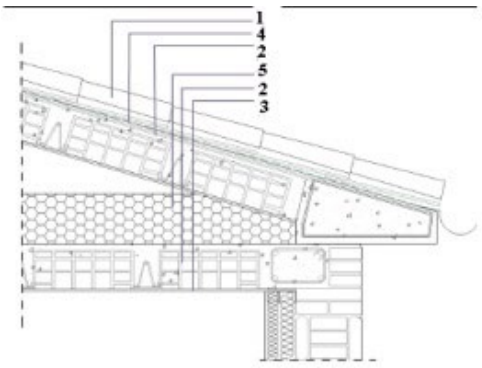
The U value in the current state is 1.5 W/m2K, while in the design state, it becomes 0.259 W/m2K, which represents an 83% reduction. Design solution is adding 14 cm of medium-density rockwool insulation panels, it is a mineral-based insulation material with a 60% recycled content and complies with recycling requirements, that are mandatory in Italy according to the Decree 23 06 2022 n. 256 [10]. 1.Internal lime and gypsum plaster 1,5 cm, 2. Brick 25 cm, 3. External plaster, 4 ETICS rockwool panel with final thin plaster layer	
In the attic, the U value of the existing roof is 2.076 W/m2K. In the design state, this value is reduced to 0.17 W/m2K, that represents a 91.7% reduction. This was made possible by adding 30 cm of cellulose flake insulation above the attic (blown in), which allows for rapid execution of the insulation project while also limiting its degree of invasiveness..	
Furthermore, cellulose is hygroscopic without losing its insulating properties, excellent in a climate like Ferrara's. It is a plant-based material, at least 80% recycled, recyclable, and meets recycling requirements 1.Clay tiles 2.Brick and concrete slab 3.gypsum and lime plaster 4. Waterproof sheath 5. Cellulose flake insulation	

Figure 9. 1 Maggio case study: passive retrofit actions on envelope, according to energy and atmosphere indicators EA5, EA6, EA7.

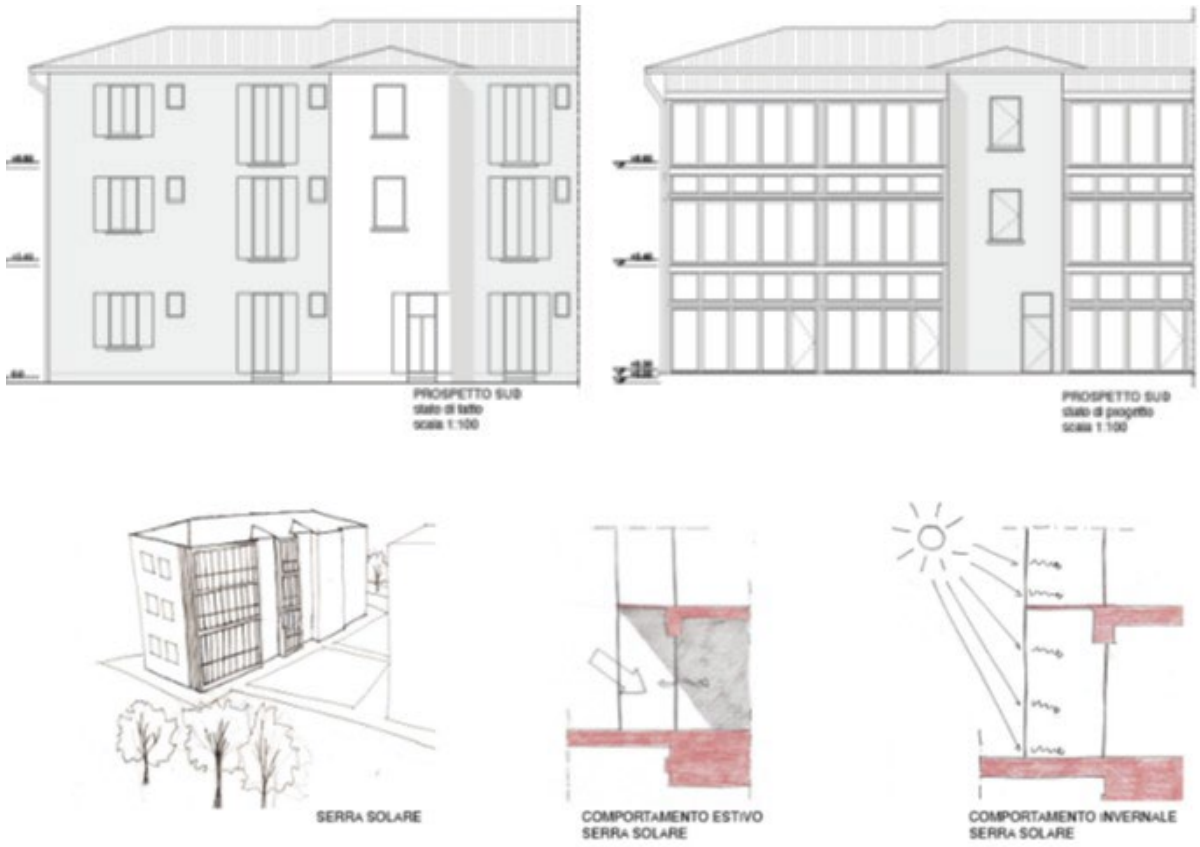


Figure 10. S. Giovanni case study: passive retrofit actions adding solar shadings and solar greenhouse (indicators EA9, EA10).

In all the three case studies, with the purposed actions the global energy performance has been improved, jumping from the G energy class (current energy performance: S Giovanni 280 KwH/m2 per year, 1 Maggio 340 KwH/m2 per year, via Fabbri 225 KwH/m2 per year) to: B energy class (S Giovanni 118 KwH/m2 per year), A1 energy class (1 Maggio 80 KwH/m2 per year , via Fabbri 82 KwH/m2 per year).

CONCLUSIONS

To achieve 2050 Climate Neutrality, building stock requires a multidimensional renovation process. This is particularly urgent in the most vulnerable households, with higher exposure to climate change, where this procedure should focus on cost-controlled passive measures. Given the complexity of identifying optimal strategies, it is urgent to improve the retrofitting process of the social housing stock to enhance its energy performance guaranteeing health and comfort for residents.

This study proposes a set of optimal retrofit packages, according to the environmental checklist for sustainable retrofits, applied to the most predominant building typology within the vulnerable social housing stock in Italy (linear block), focusing on one of the most representative climatic zone conditions in the country. The potentiality in terms of sustainability growth of city districts is very high, because these buildings, with similar characteristics, are highly energy inefficient and require urgent refurbishment.

A multiscale approach, derived from the most popular environmental evaluation protocols in the market, has been carried out: sustainable requirements, grouped by family of intervention and identified by a score, gives the line of intervention at three different scales. Weighting the action is helpful not only to define the importance of an action with respect to another, but also to find a priority in the case of partial intervention (guideline action tool.) On a large scale, the high potential to attain noticeable energy savings and improve quality of life (adding green areas, water, reducing allows improvement of the livability of the involved urban areas.

At the architectural scale, the main goal is to improve the quality of the dwellings according to the environmental parameters. An accurate analysis of the most effective environmental parameters, such as orientation, ventilation, sunshine, and shadings was functional to purpose internal modifications to have a better distribution of natural lighting and ventilation.

At the technical scale, the individual solutions resulting in the greatest improvement in the thermal performance of the blocks are related to the facade or roof. The latter option is typically more cost-effective in terms of implementation. However, the conclusions of this work can be further complemented by future studies that assess the incorporation of other relevant typologies (such as row or tower blocks) and the consideration of other climatic zones across Italy. The objective is to provide an open access archive of best practice intervention, based on the check list instruments, that can facilitate the development of a strategic renovation plan for the social housing stock, prioritizing solutions with a more consistent impact, corresponding to a higher score assignment.

This approach contributes to the achievement of sustainability goals, taking into account the specific characteristics of the typology for the climatic area.

ACKNOWLEDGEMENTS

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Use of Local Sheep's Wool for Building Insulation: Effect of Micron Count on Insulation Value

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ABSTRACT

To make building decarbonization efforts sustainable, material choice should seek to emphasize the re-use or waste source material. Reliance upon locally sourced materials can also provide advantages in shortening supply chains and preventing interruptions due to trade challenges. One opportunity for building decarbonization is the use of sheep's wool as an insulation material. Currently, several companies produce sheep's wool products, often from international sources. Virginia has the 19th largest state sheep herd in the United States, and there currently exists little to no market for wool from meat breeds of sheep. The purpose of this project was to investigate the use of local wool sourcing to produce insulation materials. Objectives included processing raw wool to insulation from local sources, and understanding the impact of micron fiber count on insulation value of the material produced. By better utilizing resources currently wasted in agricultural communities, building materials can be manufactured, potentially spurring new local industry opportunities.

Variables and Considerations in Designing Post-Occupancy Evaluations of Residential Energy Efficiency

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ABSTRACT

Post-occupancy evaluation (POE) has long been utilized to assess occupant comfort and to confirm that built conditions perform as designed. More often conducted in commercial construction, POE is valuable in residential construction for several reasons. Serving as a means of quality control, it evaluates whether the home meets design intent, performance projections, and specifications for metrics such as indoor environmental quality or energy efficiency. It also enables initial commissioning of equipment and systems as well as identification of malfunctioning systems. Furthermore, the results of post-occupancy evaluations can inform policymakers and stakeholders by providing actionable, quantifiable data.

To respond to the research objectives and yield usable results, the design of a POE must be carefully considered prior to the initiation of data collection. Variables and inputs must be tuned to yield desired outputs, with research questions framing the scope, means, and extents of data collection. Informed by multiple POE studies conducted by the research team, the paper will catalog considerations and variables—such as type of data, equipment selection, data uniformity, and subject coordination—as well as lessons learned. Utilizing these case studies, the paper will focus on key takeaways and considerations for development of future studies. Furthermore, the paper will posit on future utilization of POEs as technological innovations make data collection more accessible and affordable.

INTRODUCTION

Following project completion and occupant move-in, post occupancy evaluations (POE) provide valuable information regarding actual performance of the building relative to design intent. Evaluations can assess both quantitative and qualitative information (Meir et al., 2009); various audiences approach POE differently and use it to evaluate specific aspects of performance,

whether broad or in-depth (Leaman et al., 2010). For example, while facilities managers may assess measured energy consumption, indoor air quality, or if systems are performing as designed, designers or owners may investigate if the building is being used as intended or if goals for occupant comfort and usability are met. By no means a comprehensive list, numerous studies referenced provide literature reviews of post-occupancy evaluations surveying the different types of studies, a history of the tool, methods for conducting studies, and means of data collection and analysis (Meir et al., 2009; Leaman et al., 2010; Spataru et al., 2010; Agarwal et al., 2023; Elsayed et al., 2023). Wolfgang Preiser and his colleagues have also published decades of research on POE. Citing Preiser, Meir and team (2009) note that outcomes can have short-, medium, and long-term benefits: responding to particular solutions in the near term, informing the design and construction of future buildings through lessons learned, and contributing to the body of knowledge shaping policy and standards. Castano-Rosa and Nerweyi (2025) assert that the function and utility of POEs in shaping policy and residential design comes with a greater volume of studies conducted and a uniformity to the metrics by which a home's performance is evaluated in the study. Their study highlights a lack of POE [participation / studies] in portions of the world including North America which contributed only 8 of 104 publications analyzed in the review, compared to 42 from Europe and 38 from Asia. To effect change through POEs, more studies must be conducted within the particular cultural and legal frameworks of the United States.

Building upon previous studies cataloging the benefits and variables of POEs, this paper summarizes implementation of several POEs conducted across the U.S. by the research team, identifies practical considerations critical to generating useful empirical data, and distills lessons learned to inform future studies.

Assessment of a building's performance provides a means of ensuring quality control and evaluates if performance goals are being achieved. One aspect of assessment, equipment commissioning, provides the ability to identify and diagnose malfunctioning systems that might go unnoticed by occupants. In fact, the Pacific Northwest National Lab estimates that "about 60% of heating, ventilation, and air-conditioning (HVAC) systems have installation, commissioning, and performance problems, leading to as much as a 30% increase in annual energy consumption" (PNNL, 2023). Examples of identifying and diagnosing malfunctions have been recognized by the authors of this paper through circuit-level energy monitoring. In one case, the abnormally high energy consumption of a dehumidifier alerted the researchers to examine the unit, leading to the discovery of a faulty humidistat, which was subsequently repaired.

The basis of a post occupancy evaluation is data collection—which takes many forms— and subsequent analysis of that data in relation to the design benchmark. Kinds of data collection include measurements of objective data through monitoring or sampling, collection of subjective data by interviewing users, review of documentation, and field observation (Meir et al., 2009). Design of data collection is critical to the success of a research study. Many variables can affect the quality of data collected and, therefore, the findings drawn from it; if one aspect is problematic or if a data source is interrupted, the fidelity of data may be compromised.

This paper will lay out potential variables critical to the design of a post occupancy evaluation, particularly in residential buildings, identified through feedback generated from a series of research studies conducted by the authors and Auburn University Rural Studio (AURS). For most studies surveyed, POE focuses on how the user interacts with the building and how that behavior affects energy consumption (Meir et al., 2009; Castano-Rosa and Nerweyi, 2025; Elsayed et al., 2023; Agarwal et al., 2023; Gram-Hanssen, 2010). By comparison, the implementation studies considered in this paper seek to isolate the effect of envelope design on energy consumption, minimizing occupant behavior.

FOCUS ON RESIDENTIAL TYPOLOGY

Residential POE is of particular interest to the authors due to the opportunity for reduction in energy consumption: as the largest sector of retail electricity sales (U.S. EIA, 2023), the United States's residential building stock poses a prime opportunity for improved energy efficiency through targeted interventions. The U.S. Energy Information Administration (2021) has noted that increasing miscellaneous electric loads have "offset some of the efficiency gains made through technology improvements and standards in major end uses such as space conditioning, lighting, and water heating," which highlights the need for a focus on occupant behavioral impact. Zhang, Bai, Mills, and Pezzey (2018) estimate that homeowner education and behavior modification alone has the potential to reduce energy consumption by 10%-25%, highlighting the influence that occupant behavior has and the importance of understanding it. Moreover, energy burden in low-income households is significantly higher than the national average, and homes occupied by these households tend to be less energy efficient (HFHI, 2023), which suggests affordable housing stock as a prime candidate for study and improvement. However, POE has historically focused on non-residential construction (Leaman et al., 2010). Given the scale of potential impact, POE can identify barriers to implementation or provide feedback on where improvements in residential construction may yield greater benefit.

Beyond tangible benefits of influencing construction means and methods, studies of residential energy consumption can influence development of policy and minimum efficiency standards for appliances and equipment, as well as implementation of performance standards such as beyond-code certifications (Meir et al., 2009). For organizations interested in incentivizing reductions in energy consumption, these studies can assist in right-sizing incentives to balance impact and beneficiaries served. The POE studies described in this paper leverage findings to inform uptake of improved design standards among nonprofit developers and to correlate improved building performance with long-term housing affordability.

COMPLICATIONS

Given the benefits of POE, why are building performance assessments not more common? Leaman, Stevenson, and Bordass (2010) attribute the challenge of "closing the feedback loop from building performance in use to briefing, design, and construction" to the array of variables involved, inconsistent publication of findings, and unclear responsibility for acting upon conclusions. Beyond concerns identified by Leaman, Stevenson, and Boardass, such as

publication of building failure or exposure to litigation, post-occupancy evaluations require significant resources and buy-in from participants.

Resources required to conduct a POE include logistical coordination with subjects, cost of equipment, and labor to install it. Once collected, the capacity, time and cost to analyze the data must be accounted for. A successful study relies on the participation of occupants; in an institutional setting, this may be a single point of contact or many inhabitants in a residential study. Study results are critically dependent on occupant behavior, which varies widely.

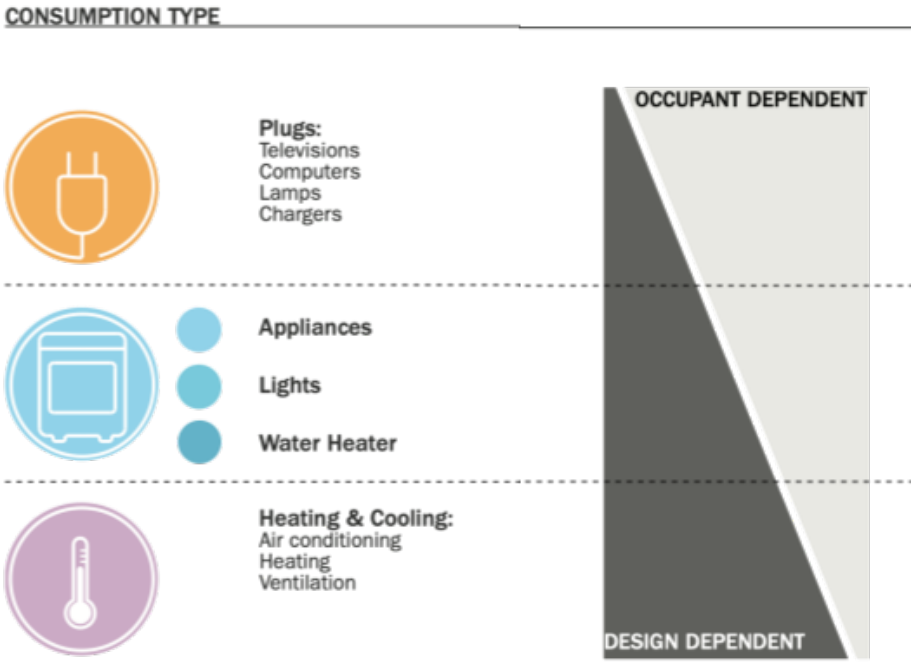

Figure 1. Categories of energy consumption and inverse relationship between occupant influence and influence of building envelope design. Credit: AURS.

Figure 1 illustrates the inverse relationship between the influence occupant behavior and building envelope design have on household energy consumption, highlighting how a study of building performance must take occupant behavior into account. Gram-Hanssen (2010) recognizes that families and households regulate heat differently based on prior experience, technical know-how, values (e.g., environmentalism or comfort), and even past housing conditions. A key player in the overall system of the house, behavior of the occupant can skew expected research outcomes and upend hypotheses through "unanticipated operating modes for innovative technologies or alterations in user behavior" (Leaman et al., 2010). The AURS research team documented examples of such behavior including operating a space heater out of habit or leaving windows open while space conditioning systems run. As such, measured performance may vary widely

from projected performance, as shown in Figure 2, where miscellaneous electric loads measured an average of 2.5 times higher than loads anticipated by an energy model that accounts for the home's location, orientation, building assemblies, air tightness and other technical specifications.

CONSIDERATIONS IN THE DESIGN OF A POE

A thorough understanding of potential obstacles and keen awareness of practical considerations critical to study success is imperative to ensure desired outcomes in post-occupancy evaluations. This knowledge enables researchers to anticipate and mitigate potential challenges. The following considerations guiding the design of post-occupancy evaluations are grouped into outputs, inputs, logistics, management, and occupant education.

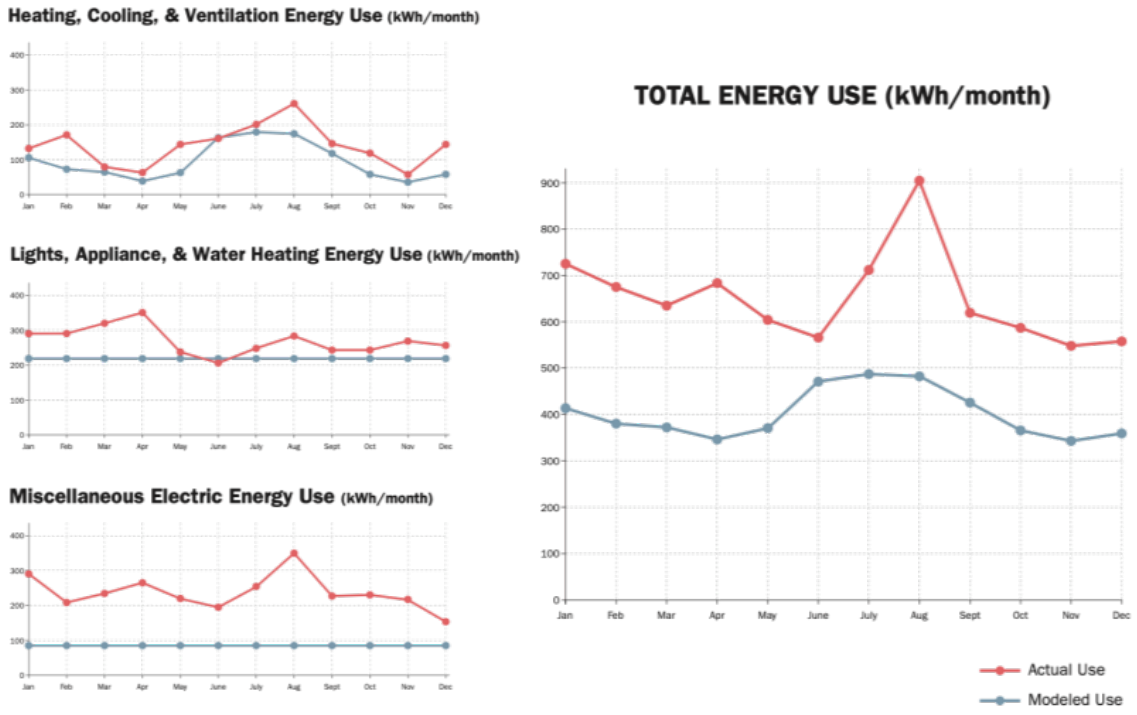

Figure 2. Measured and modeled energy consumption by category. Credit: AURS.

Outputs

The design of a POE begins with identification of the purpose of study and associated research questions. Once the purpose and research questions are determined, data collection means and methods should be tailored to provide insights to the particular focus of the study. Data can range from physical characteristics of the built condition; temporal data such as temperature or humidity; measurable data like energy consumption and production from electric, gas, solar, or

other sources; and behavioral data such as numbers of occupants, habits, setpoints, and demographic data. The scope of the study will inform the size of the dataset, from a few to thousands. Elsayed et al. (2010) considered the implications of different-sized datasets on the outcome of various studies. This variable informs how anomalies or interruptions in data collection are managed. In a large study, incomplete data can be eliminated from consideration, but if the study includes few sites or subjects, missing data might be interpolated or the length of study increased to extend data collection. Depending on how representative the study aims to be, sites may need to be selected to capture data from a range of climate zones, urban or rural sites, solar orientations, etc. Depending on the area of focus, time and the influence of seasonal variation may factor into the study; Figure 3 illustrates how steady energy consumption for appliances, water heating, and lights as well as plug loads are compared to air conditioning and ventilation for a pair of homes over the course of nearly a year; in this case, heat is generated by natural gas fuel, not measurable at a granular level. For these homes, gas consumption would be considered in addition to electric consumption for space heating but cannot be isolated from other appliances like the range and water heater.

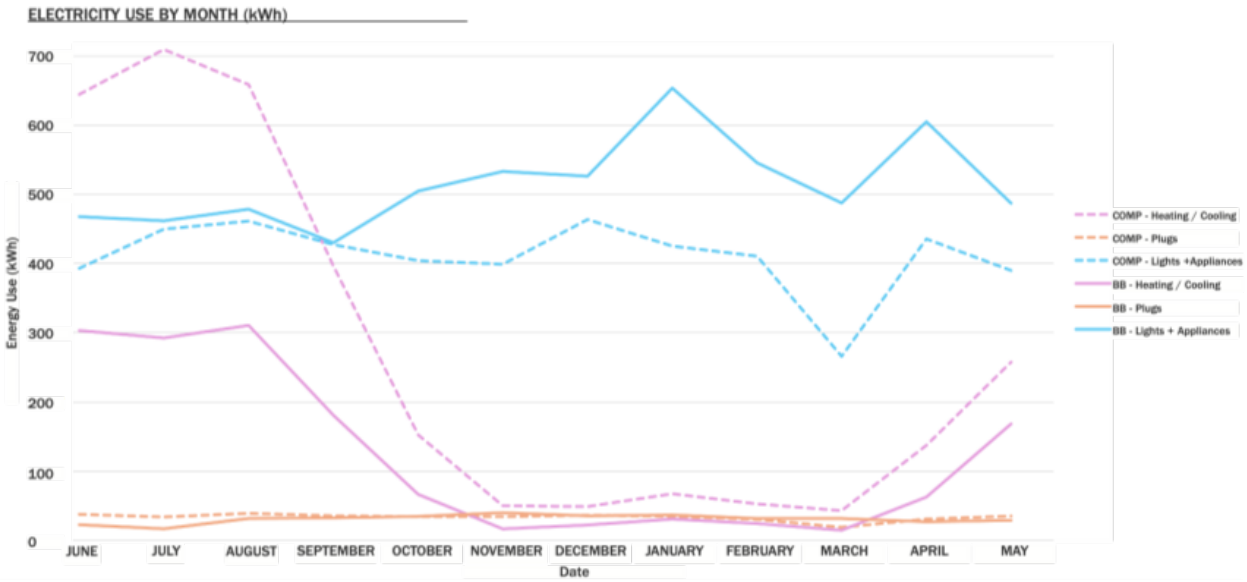

Figure 3. Comparative seasonal variability of energy consumption. Credit: AURS.

Inputs

Once the scope of a study is established, parameters such as timeline, budget, and personnel must be determined. Depending on the type(s) of data to be gathered, a collection method (or methods) must be selected. Occupant surveys will need to be developed in advance and may be subject to compliance review for privacy, safety, and/or ethical concerns. The accuracy of collection methods or sensitivity of equipment must be considered relative to the acceptable margin of error for the POE. Systems capabilities factor in as well; the scope of the study may

need modification if equipment capable of measuring study variables cannot be procured. Equipment selection may depend on such details as data retention capacity in the event of a power or internet service interruption.

Logistics

Prior to the study's commencement, permissions must be sought and relationships established. Depending on the data collected and the sensitivity of that data, Institutional Review Board (IRB) approval or exemption may be required. Contact with potential subjects must be set up, and—once subjects agree to study terms— mechanisms for data collection determined, whether remote or local. If the study is conducted remotely, a local contact is highly beneficial in the face of unexpected events such as service interruptions. Requests for external data such as utility bills must be coordinated, including permission to access it; where privacy is a concern, protocols may need to be drafted and legal services consulted. A data management plan will need to be developed outlining where information is stored and how it will be secured.

Decisions regarding equipment installation and subject interface will need to be addressed: the potential need for a licensed professional to install equipment to prevent voiding a system warranty, the ability to request access to equipment once installed, or the frequency of interface with occupants to conduct interviews or surveys. Depending on equipment selected, internet connectivity may need to be provided. In remote areas, cellular hotspots may not function reliably, but reliance on the occupant's internet service can be problematic if they discontinue service or change service providers. Utility interruptions are difficult to avoid; anticipating that service will be disrupted at some point during data collection, the research team should develop strategies and protocols for restoring collection post-outage and how to adjust data to ensure parity across all sites.

Management

Post-occupancy evaluations involve interaction with occupants, and management of those relationships is critical to success of a study, beginning with solicitation of participants. Incentivization of participants can include monetary or ancillary benefits such as access to data and retaining ownership of the equipment past conclusion of the study. Day-to-day relationship management could involve responding to participant questions, restoring access to data if credentials are changed, or administering surveys. If study parameters change, revisions to data release waivers or IRB approval may be necessary.

Occupant Education:

These types of studies require clear communication and occupant education. The many variables factoring into a POE can readily influence outcomes, user behavior most directly. For example, turning off an energy recovery ventilator can impact health by reducing ventilation air, lack of bathroom exhaust fan use can lead to mold and mildew growth, and systems performance can suffer if regular maintenance is neglected. These concerns highlight the benefit of an occupant's user manual for the residential unit. Moreover, if a piece of equipment is replaced at a later date, installation of a lower-performing unit may cause a significant increase in energy consumption,

like replacing a high efficiency heat pump water heater with a unit employing conventional resistance heat.

CASE STUDIES

A series of case studies informs these considerations in the design of POE studies. The first involved a pair of homes with the same base design but built with different specifications and pursing different beyond-code performance standards. The study sought to identify measurable differences in energy consumption with a goal of analyzing the cost-benefit of those differences. The small sample size of the study allowed for easy management, but learnings from the findings was not widely extensible. Additionally, when internet service was interrupted, the research team struggled to get remote data collection (via hotspots) back online, thus broaching the topic of how to collect a full year of comparable data if one study site experiences a gap in available data. The research team recognized the benefit of modeling the homes' expected energy consumption in WUFI, which generated estimated consumption on a monthly—rather than annual—interval; subsequent studies relied on other modeling software which offered less flexibility to fine-tune outputs.

A second POE involved a sample size of 16 homes spread across the U.S. and studied pairs of homes built to different specifications. This study underscored the importance of occupant behavior, the influence of interior setpoints on energy consumption, and the recognition that data collection systems need memory to retain data in the event of a service outage. For some sites, energy consumption was surprisingly similar for homes with significant differences in envelope construction, and in others, measured data confirmed hypotheses. The research team recognized the need for a commissioning period to confirm connectivity and review reliability of systems before the study period commences. In this study, internet service was offered as an incentive, but providing the occupants control of that system led to multiple instances where wireless passwords were changed administratively without updating the settings of the energy monitoring systems. Gaps in the data due to loss of connectivity complicates comparison of seasonally dependent data from multiple homes, requiring the research team to either extend data collection or infer data for that period of time.

A third case study emphasizes the need for redundancy of sensors in a small study with limited access to monitoring systems. The focus of the study required monitoring systems that could return data without homeowner internet service and sensors that could be buried in the wall, returning results indefinitely. Once the system was online, the research team recognized that two sensors returned data intermittently. This gap in data precludes comparison of the rest of the data collected. The inaccessible location of the sensors suggests that multiple sensors could have been installed for redundancy and data collection consistency.

CONCLUSION

US residential energy consumption is only increasing, and the gap between expected use and actual energy consumption suggests that efforts to increase energy efficiency may require further

study. Evaluating the efficacy of energy upgrades through monitoring the post-occupancy performance of homes illuminates opportunities to renegotiate aspects of the design and delivery process in the continued pursuit of affordability through energy efficiency.

The implementation studies conducted by the research team illustrate how planning is key to a successful POE. Navigating the many obstacles both foreseen and unforeseen requires that coordination, communication, adaptability, and contingency are built into the study from the onset. Thorough POE design that anticipates potential challenges can improve outcomes of a study and reduce gaps in data collection which affect usability in comparative analyses. Given the growing availability of monitoring systems and the feedback they could offer occupants and other audiences, the potential for this tool is promising. However, overcoming the obstacles to successful POEs will require a continued effort to push forward awareness, builder and occupant education, technology, and methodology to close the gaps in data recording and establish reliable best practices to yield useful, easily interpreted and actionable findings. This effort will involve the many stakeholders in the built environment from designers to occupants; everyone involved in the process will have the opportunity to benefit from participating while contributing to an expanding lexicon of building science and occupant analysis aimed at reducing the impact of homes as a contributor to emissions and an attainable framework for affordable sustainability.

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Earthquake Resistant Evaluation and Design

Advancing Use of Cold-Formed Steel Framing Systems for Mid-Rise Residential Construction in Seismic Zones via Full-Scale Shake Table Testing

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ABSTRACT

A capstone 10-story cold-formed steel (CFS) framed building was constructed at the Large High-Performance Outdoor Shake Table at the University of California San Diego (NHERI@UC San Diego). Coined CFS10, this unique, full-scale, building specimen is designed beyond current code-limits with advances in steel sheet sheathed shear walls incorporating high-capacity chord stud detailing proofed in complementary component test programs. This landmark test specimen was designed as an 11.6 m x 6.9 m slice of an archetype CFS-framed residential building. Interior and exterior finishes as well as a wide range of nonstructural systems (stairs, fire sprinkler and gas piping, windows, and doors) were designed and installed in the building. The integrated nonstructural systems add realism to the building and ultimately aid in the opportunity to document the performance of true-to-constructed CFS-framed residential buildings. Uniquely, the building embraces a variety of construction modalities including 2D panelized and 3D volumetric construction methods. Detailing and advances of the later are the subject of a companion paper (Rivera et al., 2026).

Testing of the CFS10 building specimen at the NHERI@UC San Diego shake table was recently completed and involved subjecting the specimen to a suite of 18 increasing intensity multi-

directional earthquake motions, followed by execution of two live fire compartment tests. This paper presents an overview of the salient design and construction features of the specimen, the earthquake test protocol and an early impression of the buildings' behavior during the seismic test phase. This is the first publication since testing, with final data processing in progress.

INTRODUCTION

Cold-formed steel (CFS) is a promising material for use in construction of tall residential buildings. Amongst its greatest attributes are its high strength-weight ratio, considerable use of recycled steel content, non-combustible nature, dimensional stability, corrosion resistance, and precision (e.g. Schafer, 2011; SFIA, 2025). CFS has an unprecedented level of consistency compared with most other construction materials, it is therefore easy to prefabricate and mass produce. Its lightweight nature results in components that are easier to handle and erect – leading to innovation in construction. For example, CFS can be constructed by placing individual sticks (studs, track, joists) one-by-one (also referred to as stick framing); by pre-fabricating larger wall and floor components (2D elements, also known as panelized framing); and by constructing volumetric (3D) components (modular construction). Most notably, in moderate-to-high seismic zones, lighter materials lead to reduced seismic forces. Due to advances in code-procedures and construction adoption, CFS has emerged as a popular alternative to wood framing.

In recent years, lightweight structures constructed of load bearing CFS-framing have demonstrated robust structural behavior during system-level shake table testing. Amongst the most notable are full-scale investigations of CFS-framed buildings by Peterman et al. (2016) and Hutchinson et al. (2021). In the former, a 2-story all CFS-framed building was tested at SUNY-Buffalo under increasing intensity multi-directional earthquake simulations; while the later involved a 6-story all CFS-framed building finished with gypsum sheathing tested at UC San Diego, under increasing intensity unidirectional earthquake simulations. Both programs embraced all-CFS gravity and lateral seismic resistant systems, with sheathed (OSB for the former and steel sheet sheathing for the later) shear walls and ledger-framed CFS-joist framed diaphragms adopted. Robust seismic behavior was observed in each of these programs, with overstrength contributions from non-seismically designated components and architectural finishes evident.

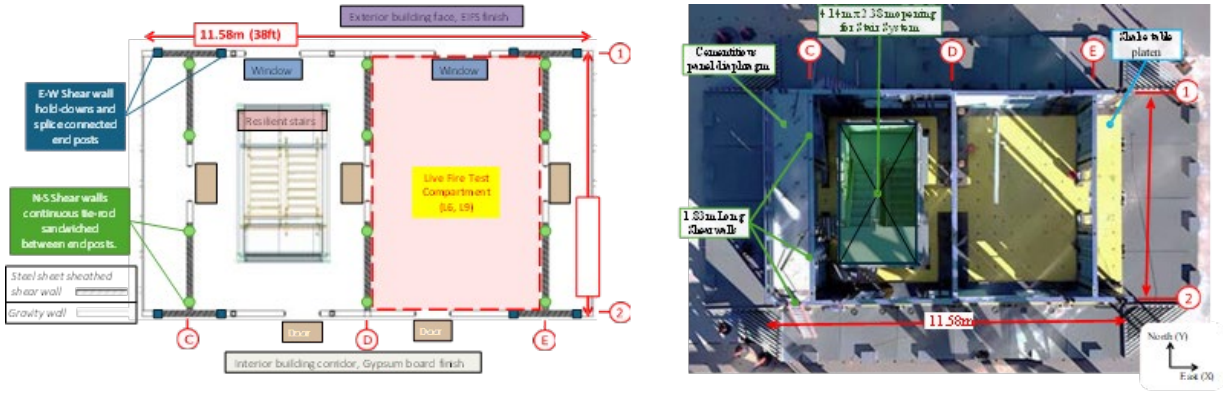
Such landmark programs provide much needed system-level experimental data for validation of all-CFS framing systems in moderate-to-high seismic zones. Despite these unique datasets and complementary component experimental and numerical data, the use of CFS framed systems for taller structures [>19.8m (>65ft), or 6-stories] remains prohibited due to code restrictions (e.g. ASCE 7-22, 2022). To contribute to understanding the seismic performance of tall CFS-constructed buildings, a 10-story full-scale CFS-framed building was recently constructed and tested under increasing intensity multi-directional earthquake shaking and post-earthquake live fire testing. Coined CFS10 (cfs10.ucsd.edu), this building specimen was constructed and tested atop the newly upgraded 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6) at the NHERI@UC San Diego Experimental Facility (esec.ucsd.edu), see Figure 1. This unique specimen serves as the capstone effort to the NSF-funded Collaborative Research Program

entitled: Seismic Resiliency of Repetitively Framed Mid-Rise Cold-Formed Steel Buildings (CFS-NHERI). CFS-NHERI is a multi-university-industry collaborative effort that intends to advance knowledge of the seismic performance of mid-rise CFS-framed buildings through connection, component, and system experiments complemented with comprehensive numerical modeling.

Design and Construction of the CFS10 Building – The design basis for the CFS10 building was inspired by archetype building designs developed by Torabian et al. (2016). Namely, a total building height of 31.6 m (including a 1.1m parapet), which exceeds the height limitation of 19.8 m set by the current ASCE 7-22 (2022) design standard, was adopted. The building footprint was selected to utilize the entire shake table platen area, with plan dimensions of 11.58m X-direction (north-south) by 6.86m Y-direction (east-west), see Figure 1. Taking a slice of the full building archetype footprint resulted in three wall lines in the Y-direction with two steel sheet-sheathed shear walls along each wall line, and two wall lines in the X-direction, also with two steel sheet-sheathed shear walls, detailed to provide lateral seismic resistance, see Figure 2a-b. This layout resulted in two room-space compartments, and two "balconies", small portions of the adjacent rooms in the archetype. In addition to the load bearing CFS studs and CFS-steel sheathed shear walls, the test building was detailed with gypsum-board-sheathed gravity walls, an exterior face with a stucco-based finish EIFS (exterior insulation and finishing system) on its north side (the south side is a corridor in the full building), and a ledger-framed CFS floor framing system with a dry cementitious panel diaphragm.

Figure 1. Annotated photograph of the CFS10 specimen, northeast view.

A hypothetical location in a highly active seismic region in Southern California (city of Irvine) with a Site Class C (very dense soil and soft rock) condition was selected as the basis for the building's seismic design. In accordance with ASCE 7-16 (2016) and an assumed Risk Category II, the seismic design parameters were defined as follows: spectral acceleration at short periods, SS = 1.261 g, spectral acceleration at a period of 1 second, S1 = 0.452 g, and design spectral accelerations, SDS = 1.009 g and SD1 = 0.452 g. The resulting lateral force resisting system of the test building embraced the concept of Type I shear walls (AISI, 2015) featuring single-sided steel sheet sheathing and ledger framing for floor-to-wall connections. The exception to the use of all CFS structural framing was the detailing of chord studs using HSS tubes on Levels 1-6 for the longitudinal X-direction shear walls (Lines 1 and 2, see Figure 2a), where overturning loads dictated larger capacity requirements and there was a desire not to use large stud packs. In contrast, in the transverse Y-direction, shear walls contain a pair of tie-down subassemblies consisting of tension tie-rods connected by couplers sandwiched between compression posts made of built-up stud packs. The ensuing lateral load resisting system dictates the seismic design parameters R (response modification coefficient), Wo (over-strength factor), and Cd (deflection amplification factor) as 6.5, 3.0, and 4.0 respectively per ASCE 7-16 (2016) in its seismic design. Additional details regarding the structural design basis are summarized in Singh et al. (2022, 2024).



(a) (b)

Figure 2. Plan view: (A) cartoon layout and (B) annotated photograph during level 1 construction.

The building construction explored a variety of methods, namely, conventional stick-framing, panelized (2D), and volumetric (3D) modular construction within one specimen (Figure 3), allowing a unique opportunity to document and compare the efficiency of each, see companion paper by Rivera et al. (2026). Finally, realistic features were incorporated in the building by integrating a wide range of nonstructural components and systems (NCSs). Notably, a 9-story stair system with drift-compatible connections, pressurized gas and fire sprinkler systems, a suspended ceiling system, roof mounted equipment with varied base conditions, select operable

doors and windows, and complete interior and exterior finishes to the wall system were incorporated. An overview of the NCSs integrated within the building and their response during the test program will be provided in future publications.

EARTHQUAKE TEST PROGRAM

Seismic Instrumentation – To capture the performance of the CFS10 building under the planned earthquake hazard scenarios, multiple forms of data collection were employed. Notably, utilizing LHPOST6 equipment, 730 seismic sensors, 47 synchronized CVI/IP cameras and 17 GoPro cameras were installed throughout the specimen. In addition, in partnership with the California Strong Motion Instrumentation Program (CSMIP) and the Community Seismic Network (CSN), an additional 34 uni-directional and 75 tri-axial accelerometers (CSMIP and CSN, respectively) were distributed throughout the building, see Figure 4. Amongst the 730 seismic sensors, 62% were dedicated to capturing structural behavior (global, walls and diaphragm); while the remaining 38% were allocated to capturing the various nonstructural systems behavior, see Figure 5.

To capture the global behavior of the specimen, absent the potential to provide a fixed reference target for direct displacement measurement to such a tall specimen, an array of unmanned aerial vehicles (UAVs) outfitted with monocular cameras were deployed. For each seismic test, the specimen was monitored by the cameras on the four UAV platforms, each with a different view (plan and three elevations) aimed at capturing structural motions in all degree-of-freedoms (DOFs), see Figure 6. More than 300 reference targets with various types of black-and-white checkerboard patterns were installed to provide image features for detection and tracking. The dynamic response of the structure under seismic excitation can then be extracted by reprojecting image points from UAV imagery to the 3-D world space based on world-to-image point correspondences (Cao et al., 2024; Ji et al., 2025).

Figure 3. Construction methods investigated: (A) stick framing (1D) (Level 1) versus panelized (2D) and (B) modular (3D) (Level 4).

(a) (b)

Figure 4. Example of seismic instrumentation installed: (A) level 4 diaphragm (southeast corner) and (B) level 2 shear distortion at wall line D (south).

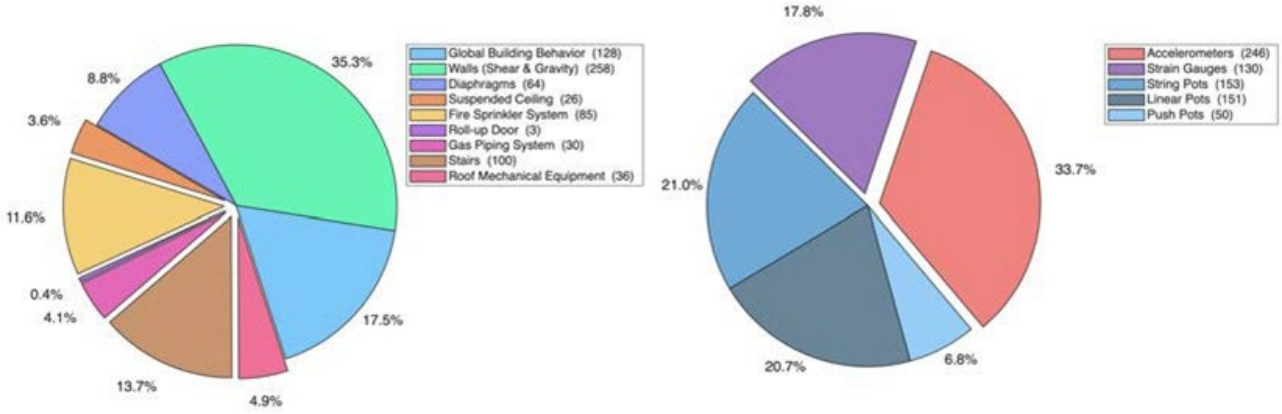


Figure 5. Distribution of LHPOST6 seismic sensors: (left) component (purpose) and (right) sensor type.

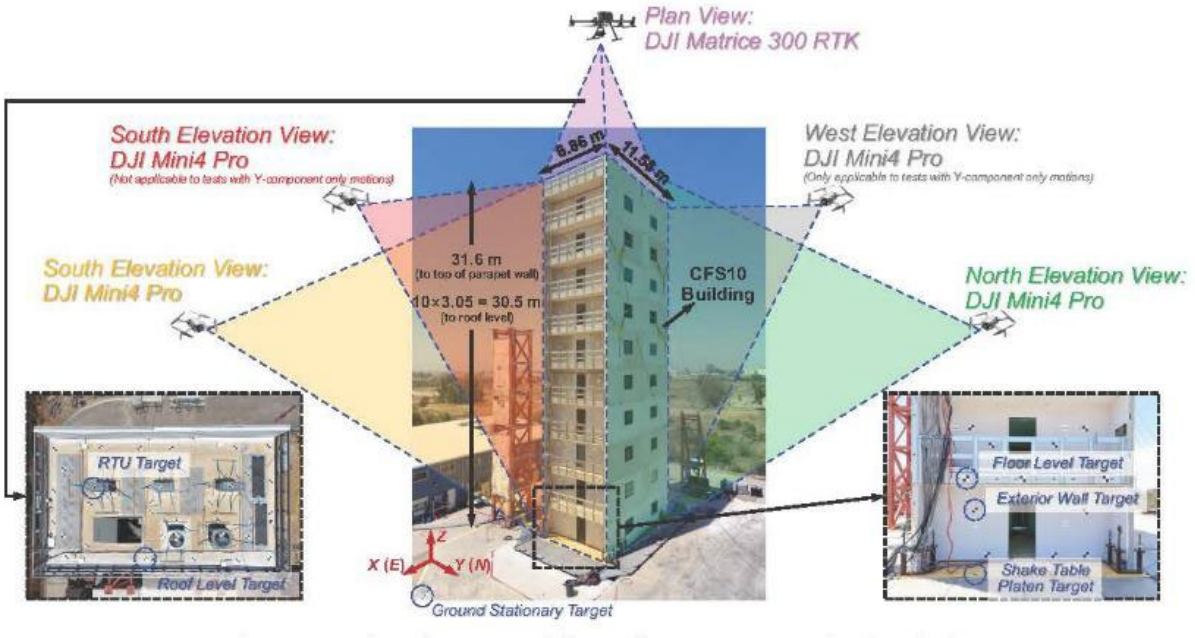


Figure 6. UAV-based structural dynamic response monitoring design.

Test Protocol

In total, 18 earthquake motions of increasing intensity and considering multi-directional input excitations were imposed on the specimen during seven (7) active days of shake table testing. These included 15 service-level earthquakes (SLE), one design-level earthquake (DE) and two risk-targeted maximum considered earthquakes (MCER). Two distinct SLE suites (MID1-10 and MID11-15) were designed considering seismological settings characterized by shorter duration far-field and longer duration events, denoted SLE1 and SLE2, respectively. As a result, while

one carry-through increasing intensity motion (1989 Loma Prieta, California – Gilroy Array #3) was utilized across all three hazard levels, a wide range of amplitudes, durations, and directionalities were ultimately imposed on the specimen, see Table 1. Additional details regarding motion selection criteria for this program, including the source selection and scaling procedures adopted, are discussed in Zhang, J. et al. (2024). In addition, to capture the evolution of dynamic characteristics of the building, low-amplitude uni-directional white noise (WN) tests in each orthogonal direction were imposed following each earthquake test. In total, 37 WN tests were conducted, typically with a target root-mean-square (RMS) of 3 or 4%g and a duration of 64 or 160 seconds. It should be noted that during MID1 and the WN immediately before and after, the stairs within the test building were restrained from movement relative to the floor diaphragm at all landings (i.e. "locked"), thus resulting in additional story stiffness contribution. The baseline configuration, i.e. seismically resilient stairs "unlocked", with all mid-landings free to move, was adopted for all subsequent tests.

Table 1. Earthquake Test Protocol Imposed on the CFS10 Building. ***(Note: MID = motion identification number, DOF = degree of freedom.)***

Hazard level	MID	Earthquake event				Input DOF	Components		$D_{5\text{-}95}$ [sec]	PIA_x [g]	PIA_y [g]	PIA_z [g]
		Name, location	Year	M_w	Station		X	Y				
SLE1	1*	Loma Prieta, California	1989	6.9	Gilroy Array #3	XYZ	90°	0°	11.4	0.126	0.122	0.082
	2					XYZ	90°	0°	11.4	0.118	0.114	0.096
	3					X	90°		11.4	0.133	0.041	0.025
	4					Y		0°	6.4	0.042	0.109	0.024
	5	Northridge, California	1994	6.7	LA City Terrace	XYZ	90°	180°	11.9	0.125	0.121	0.081
	6					XYZ	180°	90°	11.9	0.184	0.094	0.084
	7					X	180°		11.9	0.168	0.027	0.023
	8					Y		90°	11.6	0.026	0.093	0.021
	9	Cape Mendocino, California	1992	7.0	Rio Dell Overpass	XYZ	270°	360°	15.3	0.084	0.109	0.099
	10					XYZ	360°	270°	15.3	0.078	0.122	0.151
SLE2	11**	Kahramanmaras, Türkiye	2023	7.8	4611	XYZ	E	N	43.4	0.095	0.075	0.050
	12					XYZ	E	N	43.4	0.117	0.110	0.064
	13	Elbistan, Türkiye	2023	7.5	4611	XYZ	E	N	35.1	0.100	0.061	0.052
	14	Maule, Chile	2010	8.8	Curico Hospital	XY	EW	NS	45.2	0.097	0.091	0.033
	15	Kahramanmaras, Türkiye	2023	7.8	4611	XYZ	E	N	43.4	0.119	0.089	0.063
DE	16	Loma Prieta, California	1989	6.9	Gilroy Array #3	XY	90°	0°	11.4	0.454	0.388	0.014
MCE_R	17	Loma Prieta, California	1989	6.9	Gilroy Array #3	XY	90°	0°	11.4	0.723	0.619	0.016
	18	Cape Mendocino, California	1992	7.0	Rio Dell Overpass	XY	360°	270°	15.3	0.782	0.336	0.025

EARTHQUAKE TEST PROGRAM: PRELIMINARY RESULTS

Period Evolution

The vibration periods of the building's first three modes, corresponding to two flexural-dominant modes in each orthogonal direction and one torsional mode, were estimated using one Single Input Multiple Output (SIMO) and one Multiple Output (MO) system identification technique. In the SIMO method, the modal parameters were extracted using the Least Squares Rational Function (LSRF) curve-fitting algorithm (MATLAB, 2022) applied to the Frequency Response

Functions (FRFs) of the building. The FRF acts as a transfer function between one input acceleration on the shake table platen and 10 output acceleration measurements recorded on the test specimen at the theoretical center of mass and northwest corner of the building (i.e., considering two uni-directional WN tests and two sensor locations, resulting in a total of 4 input accelerations and 40 output accelerations). In this analysis, only the flexural-dominant modes that were actively excited were considered. In other words, to estimate the vibration period in the X-direction, data from white noise tests in the X-direction were used, and to estimate the period in the Y-direction, data from white noise tests in the Y-direction were utilized. Figure 7 shows the FRFs from tests WN8 and WN9, which represent the virgin state of the building with the unlocked stair system, and from tests WN35 and WN36, representing the post-earthquake test state of the building. Additionally, the building's dynamic characteristics were determined using the Stochastic Subspace Identification (SSID) technique (Peeters and De Roeck, 2001). In this method, 40 acceleration time histories recorded at the theoretical center of mass and the north-west corner of the building, and four accelerations recorded at the shake table platen are used. Adopting FRF and SSID methods, Figure 8 summarizes the building's periods corresponding to the first three vibration modes throughout the test sequence and the change in the test specimen's period during each WN test relative to WN1 and WN2 tests for "stairs locked" phase and WN8 and WN9 tests for "stairs unlocked" phase. The key observations include the following:

- Computing the building's modal characteristics using the FRF method was effective because the fundamental modes are well separated, and the FRF is well defined due to a high signal-to-noise ratio.

- Periods of the building predicted by the two different system identification techniques are in close agreement.

- SLE-scaled earthquake tests did not alter the vibration period of the building significantly, with the maximum increase of 7% in the first torsional mode. It is worth noting that damage was not visible at the completion of the SLE test suite.

- In contrast, the DE-scaled earthquake increased the vibration period of the first and second flexural modes in the X-direction by approximately 9% and 22%, respectively. Changes in other vibration modes were less than 6%.

- MCER tests increased the periods of the first and second flexural modes in the X-direction by approximately 17% and 10%, respectively, and in the Y-direction by approximately 10% and 31%, respectively. The torsional mode period increased by approximately 14%.

- From the virgin state (WN8 and 9) to the post-seismic tests (> MID18, i.e. post-MCER), the building's first flexural period increased by as much as 35 and 18% in the X and Y-directions, respectively. The torsional period increased by 23%.

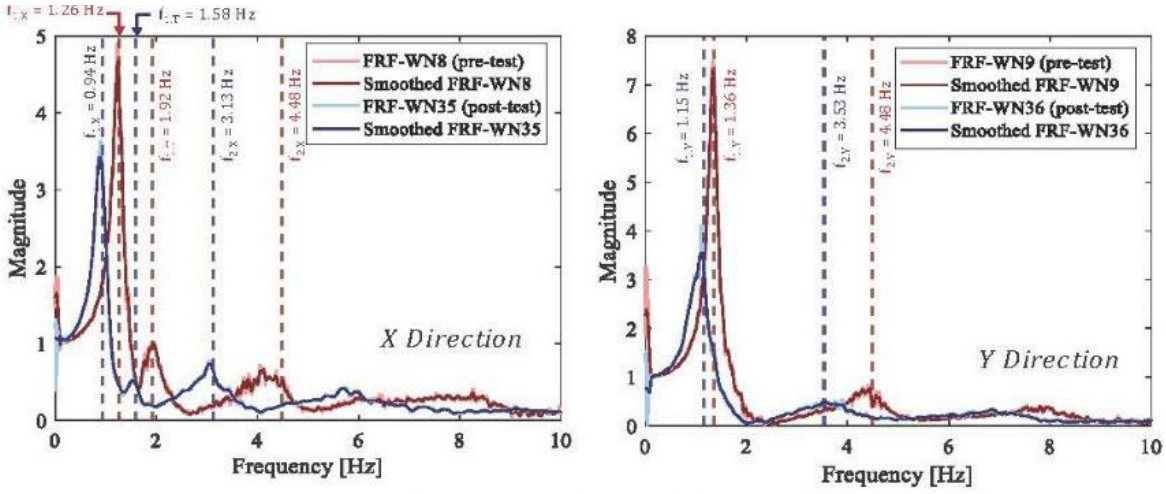


Figure 7. Frequency response function (FRF) using WN8 and WN9 (virgin state), and WN35 and WN36 (post-seismic test state). Note that subscript T refers to the torsional mode.

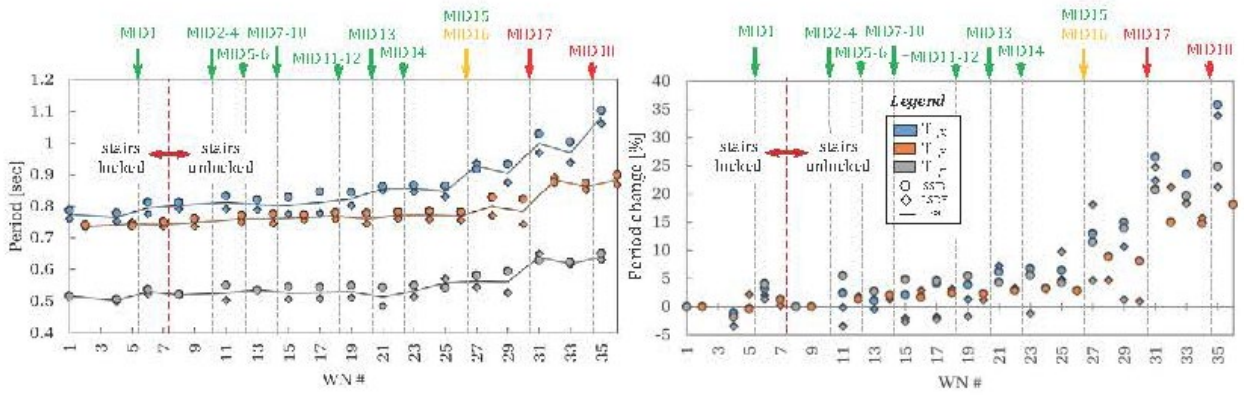


Figure 8. Period evolution of the specimen for the first three fundamental modes.

Peak Acceleration Response

The peak floor acceleration profile with height in a building is an important indicator of the seismic demand during earthquake shaking. Figure 9 presents the peak floor acceleration (PFA) profile considering the SLE suites (part a,b) and the DE+ (DE and MCER tests, parts c,d), as measured at the center of mass of the building. The SLE-scaled motions are separated by suites SLE1 (short duration, with D5-95 < 15sec) and SLE2 (long duration, with D5-95 >30sec). Under these two suites, it is notable that the longer duration shaking expresses larger PFAs within the upper floors in the X-direction, while the Y-direction consistently reports lower PFAs during the long duration tests. The largest PFA at the center of mass during both SLE suites was 0.44g, measured at the roof in the X-direction. PFA profiles during the final MCER test (MID18) were

lower than those of the DE-scaled (MID16) test at select floor levels in the Y-direction, indicating that nonlinear response was observed at select floors. The largest PFA at the center of mass during the DE and above-scaled tests was 2.02g, reported at the roof in the X-direction. Higher mode effects are evident in the measured profiles and manifest in the form of larger PFAs for select lower floors (reversals at mid-height) during both SLE and DE+ tests.

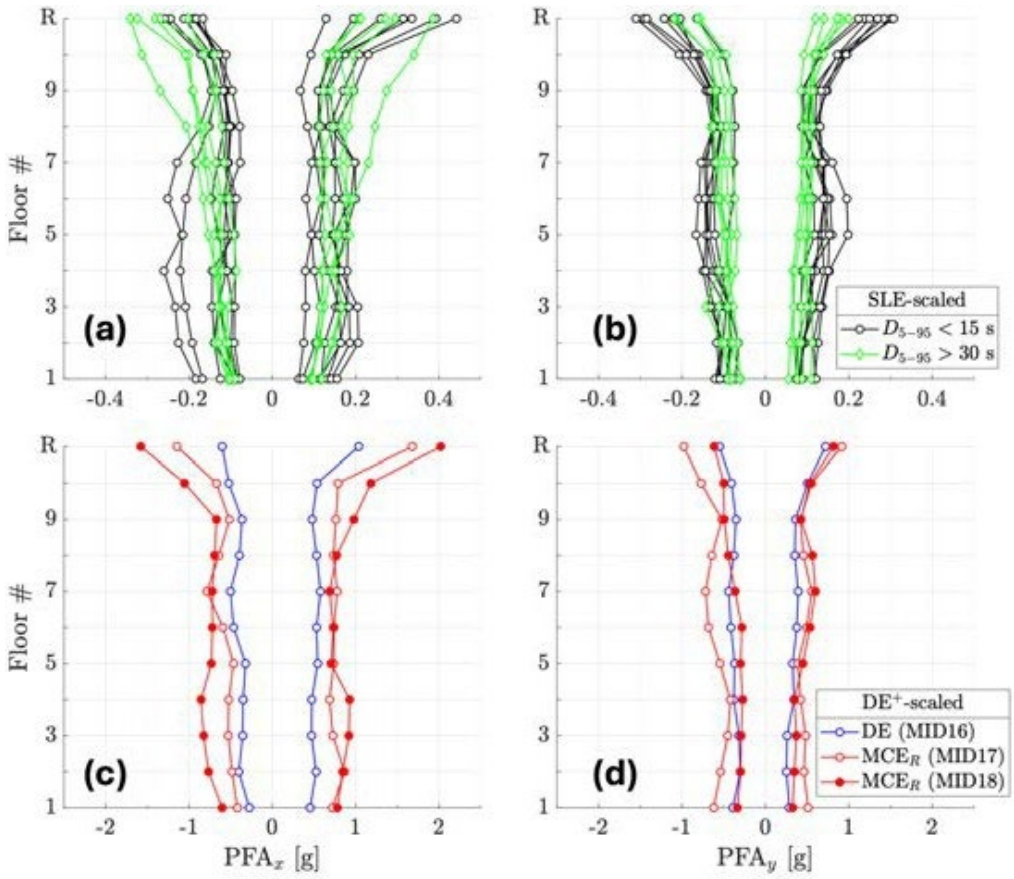


Figure 9. Peak floor acceleration profile during the: (A, B) SLE-scaled suites, considering short and long-duration test motions and (C, D) DE and MCER-scaled tests. Parts (A, C) present the X-direction response, while parts (B, D) present the Y-direction response.

It is also useful to normalize the peak floor acceleration by the achieved peak input acceleration (PIA), see Figure 10. This plot provides individual circles along with the light grey lines (linearly connecting floor-floor) to represent the PFA/PIA from an individual ground motion. The solid red line indicates the geometric mean of the PFA/PIA results from all tests at each floor. In the X-direction, the maximum average PFA/PIA ratios were 2.39 (SLE), 2.07 (DE), and 2.24 (MCER). In the Y-direction, the corresponding averages were 2.69, 1.87, and 2.23. These maxima consistently occurred at the roof, where the building's whipping action led to greater acceleration amplification. Compared with the SLE and MCER cases, the DE case exhibited

smaller roof-level amplification. However, this result may not be statistically robust, as it is based on only one DE test.

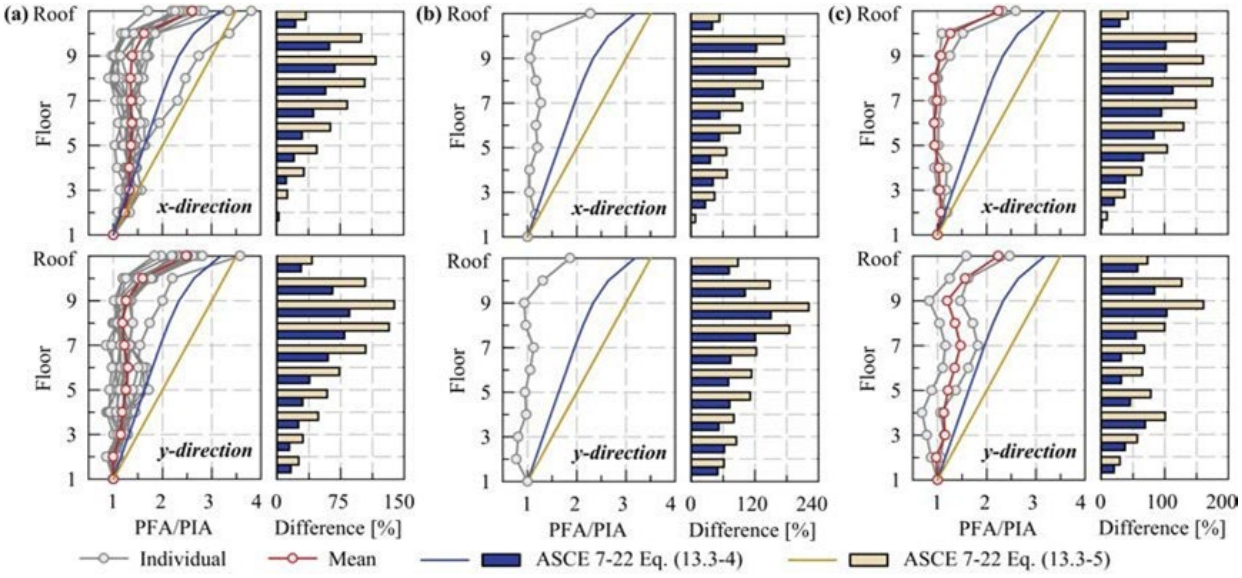


Figure 10. Acceleration amplification factor profile (PFA / PIA = peak floor acceleration / peak input acceleration) under: (A) service-level earthquakes (SLE), (B) design earthquake (DE), and (C) risk-targeted maximum considered earthquakes (MCER). Computed using the center of mass accelerometers and compared with ASCE 7-22 (2022).

ASCE 7-22 (Chapter 12, 2022) provides two alternative equations for calculating acceleration amplification factors along the height of a building. The fundamental-period-independent method (Equation 13.3-5), assumes a linear acceleration amplification profile, ranging from 1.0 at the ground level to 3.5 at the roof level. The fundamental-period-dependent method (Equation 13.3-4), introduced in the latest edition, aims to improve prediction accuracy by considering the building's fundamental period, which is calculated using the code-based formula as 0.63 sec (independent of building direction). Figure 10 includes these two code-based profiles and the difference in bar chart format with the mean measured PFA/PIA values. In general, both code-based equations provide conservative predictions of acceleration amplification, with the most conservative result typically occurring at floor 9, except for the x-direction amplification under the MCER case, where floor 8 produced a more conservative value. Using Equation (13.3-5), the predicted acceleration amplification was conservative by up to 127%, 220%, and 193% under SLE, DE, and MCER motions, respectively. The period-dependent Equation (13.3-4) consistently observes smaller (but still substantial) differences with the measured values, with corresponding maximum conservatism of 77%, 149%, and 127%. An exception is noted during MID13 (SLE2-suite), where Equation (13.3-4) fails to reliably predict X-direction acceleration amplification above the fifth floor while Equation (13.3-5) performs better in this range, but loses reliability beyond the ninth floor.

Local Response

Chord members were instrumented with uni-axial strain gages to capture the transient strain amplitude of shear wall perimeter hollow structural sections (HSS) (wall lines 1 and 2) and tie-rod elements (wall lines C, D, and E). A sample of the measured dynamic strain histories are provided in Figure 11a-b during the final MCER test (MID18). The comparison in part (a) overlays sensor SF01-17Z (HSS at story 1) and SF06-09Z (HSS at story 6). This plot reveals notable differences in strain magnitude, with the peak measured in the lower story, and approaching 21%εy, approximately 1.15 times the magnitude observed at level 6. Similarly, part (b) illustrates an even more pronounced difference between tie-rod responses comparing a tie-rod at level 1 (SF01-01Z), which exhibited peak strains of approximately 20%εy, while the tie-rod element at level 10 (SF10-01Z) maintained strains below 2%εy, representing an order-of-magnitude difference. A synthesis of maximum strain amplitudes across all 18 tests, categorized by seismic hazard level is provided in part c. These measurements indicate that monitored members maintain strains below 10% of their yield strain, indicating elastic behavior with minimal potential for damage or permanent deformation during all SLE tests, while during the DE-level test modest demands of 11% and 15%εy, for the tie-rod and HSS, respectively were recorded. The MCER-level test responses produced larger demands, with peak strains reaching 20% εy for tie-rods and 27%εy for HSS members. These strain amplitudes in chord studs are an anticipated and a welcome outcome, as they are capacity protected elements, therefore at MCER-levels, it is desired that damage occurs in other elements.

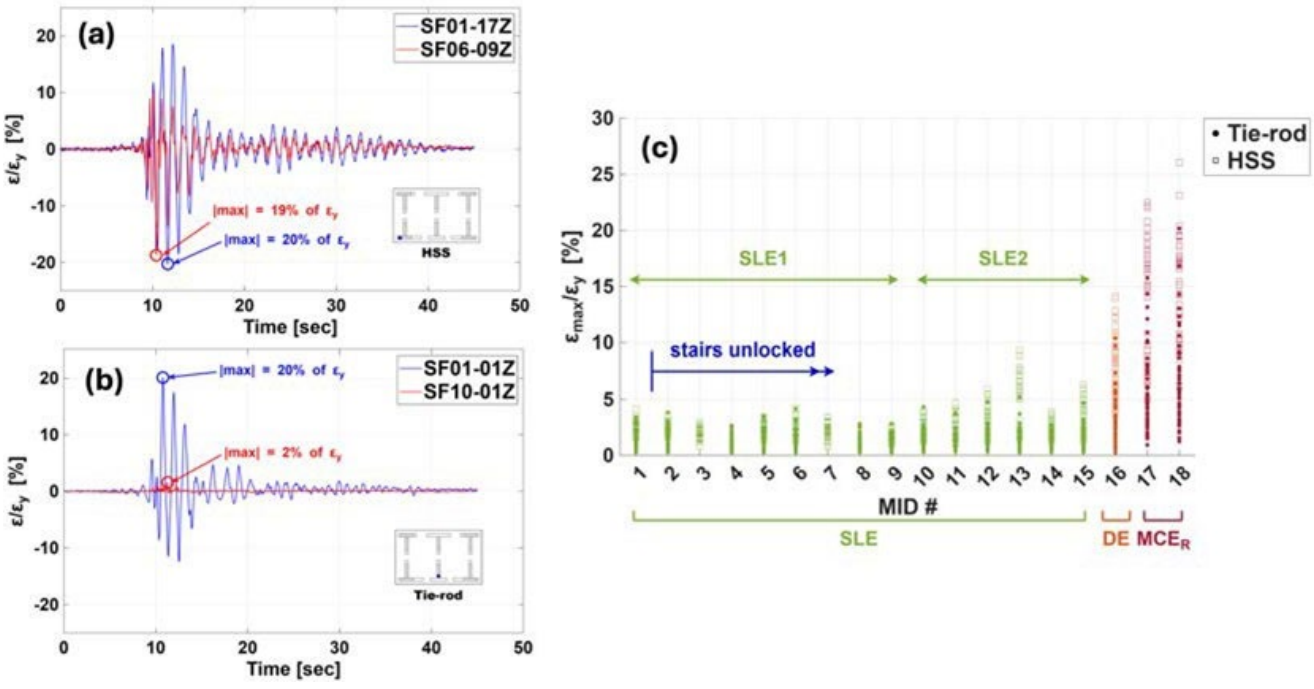


Figure 11. Measured strain on HSS and tie-rod members at the end of shearwalls: (A, B) dynamic histories during MID18, and (C) synthesis of all maximum (transient) strain measured across all tests. Values normalized by the member yield strain.

CONCLUDING REMARKS

A landmark 10-story cold-formed steel (CFS) building was constructed at the large high-performance outdoor shake table at UC San Diego. This unique, full-scale, building specimen is designed beyond current code-height limits with advances in steel sheet sheathed shear walls and unique chord stud details proofed in complementary component test programs. This paper provides a summary of the specimens' salient design and construction features, the seismic instrumentation and test protocol, and preliminary measured earthquake response results. Measured results discussed herein indicate that after 18 simulated earthquakes, two of which were MCER-level target scaled, a maximum period elongation in the flexural mode of approximately 35%, with peak floor accelerations of 2g at the roof; and maximum strains in chord stud members < 30% of the yield strain. Peak floor acceleration profiles clearly articulate higher mode effects in this tall building and indicate possible directions for improvements with ASCE7's current design acceleration amplification ratios.

Important to note, though not discussed due to brevity in the present paper, physical damage post DE and post-MCER tests was moderate and readily repairable, demonstrating the systems seismic resilience. Features observed include edge fastening damage to finish sheathing, minor crushing and EIFS exterior finish damage, particularly surrounding window openings, mud/tape damage, and one instance of a detached tie-rod at its coupler. Note that no repair actions were taken during the earthquake test sequence. Importantly, residual drift of the building was negligible and continued functionality of all nonstructural systems installed were observed. Future work by the team will explore in greater depth the specimens' measured response, correlating with salient observed damage and computational models. This unique dataset will be used to provide important benchmark comparisons with numerical modeling methods, while also guiding in advancing code-based design of cold-formed steel in mid-rise and tall-building construction.

ACKNOWLEDGEMENTS

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Investigating Construction Methods in a Landmark Ten-Story Cold-Formed Steel Residential Building Shake Table Test Program

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ABSTRACT

The CFS-NHERI 10-Story Building Capstone Test Program, coined CFS10, offered an opportunity to demonstrate, through full-scale testing at NHERI@UC San Diego 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6), the resiliency and robustness of cold-formed steel (CFS) framing, a material that has consistently shown such qualities in large scale and component-level tests. This unique test program brought together three widely used construction methods, namely, stick-framing, panelization (2D), and volumetric modularization (3D), allowing them to be directly compared within the same structure. Notably, a 9-story Modular Stair System (MSS) was also integrated into the structure. These stair modules, capable of supporting their own weight, significantly reduced construction time, which ultimately shaped

the building's construction sequence and saved labor hours and site congestion.

The layout of the 10-story specimen allowed each method to occupy its own section. The construction team needed to resolve a series of planning and coordination challenges. Building Information Modeling (BIM) facilitated this process and helped maintain smooth progress, as discussed in this paper. The result was a complete, test-ready structure that brings all three systems together in one place. While each method offered distinct benefits, the experience gained through the implementation of modular systems points toward a more controlled, efficient, and scalable path forward for CFS construction, with the potential to support more efficient construction of residential buildings.

INTRODUCTION

The construction industry is undergoing a long-awaited shift toward industrialized methods as it seeks to improve productivity, reduce costs, and meet growing housing demands. Modular and offsite construction have emerged as viable solutions, which offer greater efficiency, repeatability, and quality control compared to traditional site-built processes (Smith et al. 2023). Among the structural materials poised to benefit most from this transition is cold-formed steel (CFS), which offers high strength-to-weight ratios, seismic resilience, fire resistance, and compatibility with prefabrication. These attributes make CFS particularly well-suited for integration with panelized and volumetric modular construction (Islam et al. 2023).

Despite the growing body of research that highlights modularity's potential to scale industrialized building platforms (Islam et al. 2023), the adoption of such systems in mid- to high-rise seismic applications remains limited. This gap is partially due to a lack of comprehensive, full-scale experimental data validating their structural performance, especially under multi-directional dynamic loading. Concurrently, the development of modular design platforms in industrialized construction has emphasized more on product modularity than the complex process and on-site integration challenges that often arise in real modular projects (Islam et al. 2023).

To address these challenges, the landmark CFS-NHERI 10-Story Building Capstone Test Program, coined CFS10, which was aimed at designing and evaluating the performance of a beyond-code all CFS-framing system under earthquake loading, embraced the use of varying construction methods. Designed as an 11.6 m × 6.9 m x 10-story slice of an archetype residential building (Torabian et al. 2016). The CFS10 project incorporated three distinct construction methods: stick-framing (1D), panelization (2D), and volumetric (3D) modularization into a single structure. Figure 1 illustrates the 3D modular approach, with a prefabricated module being lifted into place. This enabled a unique, side-by-side comparison under identical structural and loading conditions, offering insights into their comparative constructability, integration issues, and seismic response.

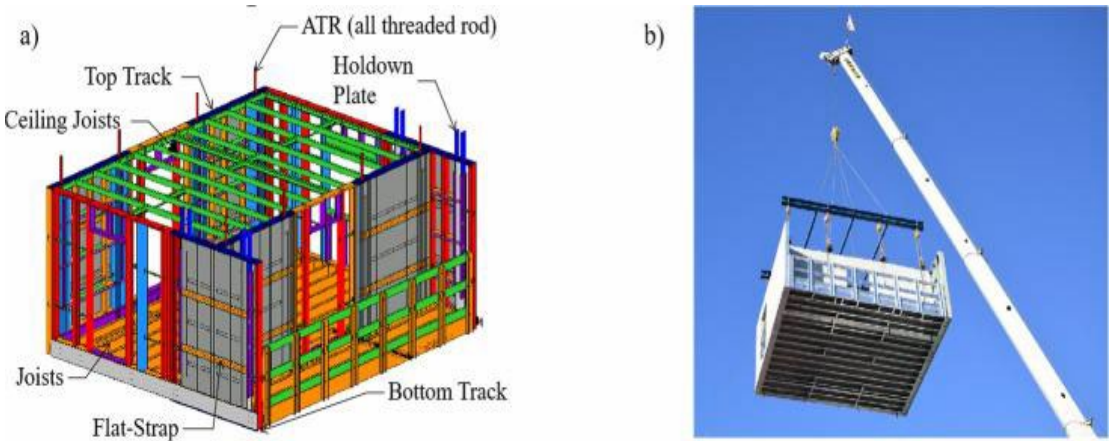

Figure 1. CFS10 volumetric module: (A) BIM model highlighting key framing elements, (B) module lifted by crane during field operations.

This paper presents detailed documentation of the planning, implementation, and coordination strategies used in the CFS10 project, focusing on the construction differences across the three methods. The aim is to assess the implications on installation workflows, field challenges, and performance outcomes. This study contributes to ongoing efforts to validate modular and prefabricated CFS construction approaches as viable, scalable solutions for resilient mid-rise housing in seismic zones.

PROJECT CONSTRUCTION OVERVIEW

The CFS-NHERI 10-Story Building Capstone Test Program, (CFS10), features a full-scale test structure with a floor plan of 11.6 m × 6.9 m, a standard story height of 3.05 m across ten stories, and a 1.1 m tall parapet, resulting in a building with a total height of 31.6 m. It employs steel sheet sheathed shear walls in each orthogonal direction to serve as the lateral force-resisting system; however, with varying chord system details, namely: a tie rod system along (6) north–south walls and a hold-down system along (4) east–west walls. The CFS10 building represents a slice of an archetype residential building, with each level divided into east and west units, both consisting of a room and a balcony (which is the beginning of the next room in the full archetype building). Stair modules were stacked at Level 1-9 to support egress/ingress into the building, while access to Level 11 (roof) was facilitated via a ships-ladder and access hatch. Additional details of the structural and nonstructural design are available in Singh et al. (2022, 2024), Sorosh et al. (2025), and Hutchinson et al. (2026). The seismic tests were recently completed in summer 2025, with select initial findings presented in this same conference (Hutchinson et al., 2026).

One advantage of CFS is its versatility: lightweight, screw-fastened framing is forgiving and customizable, allowing ready adaptation to the construction methods used in this project (see Figure 2).

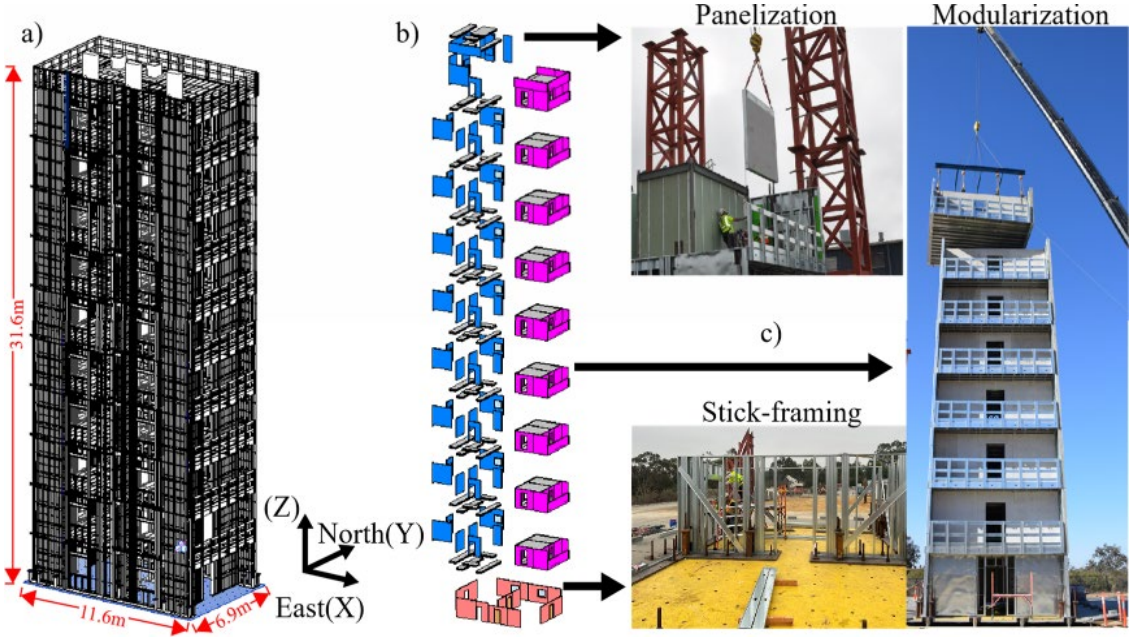

Figure 2. (A) CFS10 structure (Revit model), (B) construction methods breakdown, and (c) representative field installation photos of stick framing, panelization, and modularization.

Stick Framing (1D) is the most traditional and flexible method, with elements installed directly on site per project drawings. Stick framing is customizable, but less efficient, as it involves extended on-site assembly and greater exposure to unforeseen conditions compared to controlled environments. Stick framing was used on the first floor of the building to handle the complex integration with the shake table platen.

Panelization (2D) consists of walls and floors manufactured as 2D panels in a controlled off-site environment, improving quality and consistency. Predefined layouts Figure 2. (A) CFS10 structure (Revit model), (B) construction methods breakdown, and (c) representative field installation photos of stick framing, panelization, and modularization. improve trade coordination, reduce clashes, and minimize field issues during installation. Shipping is also straightforward for panelization. Panelization is the dominant construction method in CFS-framing today and was utilized for the west rooms for stories 2-10 of CFS10.

Volumetric Modularization (3D) is a relatively new method where partially or fully finished units are built in a controlled environment, either on- or off-site, and, if constructed off-site, delivered ready for installation, resembling a toy block set. Modular construction enables repeatable, assembly-line production, reducing on-site labor and uncertainty while offering greater quality and schedule control. On-site modularization was employed for the east rooms for stories 2-10 of CFS10.

CFS10 was a complex, real, building–far from a typical test specimen. The construction effort was supported by a variety of needed experts. BIM coordination and modeling provided the shop drawings and clash checks needed for stick-framed, panelized, and modular sections. Fabrication specialists assembled CFS profiles into wall and floor panels off-site, while modular units were assembled in parallel with site activities. Field crews erected the building by first completing the stick-framed portion of the first level, followed by stair module installation on the west side, setting the modular unit on the east side, and finally, installing the prefabricated panels on the west side.

PLANNING THE CONSTRUCTION APPROACHES

Stick and Prefabricated Components – The first floor was selected to be stick-framed to ease attachment to the shake table platen, see Figure 3. Transfer plates were anchored to the platen with shear anchors, post-tensioned rods (at shear wall ends), hollow structural section (HSS) steel tubes, square plates, and the first-level bottom tracks were fastened to these plates with power actuated fasteners (PAFs).

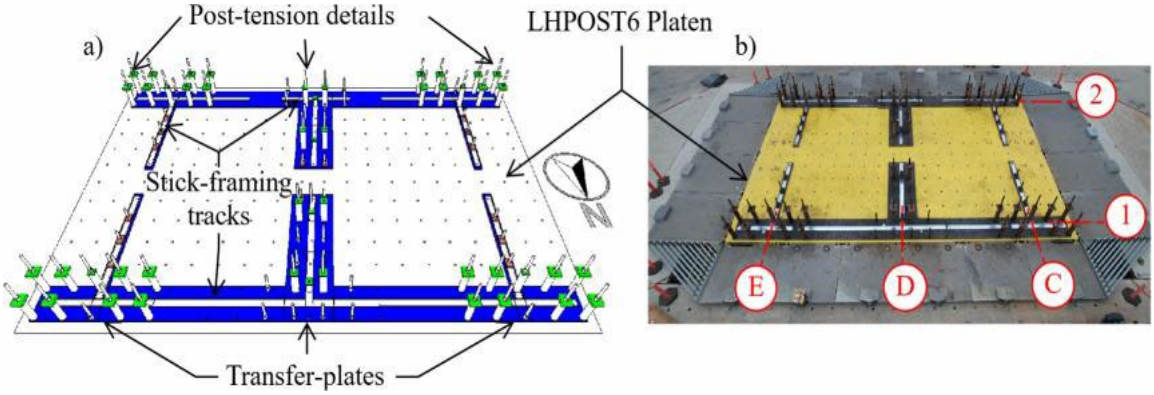

Figure 3. CFS10-LHPOST6 base transfer plate details: (A) BIM model (B) aerial site view.

The six north-south direction shear walls were detailed with tie rods threaded either directly into the table (lines C and E) or to attachment HSS stubs (line D). All tie-rods continued vertically as part of the designed lateral force-resisting system. In contrast, the four east-west direction shear walls were detailed with HSS tubes directly welded to the transfer plates. West rooms on levels 2–10 used panelization around the stair modules; with ledger-hung floors with joists spanning north-south direction, floor panels closed the level below as wall panels erected the level above. Figure 4 shows the distribution of prefabricated components in the CFS10 building by level. In this layout, F-# denotes floor assemblies and W-# denotes wall assemblies where rectangular callouts identify panelized assemblies and oval callouts identify modular ones. For clarity, ceilings are not displayed in the figure, though in the actual module, they were located above F-6 and F-7, with ceiling joists spanning perpendicular to the floor joists. Ceiling joists were

designed into the modular space only, largely to serve as the top of the modular unit. The dimensions of each component were shaped by project-specific factors such as window, door, and stair openings, with floors segmented and designed to fit around the stair modules during erection. Practical considerations, such as manageable transportation, guided the maximum panel sizes, since roadway lanes between the fabrication site and the shake table limited what could be delivered. Constructability was tied to hoisting and placement, as the substantial panel weights directly affected erection, see Figure 5. Performance guided the detailing, with panels arranged as symmetrically as possible to balance weight and stiffness across the structure. Despite these efforts, stair openings and heavier stair units created eccentricities, which were addressed by strategically adding supplemental weight at each floor (varying amount and location on floor plan) to minimize the offset in the center of mass and center of stiffness.

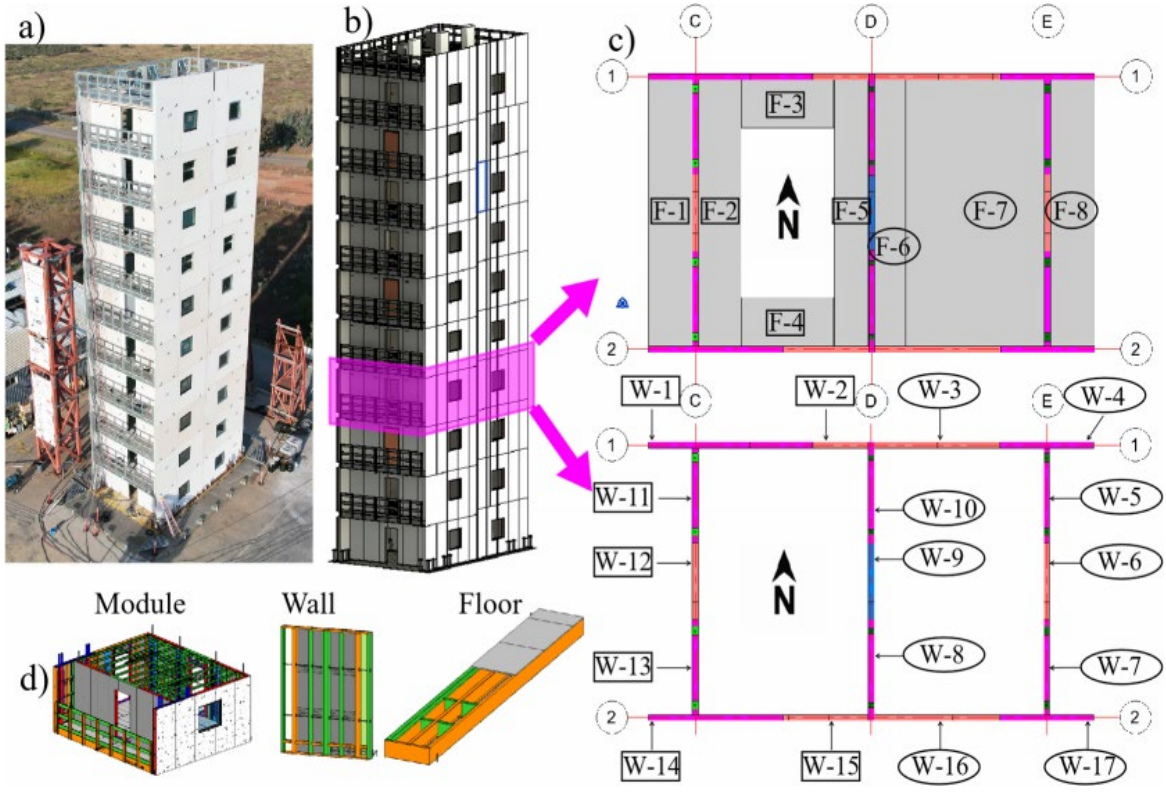

Figure 4. CFS10 assembly layout: (A) full-scale specimen; (B) BIM model; (C) floor plan arrangement, rectangular-panelized, oval-modular; (D) representative assemblies (ceiling assemblies not shown for clarity).

Figure 5 compiles the weights of the prefabricated components, bringing together floor panels of 1.5–4.5 kN, roof panels of 2.4–10.1 kN, wall panels varying from 0.7–10.6 kN, and modular walls ranging between 0.8–8.8 kN. At the larger scale, fully assembled volumetric modules weighed between 66– 91 kN. This range illustrates both the diversity of prefabricated elements

and the lightweight characteristics of CFS, where even complete modules remain within practical lifting capacities.

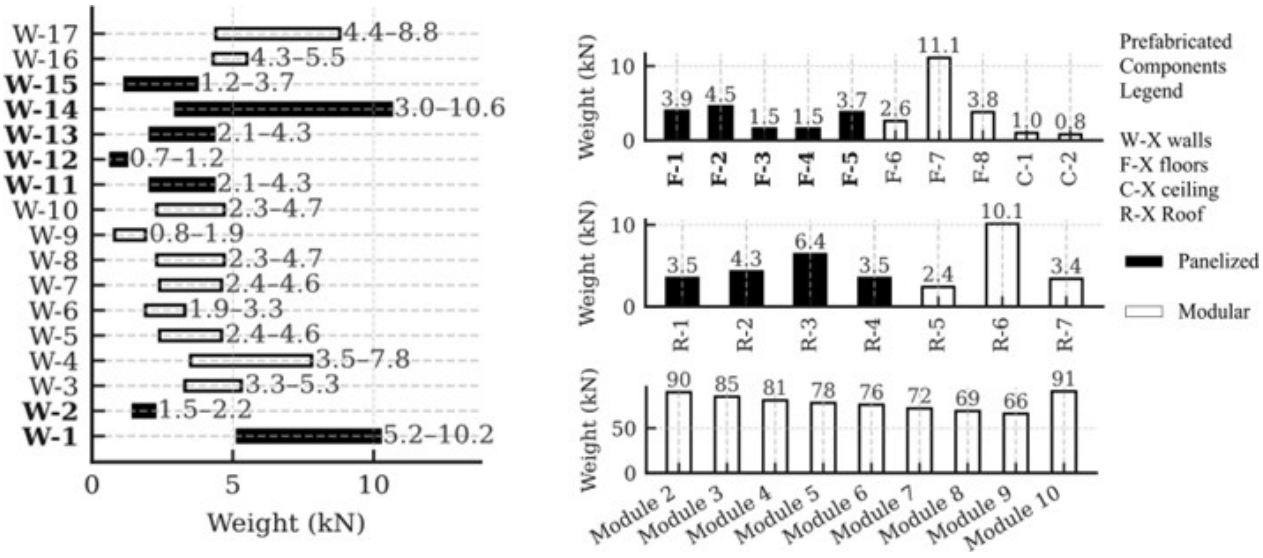

Figure 5. Prefabricated components' weights. Note that (3D) modules were assembled on-site from the noted floor and wall panels, and modules start at two, given that the first level was stick-framing.

Redesigning for Modular

To incorporate the modular concept into CFS10, adaptations were required from the original design. BIM coordination and modeling were essential in planning strategies for modular (3D) adaptation. By testing different concepts and visualizing them in the model, advantages and limitations were identified, leading to the level-by-level integration shown in Figure 2 as the most suitable approach for the project. The adaptation to modular construction introduced a series of challenges that required close coordination. Some were identified early, while others emerged as unintended consequences of implemented solutions. All were analyzed and addressed through the 3D BIM model, which remained central to navigating this evolving process. The following coordination issues illustrate both interdependent and stand-alone challenges resolved during implementation.

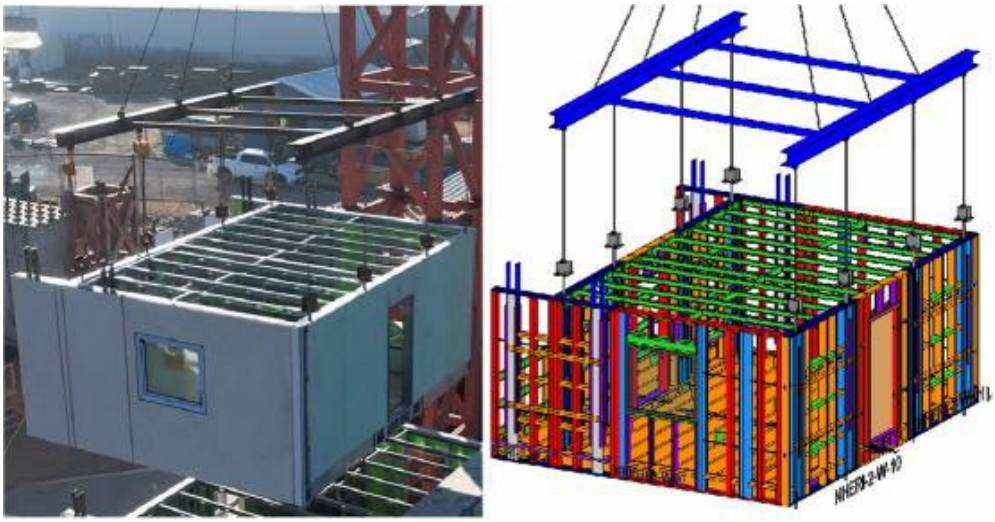

Figure 6. Module 3 lift shown in on-site operation (left) and BIM model representation (right).

To approximate real-world conditions, the six-sided module (Figure 6) was designed with the floor placed at the bottom. This configuration allowed a conventional diaphragm design to be preserved, and the ceiling to function as a drop ceiling. To ensure structural rigidity during the module lift process, ceiling joists were oriented perpendicular to the floor joists. However, this approach eliminated the ledger-hung floor design on the modular side, introducing an elevation difference between the panelized and modular portions, as shown in Figure 7. The resulting elevation difference created a diaphragm discontinuity, which risked generating undesirable stress concentrations around the module studs. To mitigate this, a continuous row of blocking in the wall assemblies was added at the diaphragm edge. It is noted that this elevation difference did not create a final floor elevation variation between the module and panel sides of the building.

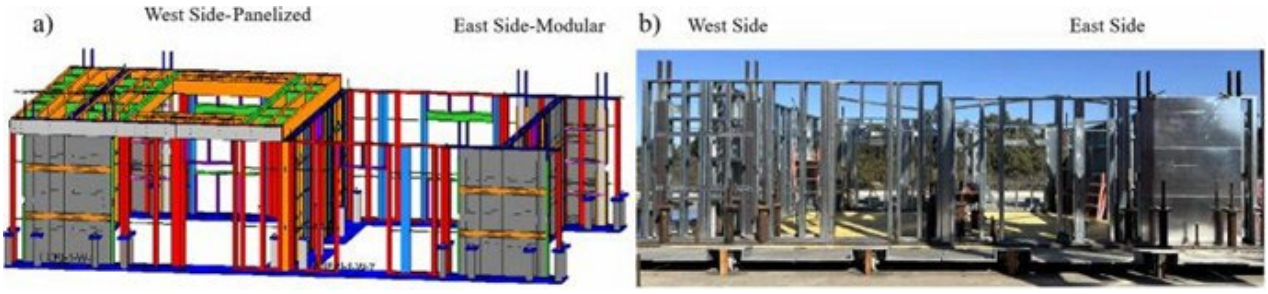

Figure 7. Modular-panelized level difference: (A) BIM model, (B) on-site condition.

As the blocking had to be installed flush with the diaphragm's top surface, the space beneath it became inaccessible, complicating the connectivity of lateral force-resisting elements between subsequent modules. The tie-rod system was adjusted by raising the elevation of the couplers, while the hold-down system for the adjacent blockings of the endposts had two conditions, see Figure 8. Condition (1) in which hold-down plates were used (levels 2-6), blocking was replaced by a flat strap, and the plates were slid up to allow welding access. Originally designed for side fillet welds, the plates were modified to include a top-access slit for a plug weld to maintain connection strength. For hold-down brackets (levels 7-10), the blockings received a customized cut and were installed in the field after placement of the hold-down; the blocking action remained effective, as the cut did not compromise the stiffness required for load transfer.

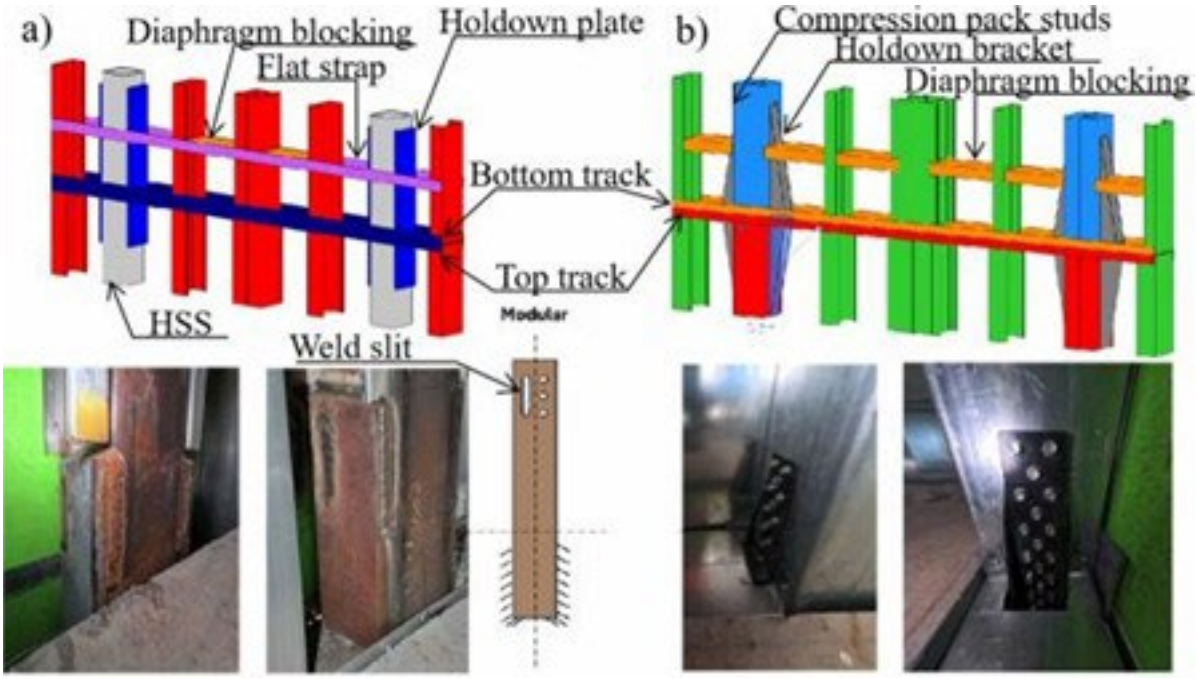

Figure 8. Hold-down system for module-module connections (A) hold-down plates and (B) hold-down brackets.

In parallel with these modifications, a module lifting strategy was developed. The system was required to ensure both robust load transfer for structural integrity and safe handling during lifting. The tie rod system provided eight strategically located all-thread rod (ATR) points, which were adapted for lifting, see Figure 9. To achieve a level and stable lift, the proposed solution was a steel lifting frame with eight pickup points for chain connections. The lifting frame and associated hardware were designed and implemented by the research team. Each chain was attached to an adaptor designed to engage the varied sized ATRs, enabling a pure vertical lift and providing the stability required under mildly windy conditions.

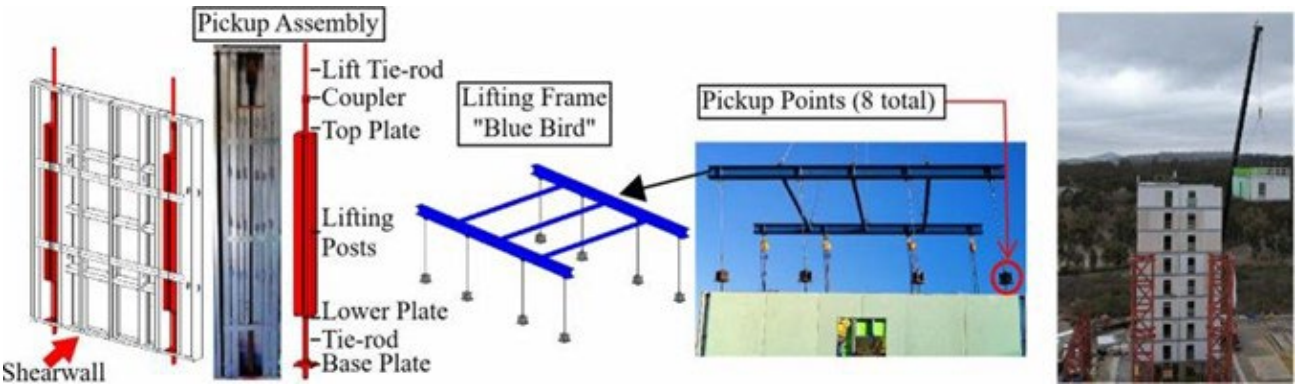

Figure 9. Modular pickup assembly showing lifting posts, tie-rod and plate connections in the BIM model, contrasted with on-site lifting using the eight-point frame.

MODULAR STAIR SYSTEM (MSS)

As part of this landmark 10-story cold-formed steel building, a 9-story prefabricated steel scissor-style stair tower was incorporated. The stair tower was located on the west side of the building, with the stairs transverse (weak) axis parallel to the X-axis of the building and the stair strong axis parallel to the Y-axis of the building. As shown in Figure 10, an individual story of stairs was assembled as a modular stair system unit (MSS). The MSS units were prefabricated, pre-assembled off of the building, with major components prefabricated off-site.

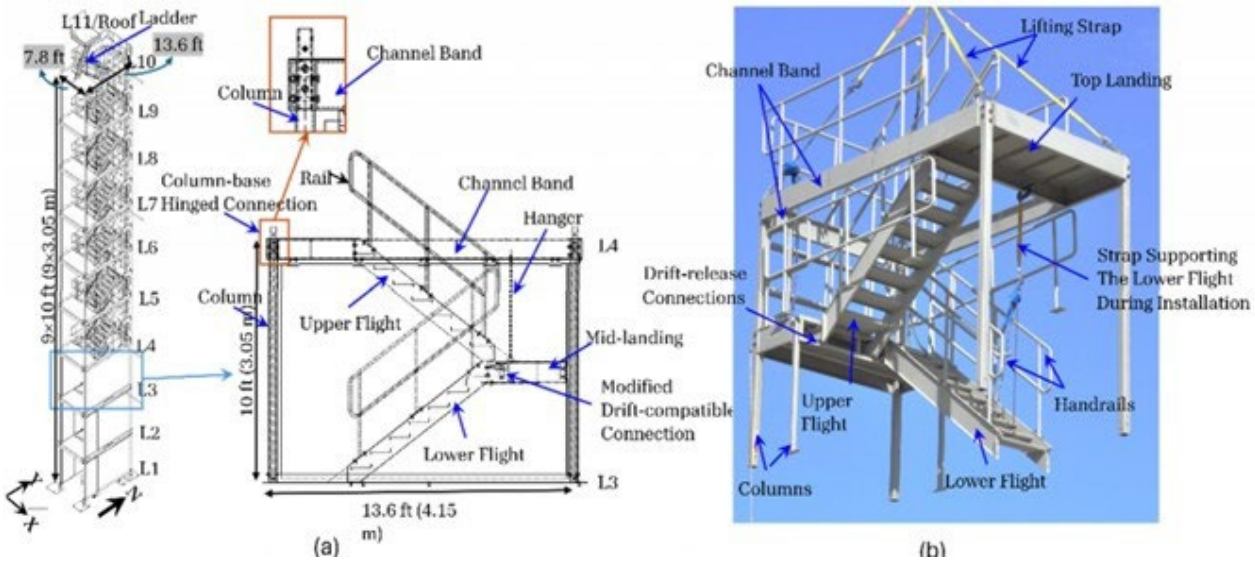

Figure 10. MSS tower (left) and typical modular stair system elevation view (right).

All units were installed as one complete MSS story. Each stair unit was a self-supporting module with hinged connections at the base of the stair columns. These columns consisted of vertical HSS that spanned floor to floor and support the gravity load of the stair channel band and landings. In traditional construction methods, commonly referred to as stick-framed, stairs lack these continuous vertical elements. Therefore, scaffolding or other temporary support around stair openings during construction is required. In contrast, MSSs are self-supporting and installed as complete units, eliminating the need for such temporary works. The use of the modularity concept in the stair system design resulted in reduced construction time and improved control over stair-to-diaphragm construction tolerances. In modular construction, MSS units can be installed either before or after the floor diaphragm and other structural elements, offering increased flexibility in the construction process. Moreover, they can be stacked multiple units at a time.

CONSTRUCTION PROCESS

Virtual Design and Coordination Phase

The coordination phase consisted of providing continuous model-based support to resolve interface issues, foresee potential clashes, and adapt sequencing strategies. BIM tools were used to generate panel layouts, placement plans, and connection details, which led to the project's smooth execution. Designers and fabricators, led by the BIM model led to the success of the program.

Stick-Framed/Panel Installation Phase

Work began at the shake-table platen interface: bottom tracks were anchored to the platen, and the designated lateral force-resisting elements were fixed to the base. With the interface established, first-floor stick framing started on Line D, and the other lines followed its layout. Once all walls were in, the west stair and the west-side floor panels were installed. Panelized construction then advanced level-by-level along the west elevation following a consistent sequence: perimeter wall panels W-15 through W-11 together with W-1 and W-2 were set to establish the plan, after which the next-level floor panels were flown. This cadence aligned crane picks and supported the staggered construction pace across stories.

Modular Assembly Phase

In this phase, the volumetric units were assembled adjacent to the main structure using a pony-wall stand as a temporary base. Due to the tight framing tolerances, especially around intersections and interior corners, the initial assembly sequence was refined through early adjustments to ensure all components could be placed without interference. Each module was constructed from the bottom up, beginning with floor panels to establish a stable base. Wall panels were then installed in a sequence that allowed clear access for fastening and alignment. Once the enclosure was complete, ceiling and diaphragm elements were added to finalize the unit. This process allowed the team to avoid rework during assembly and ensured that modules remained within tolerance for lifting and placement.

Lifting the modules demanded a high level of precision. The first lift set the precedent for all subsequent placements, refining the process through execution. To provide the required stability during lifting, four of the eight chains had to be adjustable, allowing the frame to compensate for any imbalances. Additionally, two guide cables were attached to each module to assist with alignment during hoisting. The modules were lifted slowly and steadily into position. Once placed, the crew inside the structure connected the tie rods from the lower level to the incoming module, securing its position and enabling the remaining structural and diaphragm connections to proceed.

Construction Sequence

To maintain a smooth construction flow, a sequence was planned that leveraged the advantages of each type of construction, see Figure 11. It began with the placement of the bottom tracks over the transfer plates, followed by the stick-framing of the first floor, which served as the structural base for the rest of the building. From there, the construction sequence was established: stair modules were installed first, always extending one level above the upcoming volumetric modules. Once the stair module was in place, the corresponding volumetric module was lifted and positioned alongside it, forming the east room. With the module secured, wall and floor panels were installed to complete the west room and the level's enclosure. This procedure, stair, module, then panels, not only balanced speed with control, but also created a continuous workflow. As soon as a module was lifted into place, the next one was being assembled, while panel installation proceeded in parallel. This overlapping pace allowed the teams to maintain momentum and keep construction moving steadily from level to level all the way to the tenth floor.

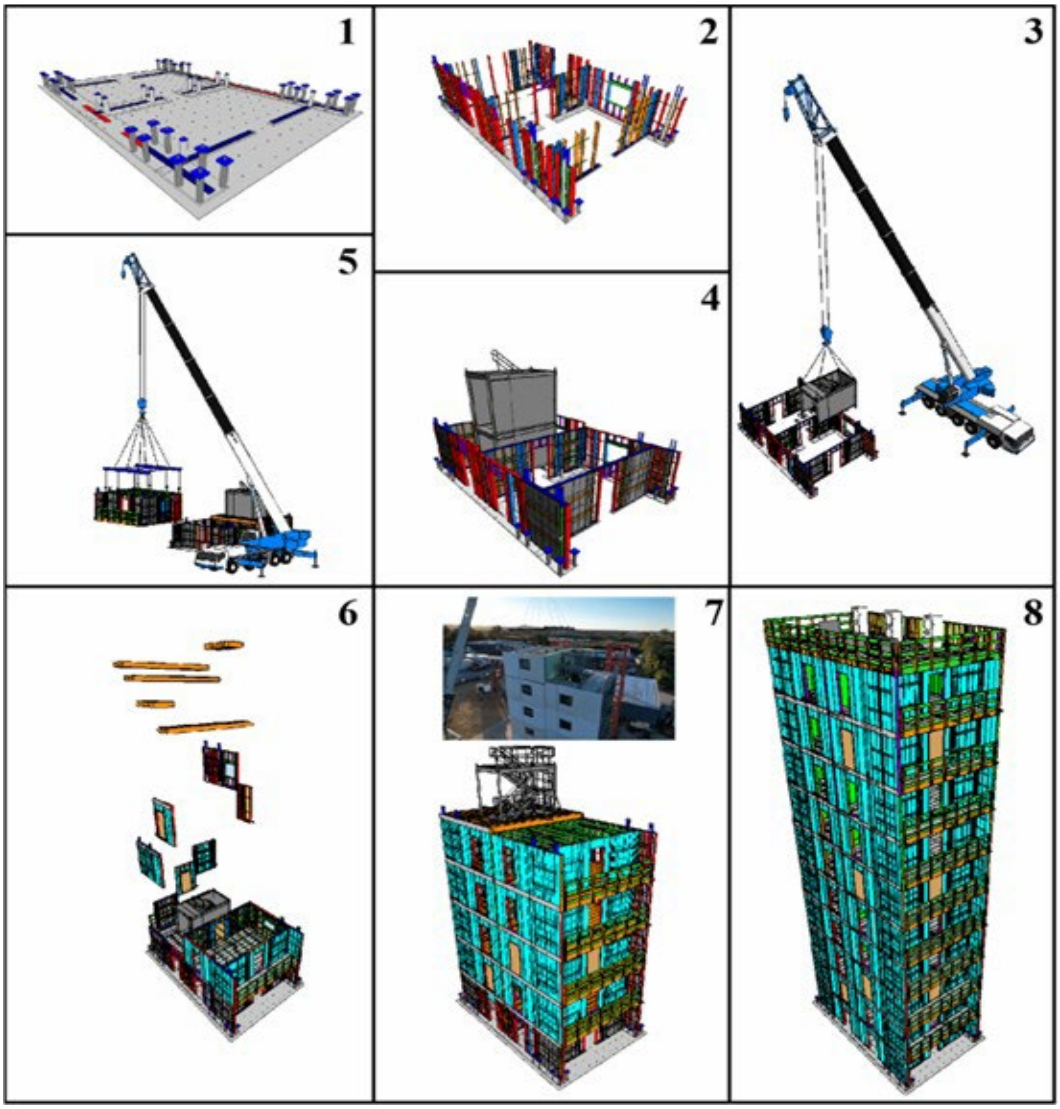

Figure 11. CFS10 construction sequence.

The gypsum board finishes within interior assemblies were deferred until after structural installation to allow the crew to complete the connections and other details required for load transfer. Once the structure was complete, gypsum finishes, and suspended ceilings were installed throughout the building.

INSTALLATION OVERVIEW AND DISCUSSION

The times presented in Table 1 correspond to on-site installation durations, defined as the period required for the field crew to flight, set, align, connect, and secure components for each construction method. These values capture on-site work only and exclude panel or module

fabrication, off-site preassembly, and shop work. This phase is critical because extended on-site work escalates costs, increases safety exposure, and heightens vulnerability to site and environmental uncertainties that lead to delays, productivity losses, and quality decline.

Table 1. Comparison of Installation-Only Time Across Construction Methods.

Construction Methods	LEVEL									
	1	2	3	4	5	6	7	8	9	10
Stick-Framed	131h23	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Panelized	N/A	12h51	9h22	5h36	6h32	5h40	5h15	3h57	3h41	5h21
Modular		0h30	1h10	1h37	0h40	0h37	0h31	0h44	0h38	0h53

Another important factor is not only the duration each team requires to complete the work, but also the size of the crew involved in the installation. On average, the crews consisted of 4 for stick-framed, 5 for panelized, and 6 for modular. Using the installation times in Table 1 and the crew sizes, Table 2 presents the total man-hours required to complete the on-site installation of all CFS components in the CFS10 project for each construction method.

Table 2. Comparison of Installation-Only Man Hours Across Construction Methods.

Construction Methods	Stick-Framed	Panelized	Modular
Man-Hours	511.6	287.77	44.32

Installation metrics show clear differences across the three methods. On Level 1, crews spent 131 hours as the whole construction process was done on-site. Once the stick-framing was complete, subsequent levels showed the effect of industrialization. Panelized portions typically took 4-7 hours each, while modular units were set in about 30–100 minutes. Accounting for crew size, total installation only man-hours were 512 for stick-framed, 288 for panelized, and 44 for modular work. It is worth noting that panelization and modularization also require man-hours for their prefabrication; however, given the industrialization of their processes, the labor becomes more efficient. With these values, the focus is on active installation, specifically the portion most tied to cost, schedule risk, and workflow continuity; within this phase, modular concepts reduce the number and complexity of crane lifts, further boosting productivity, increasing cost benefits, and promoting safety.

The implications extend beyond speed. Stick-framing was customizable and forgiving but labor-intensive and slows down the construction progress on site. However, it is better for sequencing

and working around variabilities in the field. Panelization delivered intermediate gains with prefabricated layouts and fewer clashes on site. Modularization produced the largest savings on-site by shifting complexity off-site; however, it required tighter coordination at diaphragm joints, modified hold-downs, and close tolerances with the interconnecting pieces, and significant coordination work in design. The Modular Stair System (MSS) removed temporary stairs and provided a consistent enclosure strategy across nine stories, helping keep the schedule on track. The present observations emphasize that the construction strategies enabled efficient installation while sustaining performance under severe seismic demands. Design standards do not explicitly address modular interfaces, diaphragm-edge blocking, or stair-to-diaphragm connections in multi-story CFS systems. Results from CFS10 indicate that while CFS modules demonstrated resilience and practicality, connection details still have room for improvement, warranting further research to advance modular interfaces and support future updates to design guides and codes.

PRACTICAL FINDINGS AND APPLICATION FOR CONSTRUCTION

The CFS10 test program resulted in several practical findings with direct application for construction, including the following:

- Clear differences in on-site labor across stick-framed, panelized, and modular installation were observed. Modularization was the fastest approach, requiring only 15% of the panelized man-hours and 9% of the stick-framed man-hours. The shorter on-site duration reduced congestion, crane use, weather exposure, and risk, which improved working conditions for the crew. However, it is notable that modular construction requires higher coordination compared with other construction methods, therefore full BIM integration was vital for its success.

- The design and installation of CFS modules advantageously served to facilitate lift of additional materials required for completion of construction within a given floor level, leading to an efficient use of crane effort due to the enclosed nature of the module.

- In this program, the modules required assembly on-site due to transportation limitations. While the efficiency of their assembly was improved by constructing them of panelized floors and walls, designing the project as modular in the early stages should consider transportation limitations (from shop to site), with the aim of avoiding these constraints and assuring factory quality from the beginning.

- Module-to-module interlocking was easier for the construction team when the crew had a positional reference, such as the hold-down plates, to guide the module during lifting and placement. It is important in module connection design to provide simple reference points that help the crew align the module as it is set.

• The self-supporting modular stair system often ran one floor above the active work level during construction. This layout improved access and eliminated the need for scaffolding.

As of this writing, the specimen has completed all testing phases and was fully deconstructed. An interesting aspect of this phase was during deconstruction, the modular units were removed intact while the panelized side had to be taken apart panel by panel, which underscored modular construction's advantages for speed, safety, and control in both assembly and deconstruction. Future publications will build upon data and observations from this effort, including the lead author's thesis (in progress at the time of writing), which aims to synthesize the design decisions, implementations, and their relation to practice as implemented within the landmark CFS10 building program.

ACKNOWLEDGMENTS

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Pre-Test High-Fidelity Numerical Modeling of a Ten-Story Cold-Formed Steel-Framed Building Under Seismic Loading

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ABSTRACT

In the United States, current seismic code provisions restrict cold-formed steel (CFS) framed buildings to a maximum of six stories. To assess the potential for constructing taller buildings and to address the increasing demand for resilient, efficient, and non-combustible urban housing, a ten-story CFS-framed archetype building was designed using component-level test data utilizing strength capacities exceeding current code-based values. This archetype was the subject of a seismic testing program performed in June 2025 at the University of California San Diego's Large High-Performance Outdoor Shake Table (LHPOST6), as part of an NSF-funded research project focused on advancing the use of CFS in mid-rise buildings in moderate-high seismic zones. In preparation for the full-scale dynamic tests, a high-fidelity nonlinear finite element model of the ten-story building was created using OpenSeesPy. The model incorporates detailed representations of the structural components and connections, capturing both material and geometric nonlinearities. The development of the model is grounded in experimental results from prior studies of CFS-framed wall lines. Focus is placed on accurately modeling the in-plane

behavior of all aspects of wall lines, including chord studs, field studs, gravity studs, top and bottom tracks, rim tracks, steel sheets, finishes, and story-to-story connections. The model considers the effects of geometric nonlinearities (either implicitly or explicitly), including buckling of steel sheet sheathing; local, distortional, and global buckling of CFS members; and member and story-level (P-δ and P-Δ) effects. This paper presents pre-test simulation results that characterize the expected dynamic response of the building under earthquake excitation. The findings helped inform expectations during the experimental program and provide preliminary indicators of system-level performance trends in taller CFS-framed buildings.

INTRODUCTION

The utilization of cold-formed steel (CFS) framed structural systems has experienced substantial growth within North American building construction, especially for structures of low to moderate height. Present seismic provisions in building standards (ASCE/SEI 2016, 2022) restrict CFS-framed buildings to a maximum height of 19.8 m when located in regions classified as Seismic Design Categories C and D. Despite extensive investigations into the behavior of individual CFS elements, which have contributed to significant improvements in design specifications including AISI S100 (2016), S240 (2015a), and S400 (2015b), research examining the seismic response of complete CFS structural systems has been sparse. North American research efforts have produced two comprehensive experimental programs that investigated full CFS building systems through large-scale shake table testing utilizing the National Science Foundation (NSF) funded Network for Earthquake Engineering Simulation (NEES) and the Natural Hazards Engineering Research Infrastructure (NHERI). The initial program, designated as the CFS-NEES project, featured experimental testing of a two-story, full-scale CFS structure with OSB sheathed shear walls conducted by Peterman et al. (2016) utilizing the NEES@Buffalo testing facility. This investigation represented the pioneering North American study to evaluate comprehensive system-level seismic behavior of CFS construction. The test specimen consisted of a two-story structure with plan dimensions of 15.2 m by 7 m. Subsequently, the CFS- HUD (Housing and Urban Development) program was executed by Hutchinson et al. (2021) at the NEES@ UC (University of California) San Diego testing facility. This experimental program included both seismic performance testing and subsequent fire testing on a six-story, full-scale CFS-framed building utilizing steel sheet sheathed shear walls. The test structure had a floor area of 10.4 m by 7.3 m and maintained a typical story height of 3.1 m.

A collaborative research program involving multiple universities and industry partners, under the project name: Seismic Resiliency of Repetitively Framed Mid-Rise Cold-Formed Steel Buildings (or CFS-NHERI for short), was established with principal support from the NSF. This initiative aims to advance the understanding of how mid-rise CFS structural systems respond to seismic forces and to translate these findings into enhanced seismic design provisions for these structures. Within the scope of the CFS-NHERI program, extensive experimental investigations have been performed to characterize the inelastic response characteristics of structural components and connections. Significant research outputs from this program include the work of Singh et al. (2022b, 2022c), who examined steel sheet sheathed shear walls; Z. Zhang et al.

(2021, 2022b), who focused on computational modeling of connections and shear wall systems; and Castaneda (2022), who investigated floor system and diaphragm performance.

In June of 2025, seismic testing of a ten-story CFS building was successfully completed utilizing the recently upgraded 6-degree-of-freedom Large High-Performance Outdoor Shake Table Facility (LHPOST6) located at the NHERI@UC San Diego research center (Van Den Einde et al., 2021). This capstone experimental investigation (commonly referred to as CFS10 – see cfs10.ucsd.edu) presents a significant opportunity to evaluate both structural and non-structural seismic response characteristics for this distinctive building category, and concluded with full-scale fire compartment tests. Notable aspects of this tall test specimen include the incorporation of fully detailed non-structural components and a structural height that exceeded existing limitations specified in current U.S. seismic provisions (ASCE/SEI 2016, 2022). These experiments generated essential full-scale, system-level validation data for an advanced CFS structure exposed to three-dimensional earthquake excitations, thereby facilitating improvements in both structural and non-structural seismic design specifications as well as performance-based engineering guidelines. Furthermore, supplementary fire exposure experiments performed in July of 2025 yielded important data regarding thermal response and smoke propagation characteristics in seismically damaged building compartments. A more detailed description of the CFS10 building and its design is provided later in this paper. An overview of the specimen and preliminary seismic test phase findings are also presented in the current conference (Hutchinson et al., 2026).

A high-fidelity numerical model was developed to simulate the anticipated behavior of the test building prior to the shake table experiments. This pre-test model, implemented in the open source software OpenSees (McKenna et al., 2000; Zhu et al., 2018), represents one of the most comprehensive CFS structural models created to date, capturing the complete ten-story system with detail. This modeling approach utilizes discrete elements to capture each individual structural component, including studs, tracks, sheathing panels, hold-down assemblies, and tension tie-rod systems. The model accounts for a wide range of geometric nonlinearities, in some cases employing phenomenological models including for steel sheet sheathing panel buckling and CFS member local and distortional buckling, and in other cases explicitly accounting for member and frame global buckling in the overall formulation and solver. Material nonlinearity is incorporated through phenomenological hysteretic models that capture the cyclic strength and stiffness degradation as well as pinching behavior typical of CFS-framed shear wall assemblies (with different models for the shear wall itself, the story-to-story connections, etc.) and some elements modeled with traditional metal material nonlinearity such as the elastic-plastic model for the tie rods.

Model development was validated through comparison with experimental results obtained from component-level testing. This validated high-fidelity model in parallel with a practice-oriented computational model (J. Zhang et al., 2024, Singh et al., 2024b) served multiple critical purposes: providing pre-test predictions and establishing baseline expectations for structural response, guiding the selection and scaling of ground motions applied during the experimental program, and enabling future comparison studies with the actual test data. In this paper, only the

pre-test predictions by the high-fidelity model are presented, focusing on the model development methodology and the simulated seismic response of the ten-story CFS structure. Comparison with CFS10 experimental measurements is not included in the current study, as the test data from the recently completed shake table tests were still undergoing processing and analysis during the completion of this paper.

DESCRIPTION AND VALIDATION OF THE DEVELOPED MODEL

Earlier research on the dynamic modeling of CFS-framed buildings has generally employed simplified approaches to minimize computational expense. Typical modeling strategies involve representing lateral force-resisting walls through either single nonlinear spring elements or pairs of diagonal nonlinear truss members (Shamim and Rogers 2012). Gravity-load-carrying components are frequently omitted from these models, with the exception of incorporating leaning P-Δ columns, while floor systems are conventionally treated as infinitely rigid diaphragms represented by single-node constraints. Leng et al. (2017) developed high-fidelity numerical models of the two-story CFS-NEES experimental structure, which facilitated enhanced accuracy in simulating the response of discrete CFS structural elements subjected to earthquake excitation. This modeling approach permitted comprehensive evaluation of force redistribution mechanisms among various components including boundary studs, top and bottom tracks, and sheathing materials that form the lateral resistance system.

Extending these developments, Z. Zhang et al. (2022c) created a high-fidelity model to investigate the lateral response characteristics of CFS wall lines, explicitly modeling steel sheet-sheathed shear walls, gravity walls, and effects from non-structural finishes. In contrast to conventional simplified modeling techniques, the detailed modeling methodologies presented by Leng et al. (2017) and Z. Zhang et al. (2022c) exhibited substantial improvements in their ability to accurately simulate the earthquake response of CFS structures and wall systems, respectively. The current investigation employs the high-fidelity modeling techniques established by Leng et al. (2017) and Z. Zhang et al. (2022c). This high-fidelity modeling approach provides enhanced understanding of force transfer mechanisms within wall assemblies and among individual elements of both shear walls (SW) and gravity walls (GW).

Model Description

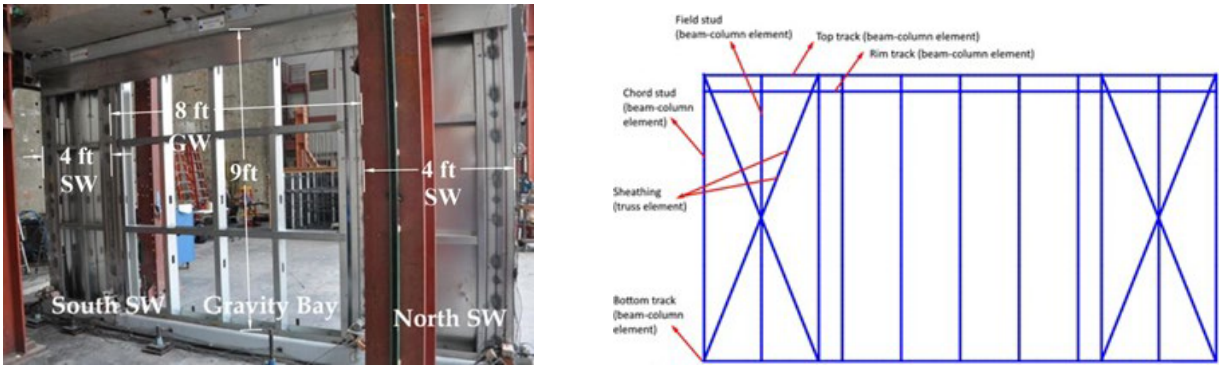
Utilizing the OpenSeesPy framework, a high-fidelity numerical model is constructed. To explain the modeling technique, the numerical model of the test specimen SGGS-1HD from the wall-line dynamic tests by Singh et al. (2022b, 2022c) is used as an example (see Figure 1a). The modeling framework employs displacement-based beam-column line elements to simulate all structural framing components, including studs and track sections, as illustrated in Figure 1b. The "section aggregator" command is implemented to independently specify the axial and flexural behavior of these beam-column elements.

The nonlinear axial and flexural response of tracks and studs is represented through an elastic-perfectly plastic (EPP) material formulation, scaled to match nominal capacity values. Element strength limits are determined following AISI S100-16 (AISI, 2016) provisions, which consider

local buckling, distortional buckling, and material yielding (detailed further in the following subsection).

While the majority of framing elements employ centerline modeling conventions, ledger (rim) tracks and end joists are modeled to capture their complete web depth through the inclusion of supplementary beam elements, which are positioned orthogonally and connected with rigid constraints to the primary horizontal beam-column elements that represent the ledger tracks or end-joists. This modeling strategy enables the distribution of moments throughout the full depth of the ledger or end-joist components, rather than concentration at a single nodal connection, thereby providing enhanced accuracy in simulating the moment transfer characteristics (typically ignored in design) at stud-to-ledger-track and stud-to-end-joist interfaces.

The steel sheet sheathing, illustrated in Figure 1a, is modeled through a pair of diagonal truss elements (Figure 1b), incorporating a Pinching4 (P4) material formulation (Figure 2). This P4 constitutive model employs a four-point linear segment backbone curve and simulates cyclic degradation phenomena including unloading stiffness deterioration, modified reloading paths, and strength degradation, following the requirements outlined in Section 9.8 of ASCE 41-17 (ASCE/SEI 2017). As shown in Figure 2, the backbone curve is defined by four positive envelope points (ePd_1, ePf_1) through (ePd_4, ePf_4) and four negative points (eNd_1, eNf_1) through (eNd_4, eNf_4), where ePd_i and eNd_i represent deformations while ePf_i and eNf_i represent forces at each point i. The reloading path creates the pinching effect through four control factors: rDispP and rForceP define the positive reloading pinch point as fractions of the maximum deformation and force, while rDispN and rForceN define the negative reloading pinch point as fractions of the minimum values. The unloading path is controlled by uForceP and uForceN. Calibration of the P4 model parameters was performed based on cyclic experimental data from steel-sheathed CFS shear wall tests, particularly specimen CW2 tested by Rizk and Rogers (2017).



(a) (b)

Figure 1. (A) Test specimen SGGS-1HD tested by Singh et al. (2022b, 2022c); (B) OpenSeesPy numerical model of SGGS-1HD wall-line specimen.

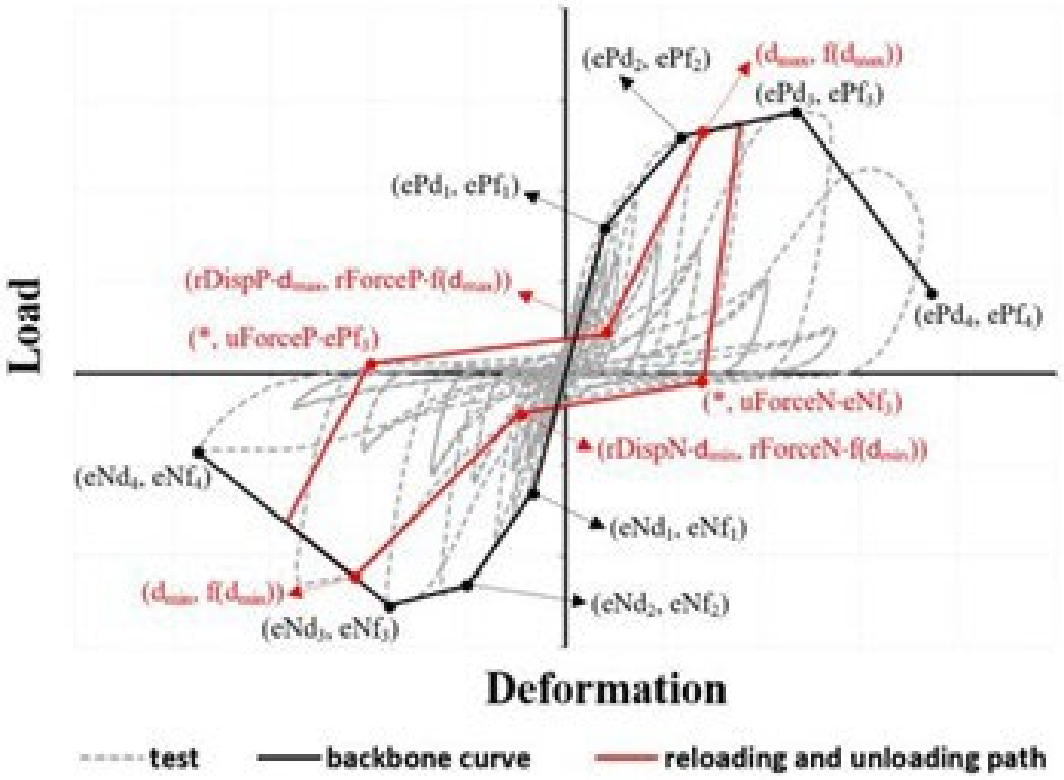


Figure 2. Equivalent energy pinching 4 fit to an experimental response.

The selection of this specimen was based on its similarity to the SGGS-1HD wall-line configuration, sharing equivalent framing dimensions, sheathing thickness, and fastener patterns. The constitutive model additionally considers the height variation between the CW2 test specimen (2.44 m) and the SGGS-1HD wall assembly (2.74 m). In cases where architectural finishes are present, supplementary diagonal truss elements are also included, similarly utilizing the P4 hysteretic material. Gypsum finish parameters were established from cyclic experimental results of CFS-framed walls with gypsum boards, as reported by Z. Zhang (2024). This modeling technique provides more accurate representation of both sheathing and non-structural finish response characteristics during reversed cyclic loading.

Stability Assumptions

Recent experimental investigations involving CFS shear walls, wall lines, and complete structural systems have frequently documented buckling in CFS framing elements (Schafer et al., 2016; Brière and Rogers, 2018; Rizk and Rogers 2018; Santos and Rogers 2018; Singh et al. 2021). Therefore, accounting for the mechanisms associated with buckling in the capacity of framing components is crucial when modeling CFS structures and their subsystems. The present investigation (as previously noted) employs displacement-based beam-column elements with displacement-based formulations to model studs and track members (Mazzoni et al., 2006).

Global flexural buckling effects are captured at the member level by subdividing each framing element into several beam-column segments (P- δ) and at the frame-level (P-Δ) by conducting analyses that incorporate geometric nonlinearity through the corotational coordinate transformation. The section aggregator command (Mazzoni et al., 2006) facilitates the integration of separate uniaxial material formulations representing axial, bending, and torsional responses into a single beam-column element cross-section. These individual uniaxial material models operate independently from one another.

The 3D beam-column elements within the model incorporate axial, in-plane flexural, and out-of-plane flexural responses. The nominal member strength, which considers limitations from yielding and multiple buckling modes, is used in place of the yield strength for both axial and bending material models. This methodology guarantees that all elements remain within their nominal capacity limits and insures the model implicitly accounts for local and distortional buckling of the cross-sections as well as material yielding. Member global flexural buckling is captured explicitly through the finite element model formulation Additional information on this modeling strategy is available in Z. Zhang's numerical work (Zhang, 2023; Zhang, 2025).

Model Validation

The validation of the established finite element modeling approach is conducted through comparison of model predictions against experimental results from the SGGS-1HD wall-line test (Singh et al., 2021). Figure 3 illustrates good correlation between simulated and measured cyclic behavior. Additional details on the model validation could be found in Eladly et al. (2025).

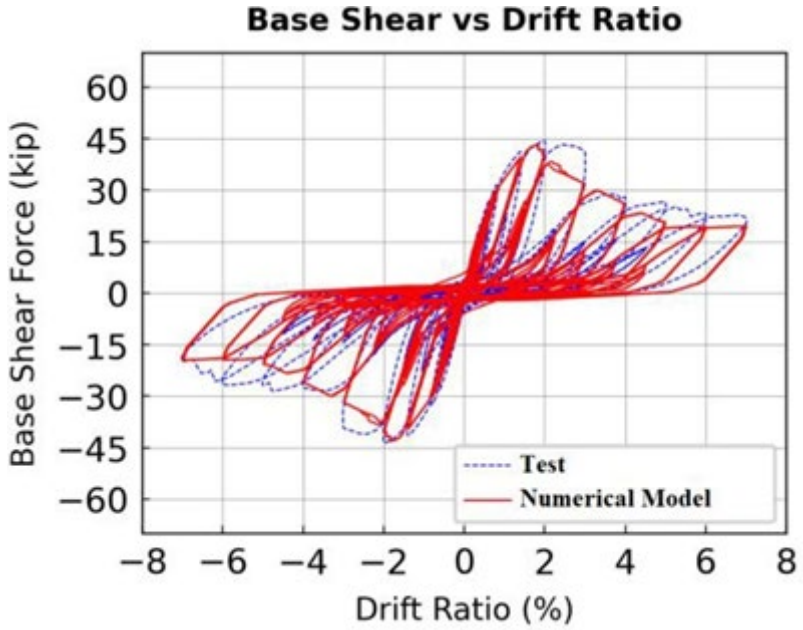


Figure 3. Experimental and FE base-shear vs. drift ratio response (specimen SGGS-1HD). Tests described in Singh et al. (2021) (1 kip = 4.48 kN).

CFS10 BUILDING DESCRIPTION AND DESIGN

The ten-story test building is shown in Figure 4. It was designed as a CFS-framed building positioned at a theoretical location within a high-seismicity zone adjacent to Irvine, California, featuring Site Class C soil conditions (characterized by very dense soil and soft rock formations) as documented by Singh et al. (2022a). This test specimen incorporates CFS steel stud framing, lateral force-resisting walls with single-face steel sheet sheathing, and gravity walls. The tested building is taken as a slice from a larger building archetype motivated by the work of Torabian et al. (2016). Consequently, the northern elevation constitutes an exterior facade incorporating an EIFS (Exterior Insulation and Finish Systems) system, while the remaining three exterior elevations feature interior finishing systems. The floor construction employed a dry assembly system (no poured concrete), utilizing ledger-framed CFS floor joists overlaid with cementitious structural panels configured within panelized or modular construction (Rivera et al., 2026).

Lateral seismic resistance was achieved through three Y-direction wall lines, each incorporating a pair of steel sheet-sheathed lateral walls, along with two X-direction wall lines that similarly featured two steel sheet-sheathed lateral walls per line. Numerous design aspects of these shear wall extend beyond the scope of current AISI S400 specifications, notably incorporating HSS members as chord studs in the lower levels, Power-Actuated Fasteners (PAFs) for steel sheet attachment to HSS chord studs, and steel sheet fastener patterns (whether PAFs or screws) that fall outside standard AISI S400 design tables. Tension forces in shear wall chord studs are accommodated through tie-rod systems in one principal building direction and direct chord stud connections employing splice plates in the perpendicular direction. The building overall height is 30.5 m, exceeding the 19.8 m restriction established in ASCE 7-16 (ASCE/SEI 2016) and ASCE 7-22 (ASCE/SEI 2022). The calculated effective seismic weight, W, equals 1575.0 kN, with the corresponding design seismic base shear, Vb , determined to be 173.2 kN for both principal directions, based on an assumed R = 6.5 and the selected Irvine, California site conditions. Comprehensive structural design documentation is available in Singh et al. (2022a), with subsequent design modifications detailed in Singh et al. (2024a), including the incorporation of an operable (stair) egress assembly featuring drift-release connections, shake table interface details, and an expansion of construction methods (modular and panelized construction details). The stair system was designed to be seismically resilient, with drift release connections to avoid introduction of excessive lateral stiffness (Sorosh et al., 2025).

Figure 4. Northeast view of the CFS10 specimen with annotations (Hutchinson et al., 2026).

CFS10 BUILDING HIGH-FIDELITY MODEL

The high-fidelity model of the CFS10 building is (to the team's knowledge) the largest OpenSees model ever developed for CFS-framed structures. With above 17,000 nodes and 21,000 elements, the model simulates the behavior of all studs, tracks, SW sheathing, finishes, hold-downs, tie rods, shear anchors, and wall openings. Studs, tracks, SW sheathing, and finishes are modeled the same way described earlier in the wall line model description section. Connections between perpendicular wall lines and story-to-story shear anchors are both modeled using a combination of zeroLength elements and equal DOF constraints. In the CFS10 building, there are four shear walls in the X (E-W) direction with holddowns and splice connected end posts. In the Y (N-S) direction, 6 shear walls are employed with continuous tie-rods sandwiched between end posts. ZeroLength elements are utilized to model holddowns and tie-rods. The lateral resistance of wall nonstructural finishes is modeled using diagonal truss elements with Pinching4 material. The masses of these finishes are assigned to mass nodes. For other nonstructural components that do not provide significant lateral resistance, only their mass is considered, and any contribution to lateral stiffness or strength is neglected. A 3D rendering of the high-fidelity OpenSeesPy model of the CFS10 test building is shown in Figure 5. Detailed description of the model will be provided in the PhD thesis of the first author and additional details in the model development are in Eladly et al. (2025).

TIME HISTORY ANALYSIS RESULTS FOR THE CFS10 BUILDING

This section presents pre-test time history analysis predictions generated by the high-fidelity model for the CFS10 test building. The numerical results presented herein examine the test building's response under bi-directional (XY) design earthquake (DE)-level ground motion from the 1994 Northridge earthquake, specifically the Canoga Park – Topanga Can record (with the 106° component of the input ground motion applied at the X direction of the CFS10 building and the 196° component of the input ground motion applied in the Y direction of the building). DE denotes the design earthquake intensity level for which the ground excitation is scaled. Additionally, analyses using three different ground motions scaled to service-level earthquake (SLE) intensity and to DE intensity are included at the conclusion of this section. These motions were selected from a suite of candidates used in prior large shake table tests, from within the Federal Emergency Management Agency (FEMA) P695 record set (FEMA 2009), and a site-specific record set developed for a nearby site in Irvine, California (Zhang, J. et al., 2024). During the recent shake table test program, a subset of these records were identified and scaled to target hazard levels of service, design, and risk-targeted maximum considered earthquake (SLE, DE, and MCER; see Zhang, J. et al., 2026).

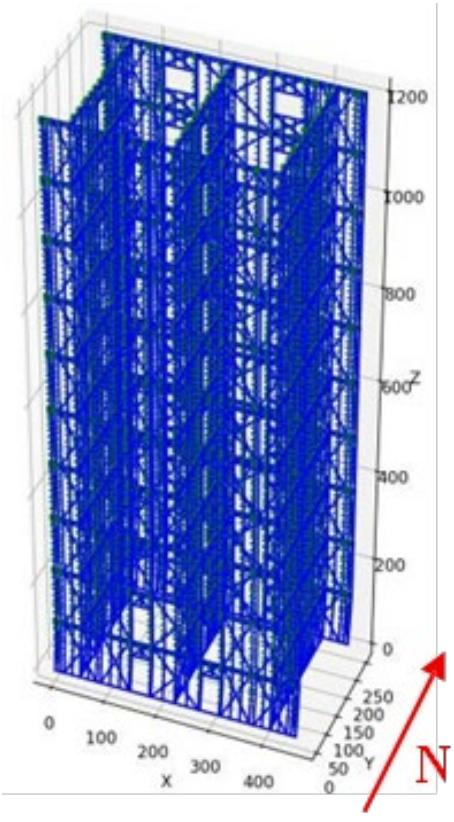


Figure 5. 3D rendering of the high-fidelity numerical model of CFS10 building (units: inch, 1 inch = 0.0254 m).

Figures 6 and 7 illustrate the roof acceleration time history in the X (E-W) and Y (N-S) directions, respectively, of the CFS10 building as predicted by the high-fidelity model for the DE-level 1994 Northridge - Canoga Park - Topanga Can excitation. As observed in the figures, the peak roof acceleration in the Y direction approaches 1g, which is approximately 20% higher than the peak roof acceleration in the X direction. Figure 8 presents the total roof drift ratio time history in both directions, also predicted by the high-fidelity model. The Y direction (N-S) experienced a higher peak roof total drift ratio compared to the X direction (E-W), reaching a maximum of 0.37% compared to 0.23% in X direction. The base-shear versus drift ratio response predicted by the model in both directions, as shown in Figure 9, reveals characteristic pinched behavior typical of CFS systems. From the figure, it can also be seen that the high-fidelity model predicts significant overstrength capacity beyond the design demand levels. Analysis of the base shear response reveals a peak value of around 400 kN in both directions under the DE-level ground motion, which represents an overstrength factor of approximately 2.3 when compared to the design base shear demand of 173.2 kN. This observed overstrength is notably lower than the code-prescribed system overstrength factor (Ω_0) of 3.0 specified in ASCE 7-22 (ASCE/SEI, 2022) for cold-formed steel light-frame shear wall systems with steel sheets. It is important to note that this ratio represents only the overstrength developed during the DE-level event, not the ultimate overstrength capacity of the system.

Figures 10-15 present the numerical Peak Interstory Drift Ratio (PIDR) profiles and Peak Floor Acceleration (PFA) profiles for the CFS10 test building subjected to three different ground motion records scaled to two different scales: SLE and DE. The three ground motions investigated include:

- 1994 Northridge - Canoga Park - Topanga Can record (with the 106° component of the input ground motion applied at the X direction of the CFS10 building and the 196° component of the input ground motion applied in the Y direction of the building);

- 1994 Northridge - LA - City Terrace (with the 90° component of the input ground motion applied at the X direction of the CFS10 building and the 180° component of the input ground motion applied in the Y direction of the building);

- 1989 Loma Prieta - Gilroy Array #3 record (with the 90° component of the input ground motion applied at the X direction of the CFS10 building and the 0° component of the input ground motion applied in the Y direction of the building).

It should be noted that all analyses presented in the current paper consider single ground motion records; cumulative damage from sequential ground motions is not considered.

The results indicate that the finite element model predicts peak interstory drift ratios below 0.2% for SLE-level excitations, with values approaching 0.5% under DE-level motions. Correspondingly, peak floor accelerations remain within 0.3g for SLE-level motions but increase to approximately 1.22g under DE-level seismic demands.

Based on these numerical predictions, the ten-story CFS test building demonstrates adequate structural performance with interstory drifts remaining below 0.5% even under DE-level excitations—well below typical permanent damage thresholds for CFS systems. The predicted response indicates that the structural system maintains sufficient lateral stiffness and strength to control deformations within acceptable limits at SLE and DE levels.

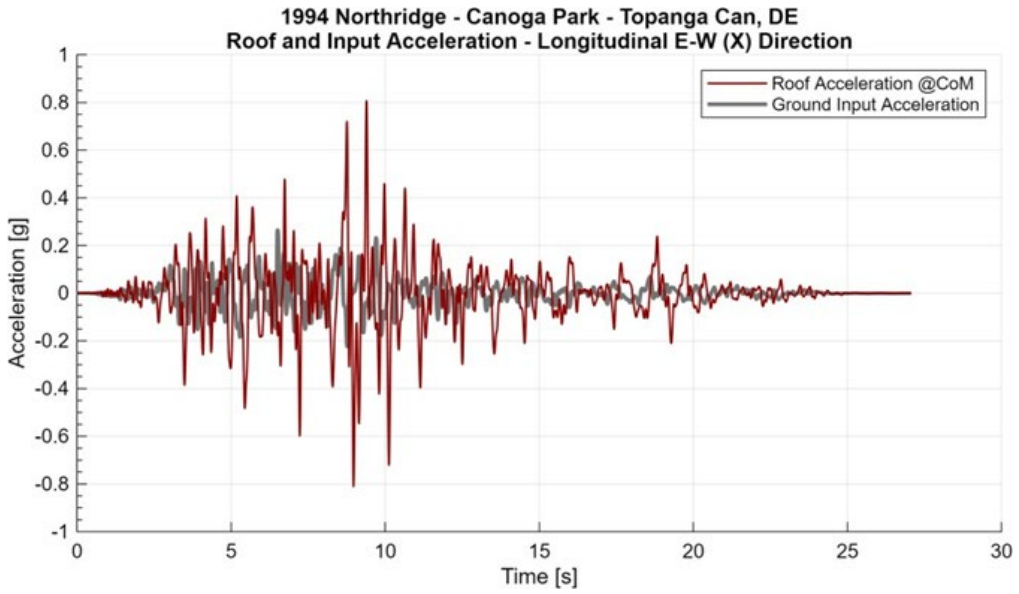


Figure 6. Roof acceleration time history at center of mass (CoM) (predicted by the high-fidelity model) and input acceleration in X direction (1994 Northridge, Canoga Park, Topanga Can, DE). *(Note: the input accelerations used for analyses presented in the current study are achieved input motions during "bare" shake table tests.)*

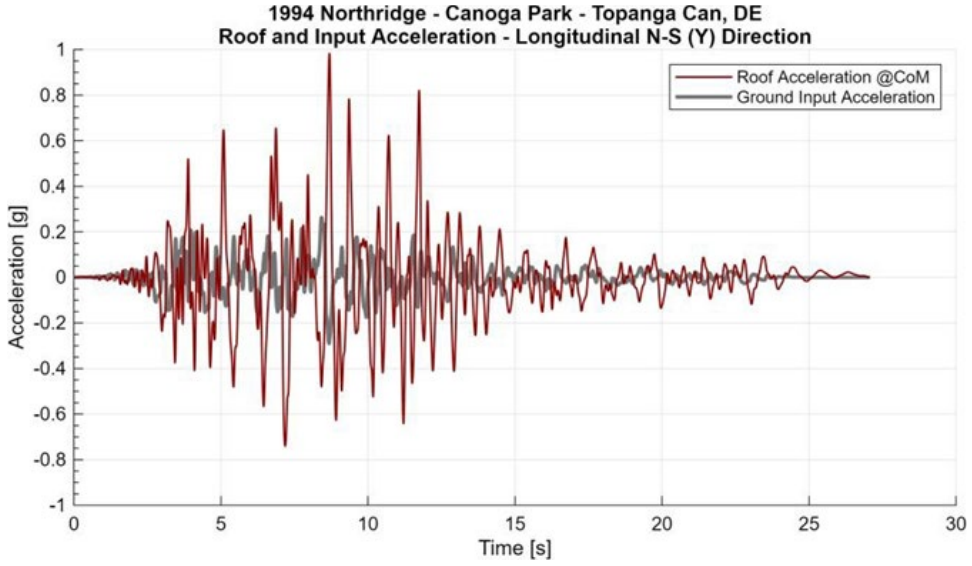


Figure 7. Roof acceleration time history at center of mass (CoM) (predicted by the high-fidelity model) and input acceleration in Y direction (1994 Northridge, Canoga Park, Topanga Can, DE). *(Note: the input accelerations used for analyses presented in the current study are achieved input motions during "bare" shake table tests).*

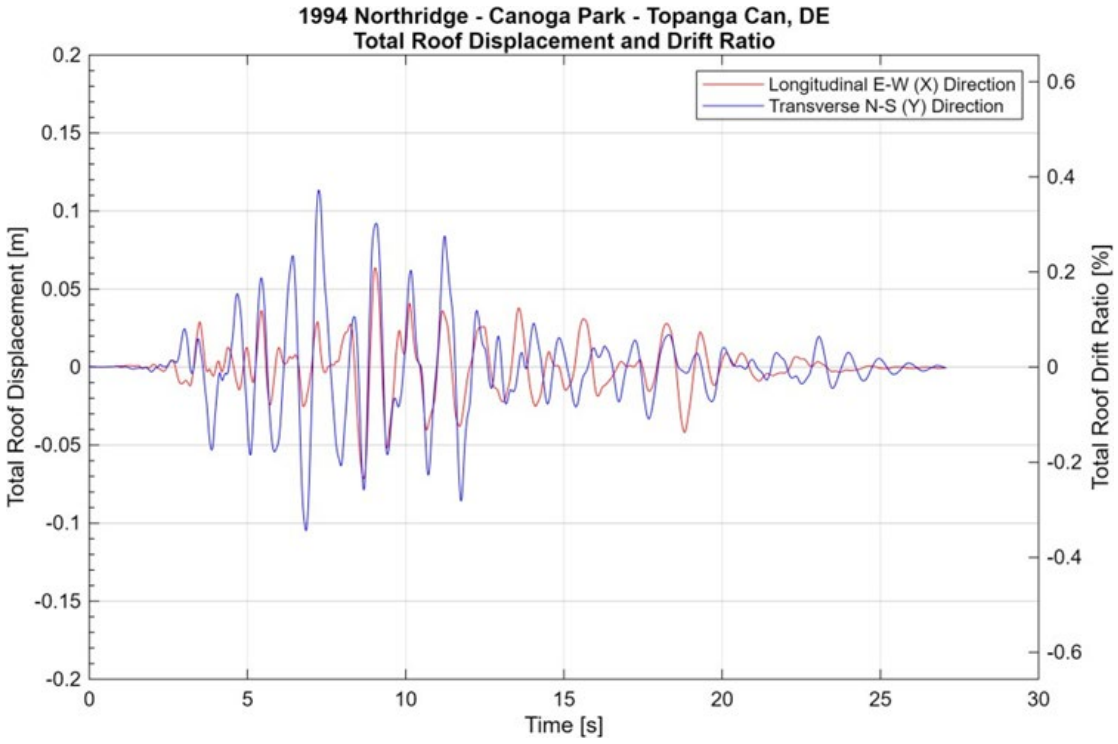


Figure 8. Total roof displacement and drift ratio time history (predicted by the high-fidelity model) in both directions (1994 Northridge, Canoga Park, Topanga Can, DE).

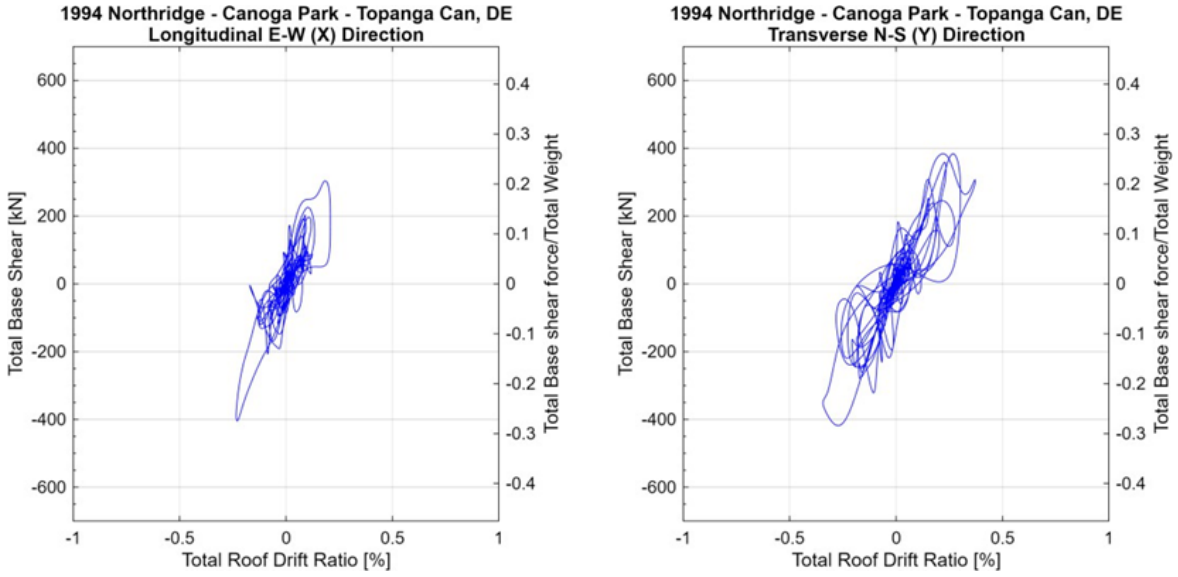


Figure 9. Comparison of base-shear vs. roof drift ratio responses predicted by the high-fidelity model in both directions (1994 Northridge, Canoga Park, Topanga Can, DE).

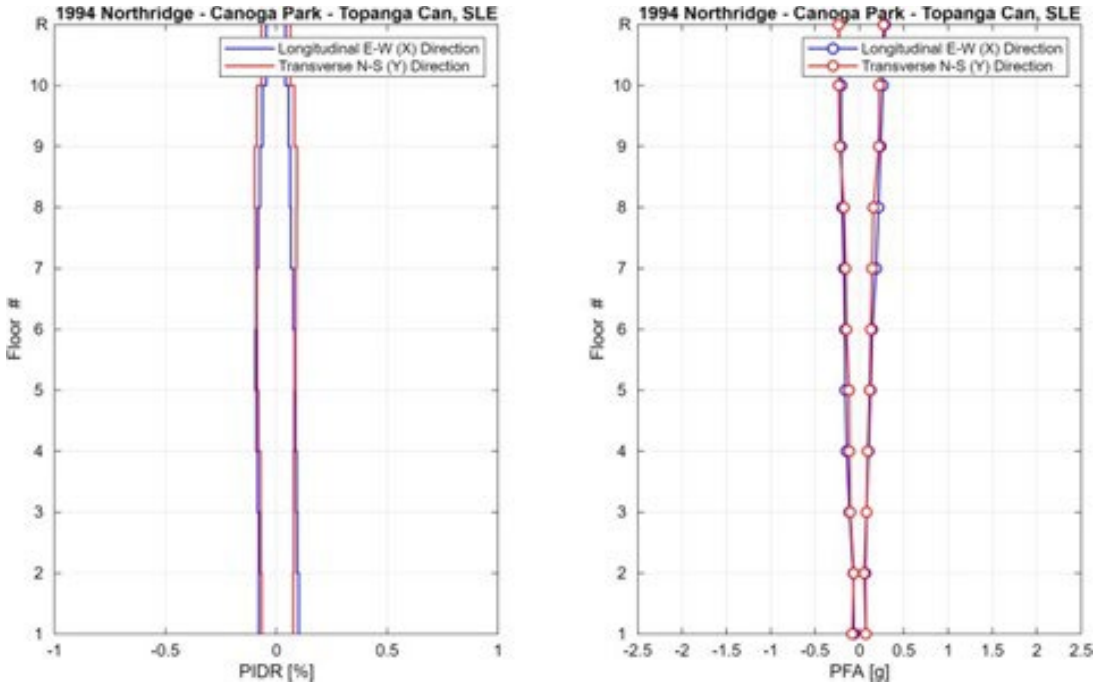


Figure 10. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1994 Northridge, Canoga Park, Topanga Can, SLE).

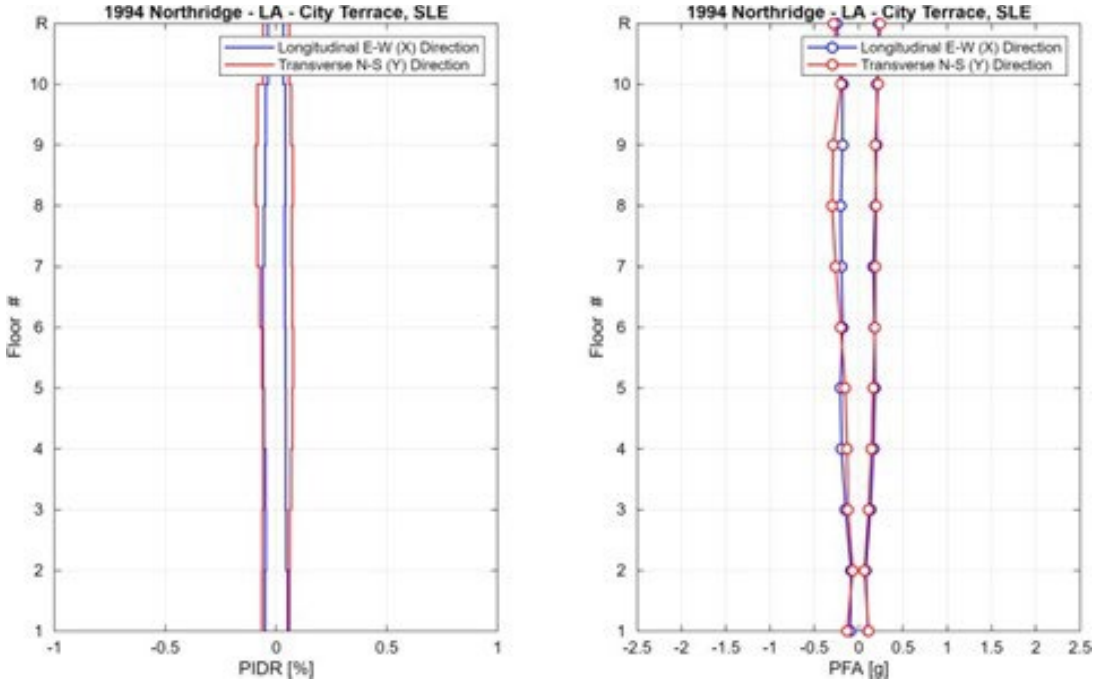


Figure 11. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1994 Northridge, LA, City Terrace, SLE).

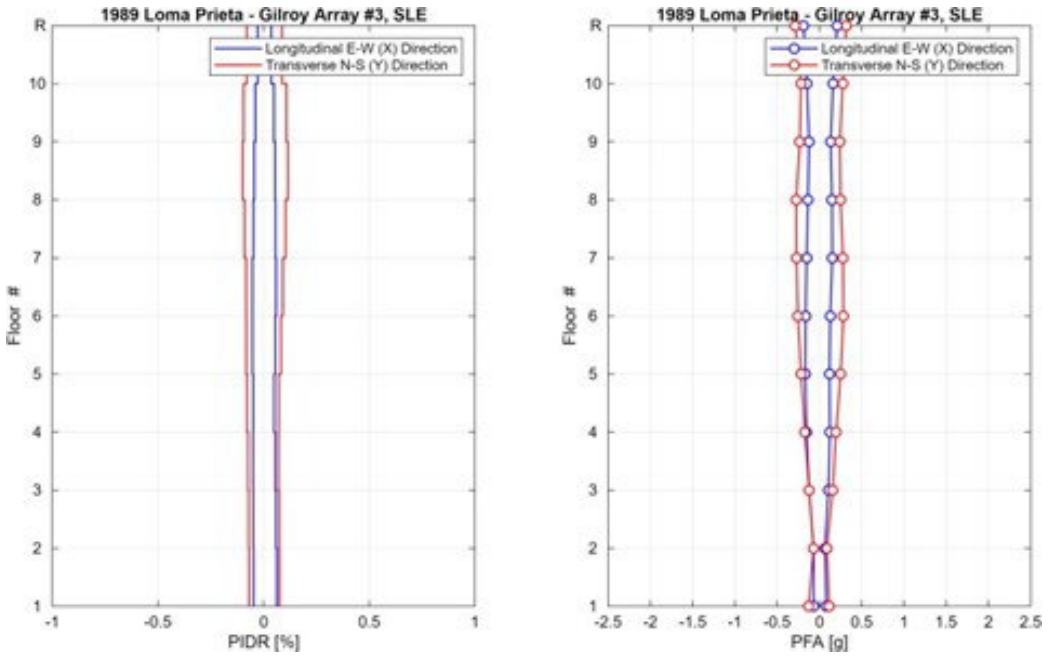


Figure 12. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1989 Loma Prieta, Gilroy Array #3, SLE).

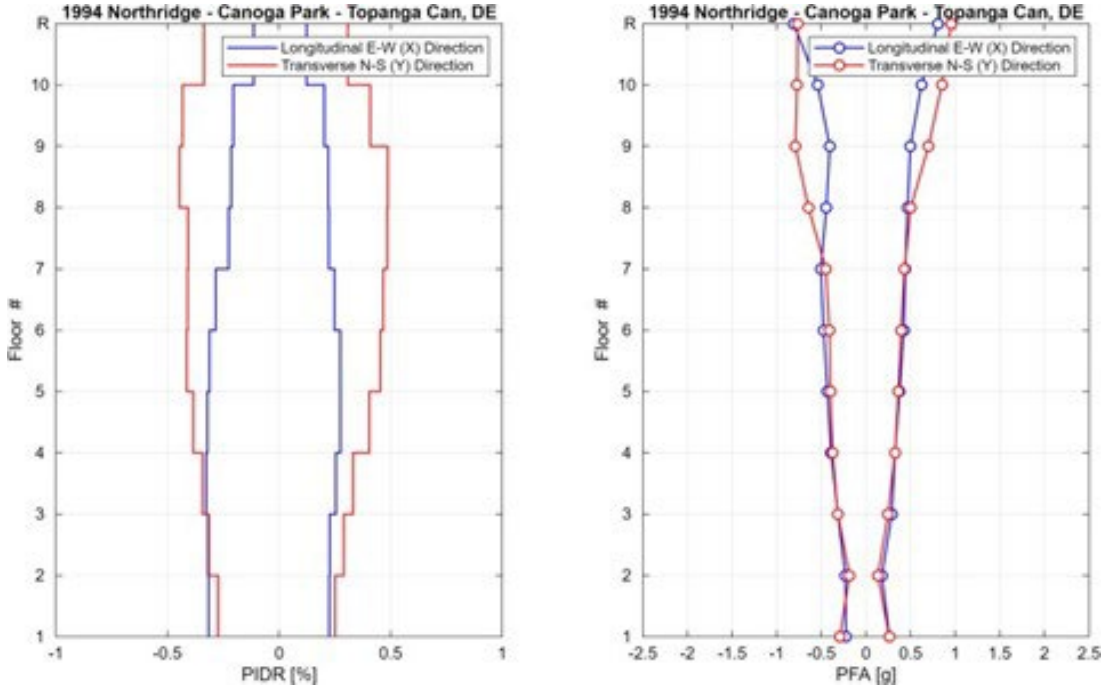


Figure 13. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1994 Northridge, Canoga Park, Topanga Can, DE).

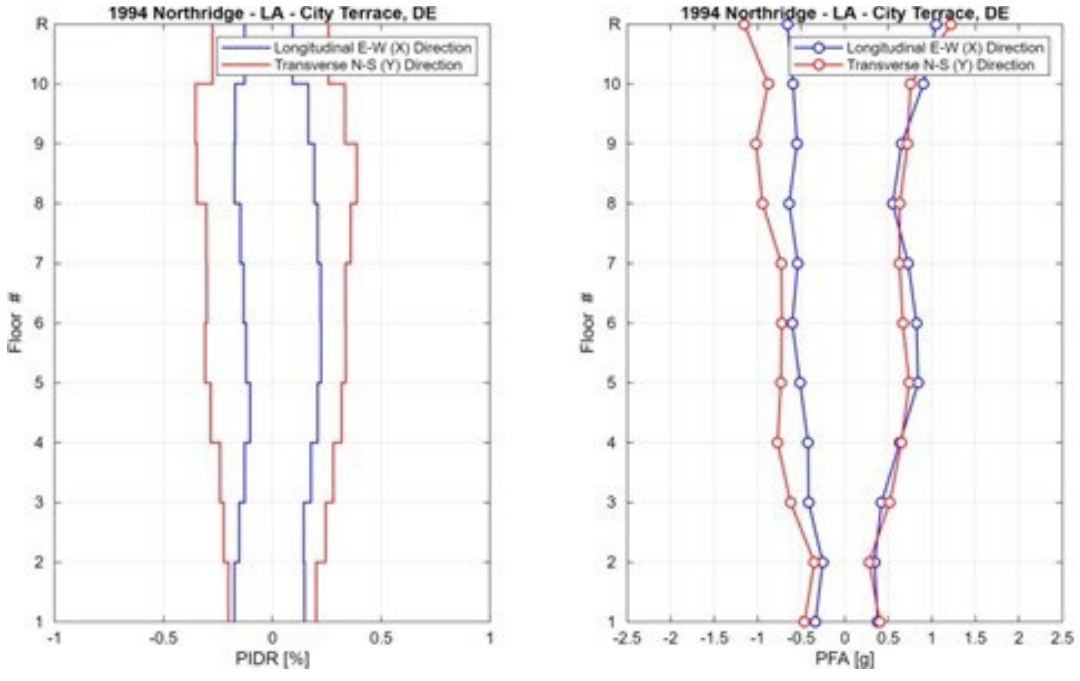


Figure 14. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1994 Northridge, LA, City Terrace, DE).

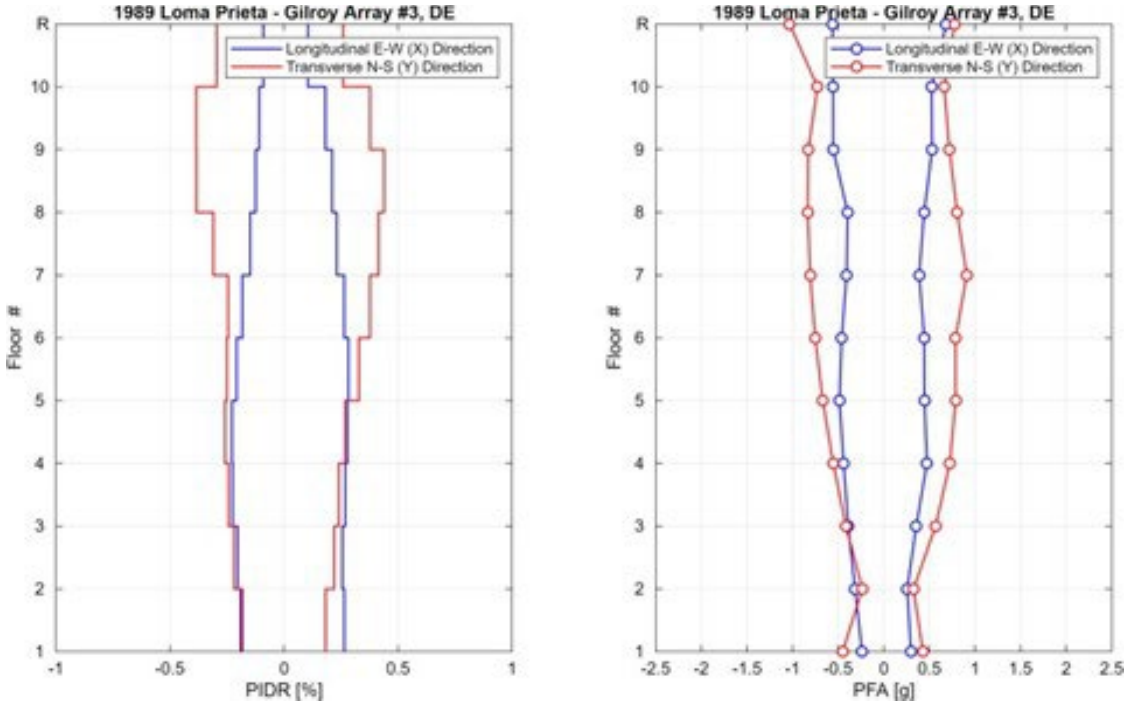


Figure 15. Comparison of peak interstory drift ratio (PIDR) and peak floor acceleration (PFA) profiles predicted by the high-fidelity model in both directions (1989 Loma Prieta, Gilroy Array #3, DE).

CONCLUSIONS

This paper presents a high-fidelity numerical model for a 10-story CFS-framed building developed using OpenSeesPy, incorporating detailed representations of structural components and capturing critical nonlinear phenomena including material degradation, cyclic pinching, and different buckling modes. The modeling approach, validated against component-level experimental data, demonstrated good correlation with measured cyclic responses. Pre-test simulations of the CFS10 full-scale test building predicted that the ten-story structure will maintain adequate seismic performance despite exceeding current 19.8 m code height limits. Peak interstory drift ratios remained below 0.2% under SLE-level and approximately 0.5% under DE-level ground motions—well below permanent damage thresholds for CFS systems. While this study focused on pre-test predictions, future correlation with data obtained from the recently completed experimental program for the CFS10 test building will further validate the modeling approach and advance performance-based design methodologies for tall CFS construction.

ACKNOWLEDGMENTS

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list of all sponsors/partners to the CFS10 program may be found at: cfs10.ucsd.edu/sponsors-partners. Findings, opinions, and conclusions are those of the authors and do not necessarily reflect those of the sponsoring organizations.

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Hurricane and Wind Hazard for Homes

Cost-Effective Wind-Resistant Gable Roof Retrofits in Kentucky and Tennessee: A BIM-Driven Approach to Residential Hazard Mitigation

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ABSTRACT

Homes in Kentucky and Tennessee are increasingly vulnerable to high winds and medium-strength tornadoes. However, affordable wind-resistant retrofit options are still not widely used. This research presents a cost-benefit analysis of gable roofing retrofit approaches aimed at enhancing wind resilience, supported by Building Information Modeling (BIM) created in Revit. Drawing on federal guidelines and private sector standards, we propose three tiers of retrofitting, ranging from basic roof deck enhancements to comprehensive structural reinforcements. The least costly option includes improvements to the roof deck attachment, sealed decking, and better water intrusion resistance. The mid-tier includes wind-resistant roofing and reinforced gable end walls. The highest-tier further enhances the structure with chimney and overhang strengthening, along with other upgrades. These tiered options offer homeowners scalable and cost-effective ways to mitigate wind damage.

INTRODUCTION

As climate change worsens, residential areas are increasingly facing more frequent and intense wind events, such as tornadoes and powerful storms. These hazards pose a significant threat to the structural safety of homes, cause substantial property damage, displace residents, and increase recovery costs. Despite the danger, many homeowners have yet to consider cost-effective, proactive measures to retrofit their homes. Both Kentucky and Tennessee have mountainous eastern regions, rolling hills across the central areas, and flat western parts. The climate is similar, although Tennessee tends to be warmer on average, particularly in the southern part of the state. Additionally, both states are mainly rural, with only a few urban centers. The annual number of EF1+ tornadoes nationwide increased from 474 to 521, a 10% rise, while the western United States saw a 34% decrease, and the eastern United States

experienced a 60% increase (Coleman et al., 2024). These regions are defined by dividing the U.S. along the 93.5°W longitude line. This paper aims to demonstrate the connection between the limited use of integrated cost analysis and BIM in retrofit planning, as a way to motivate homeowners to pursue cost-effective retrofitting projects. To accomplish this, it will assess roofing retrofit strategies based on performance and cost, use BIM to model retrofits for better architectural clarity, and introduce a scalable, tiered retrofit framework.

LITERATURE REVIEW

Kentucky and Tennessee lie within a region that has experienced increasing variability in severe convective storms and tornado activity over recent decades. From 1995 to 2024, Tennessee experienced an average of 31 tornadoes per year, while Kentucky averaged approximately 24 tornadoes per year from 1991 to 2019 (National Weather Service Nashville, 2025; NOAA State Climate Summaries, 2022). These figures mark a modest but meaningful increase compared to the 1991–2020 baseline averages of 28 and 24, respectively (National Centers for Environmental Information, n.d.). Broader climatological studies also confirm a regional shift: tornado activity in the eastern United States has risen by nearly 60% over the past three decades, while the western U.S. experienced a 34% decline (Coleman et al., 2024). This eastward shift of "Tornado Alley" places both Kentucky and Tennessee at heightened and evolving risk.

FEMA's National Risk Index further classifies most counties in both states as being at "Relatively Moderate" or "Relatively High" risk for tornadoes and severe wind events (FEMA, n.d.). In addition to tornadoes, both states regularly face derechos. Central and Northern Kentucky average one derecho annually, while the remainder of Kentucky and Tennessee average one every two years (National Weather Service, n.d.). The combination of tornadoes and derechos underscores the need for resilience strategies tailored to residential structures in this region. The 2024 International Building Code also introduced tornado-load provisions (ENR, 2024).

Although to address these risks, several federal and private organizations have issued retrofit guidelines, recent reviews highlight persistent gaps in tornado-specific standards (Badmus et al., 2025). FEMA's technical manuals and fact sheets (2010; 2023a; 2023b) emphasize strengthening roof systems through improved sheathing, fastener spacing, and sealed decking to prevent progressive roof failure. The Insurance Institute for Business and Home Safety (IBHS, 2020) developed the FORTIFIED Home program, a tiered framework of retrofits aimed at minimizing wind-related losses. Both FEMA and IBHS highlight common vulnerabilities—such as insufficient sheathing thickness, improper nailing patterns, and unsealed shingle edges—that can result in catastrophic roof failure. Even the loss of a single sheathing panel may lead to complete structural failure in high winds (FEMA, 2023a). Similarly, gable ends taller than 3 feet and gable overhangs are particularly vulnerable to uplift and suction pressures, while weak soffit connections often exacerbate failures (IBHS, 2020; FEMA, 2023b).

Case studies demonstrate the benefits of adopting enhanced codes and retrofit strategies. For example, Moore, Oklahoma—after experiencing three violent tornadoes within 14 years—

adopted stronger wind-resistant building codes. Analysis showed that these measures delivered a benefit–cost ratio of 3:1, underscoring the economic rationale for resilience (Simmons, Kovacs, and Kopp, 2015). Empirical data further confirm that sealed roof decks and enhanced fasteners substantially reduce loss ratios, particularly for EF0–EF2 tornadoes, which account for more than 95% of observed events (FEMA, 2021).

Taken together, the literature highlights that cost-effective, roof-focused retrofits are among the most impactful strategies for mitigating wind-related losses. Both policy guidance and empirical studies converge on the same conclusion: integrating resilient roofing measures into routine reroofing cycles offers households in Kentucky and Tennessee significant protection against their most prevalent hazards.

Hazus-MH Modeling and TELR Loss Estimates

The Hazus-MH model, developed by FEMA, provides a standardized framework for estimating potential losses from natural hazards, including tornadoes and severe wind events. Within Hazus, the Tornado Event Loss Ratio (TELR) is used to quantify expected losses relative to building value. TELR values are sensitive to factors such as wind speed, building type, and retrofit adoption. For single-family wood-frame dwellings (WSF1), which dominate the Kentucky and Tennessee housing stock, TELR can be significantly reduced through the adoption of even basic retrofits, such as improved roof deck attachment and sealed decking.

Recent FEMA studies (2021; 2023a) demonstrate that wind-resistant retrofits can reduce TELR by as much as 30–40% for EF0–EF2 tornadoes. Incorporating retrofit parameters into Hazus-MH scenarios allows planners to model reductions in expected annualized losses at both the household and community scale. For example, when gable end reinforcement and upgraded shingles are included, simulations show a marked reduction in both structural and contents losses. These findings are consistent with IBHS field data, which confirms that homes meeting FORTIFIED standards suffer substantially fewer insurance claims following severe weather events (IBHS, 2020). Therefore, Hazus-MH modeling provides not only a performance metric but also a policy-relevant estimate of avoided losses.

Insurance Implications and Incentives

Insurance plays a critical role in incentivizing resilience adoption. Carriers are increasingly offering premium discounts for homes that meet FORTIFIED Home standards or have Class 4 impact-resistant shingles (IBHS, 2020). These discounts can range from 5% to 25%, depending on the state and insurer. In Tennessee and Kentucky, where hail and wind claims are significant contributors to annual losses, these incentives can offset a substantial portion of retrofit costs over the life of a policy.

Beyond direct discounts, insurers are also using resilience credits to shape long-term risk pools. By reducing TELR through retrofits, insurers lower their exposure, which in turn stabilizes rates for entire communities. FEMA (2023a) notes that retrofitted housing stock has a community-wide impact, as fewer claims lead to reduced reinsurance costs and increased affordability of coverage. Case studies from Alabama and Florida, where FORTIFIED adoption is highest, show

both reduced damage and measurable decreases in insurance payouts following tornado and hurricane events (FEMA, 2023b). In this context, Kentucky and Tennessee stand to benefit from greater adoption of resilience standards. As insurers continue to link premium structures to retrofit compliance, homeowners have a financial incentive to integrate resilience upgrades during reroofing cycles. Aligning insurance incentives with Hazus-MH modeled benefits provides a dual justification: reduced household-level TELR and enhanced financial resilience at the community scale.

METHODOLOGY

This paper created a Tiered Retrofit Framework with three cost categories: Least Expensive, Intermediate, and Most Expensive. This framework is specifically applied to gable roofs, given their prevalence in the region, but there is no reason it could not be applied to other roof types where applicable. The data used to develop these tiers was collected from FEMA, IBHS, the Department of Energy's Building America Solution Center, and the International Existing Building Code. The costs associated with each element were obtained through the utilization of building estimating software, RSMeans. Building Information Modeling (BIM) software Revit is also used to help homeowners visualize retrofits on two of the most common roof types.

Cost-Benefit Metrics

The chosen retrofits are designed to withstand winds of up to 111 miles per hour (EF0-EF2), which account for approximately 95 percent of the 56,221 recorded tornadoes between 1950 and 2011 (FEMA, 2021). The National Institute of Standards and Technology (NIST) has found that even in more powerful tornadoes, more than 70% of the total damage path stemmed from lower wind speeds farther out (Kuligowski et al., 2014). Beyond this, in more powerful tornadoes, structural damage typically occurs elsewhere, no longer making the roof the point of failure (FEMA, 2023a).

Retrofit Strategy Descriptions

Table 1 summarizes the proposed tiered retrofit framework for each level of intervention. The framework is designed to align with the typical reroofing cycle of 20–25 years, making it more feasible for homeowners to adopt resilience upgrades during scheduled maintenance rather than as standalone projects. Progression through the tiers is cumulative- each subsequent tier builds on the measures of the previous one. The only exception is standard shingles, which may be replaced when advancing to Tier 3. Tier 1 to tier 3 is from least costly to most costly option.

- **Tier 1** (Least Costly): Focuses on foundational improvements that directly secure the roof deck and limit water intrusion. Measures include denser roof deck nailing, sealed joints, enhanced underlayment, attic vent protection, and the use of starter strips with Class_F shingles.

- **Tier 2** (Intermediate): Expands protection by addressing structural vulnerabilities in gable ends over three feet in height, reinforcing soffits, and upgrading garage doors and framing. These measures provide additional lateral and vertical resistance against uplift

forces.

- **Tier 3** (Most Expensive): Provides comprehensive reinforcement through the installation of wind-rated shingles (ASTM D7158 Class H), retrofits for gable overhangs, and chimney bracing. Together, these measures target the most common points of catastrophic failure during high-wind events.

Table 1. Tiered Retrofit Framework.

Ties #	proposed tiered retrofit framework
Tier 1	Roof deck attachment (8d nails, 6" spacing) Sealing roof deck joints Enhanced underlayment (#30 felt), Attic vent protection Class F shingles, starter strips
Tier 2	Gable end wall reinforcement (IEBC Appendix C A–C) Soffit intermediary nailing reinforcement Rated garage doors and framing upgrades
Tier 3	Wind-rated shingles (ASTM D7158 Class H) Gable overhang retrofits Chimney bracing

BUILDING INFORMATION MODELING (BIM) INTEGRATION

BIM models created have been used the visualization of the tiered framework and can also demonstrate BIM's viability as a planning tool for home retrofitting projects. The gable roof design chosen was selected due to its compatibility with the unique home styles found in Kentucky and Tennessee, such as Shotgun homes, English-style homes, and Rustic homes, which are regionally popular (American Home Shield, 2022), as well as more traditional and ranch-style home designs.

Figure 1(a)-1(d) shows the most common roofing style throughout Kentucky and Tennessee: the gable roof. Figure 1(a) is the typical house roof construction with no retrofits done to make it stronger. Figure 1(b) shows the first tier strategy, which includes roof deck attachment (8d nails, 6" spacing), sealing roof deck joints, enhancing underlayment (#30 felt), attic vent protection, new starter strips, and Class F shingles. Figure 1(c) shows the intermediate additions to the retrofit, which include gable end wall reinforcement and soffit intermediary nailing reinforcement. Figure 1(d) illustrates the addition of wind-rated shingles (ASTM D7158 Class H) and gable overhang retrofits. Not pictured are the chimney attachments due to limitations in the Revit software.

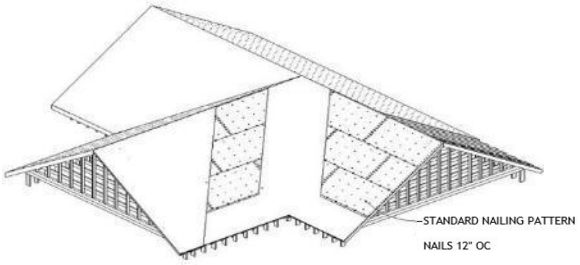

Figure 1(a) Typical house roof construction with no retrofits

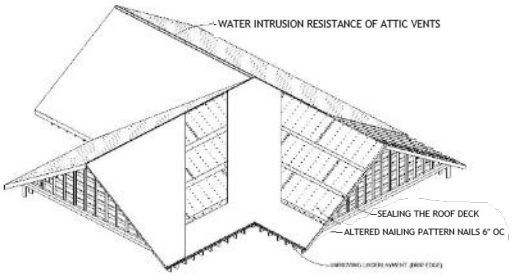

Figure 1(b) Tier 1 strategy

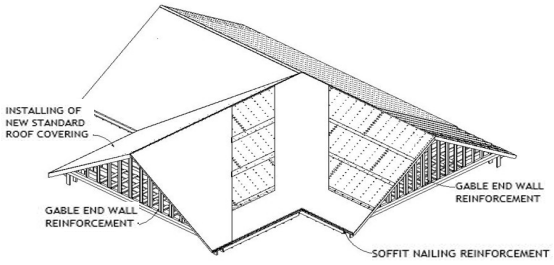

Figure 1(c) Tier 2 strategy

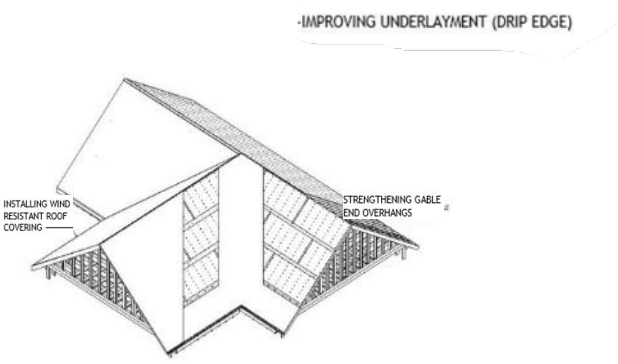

Figure 1(d) Tier 3 strategy

Figure 1(A)-1(D). From left to right, top to bottom. Tiered framework based on retrofitting at different price points.

COST-BENEFIT ANALYSIS

This section presents a quantitative and qualitative evaluation of the proposed tiered retrofits. Benefits are estimated as the present value (PV) of (i) avoided structural losses derived from reductions in Hazus-MH Tornado Event Loss Ratio (TELR) for wood-frame single-family dwellings (WSF1), and (ii) insurance premium savings associated with recognized resilience measures (e.g., FORTIFIED elements and Class 4 or ASTM D7158 Class H shingles). The analysis spans a 20-year reroofing cycle at a 3% discount rate, consistent with long-lived residential investments (FEMA, 2021; FEMA, 2023a; IBHS, 2020).

Application of Hazus-MH Framework

The Hazus-MH platform developed by FEMA provides a standardized method to evaluate hazard-driven loss potential. For this study, a representative single-family dwelling with a structure value of $250,000 in Kentucky or Tennessee was modeled. Expected Annual Loss (EAL) was parameterized at 0.2% (Low), 0.5% (Base), and 1.0% (High) to capture spatial and

hazard variability across counties. Consistent with FEMA guidance, retrofit effects were modeled as TELR reductions of 30% for Tier 1, 35% for Tier 2, and 40% for Tier 3, reflecting incremental improvements in roof decking, fastening, and gable reinforcement. This approach ensures that modeled avoided losses are grounded in empirical performance studies rather than assumed efficiencies.

Cost Data Collection

Retrofit costs were derived from RSMeans 2025 building construction assemblies and line-item estimates corresponding to roof system upgrades, structural reinforcements, and associated labor. Unit costs were adjusted using the RSMeans City Cost Index (CCI) for representative counties in Kentucky and Tennessee, where CCI values range from 0.86 to 0.92 relative to the national average. Material and labor rates were escalated to Q1 2026 values using published construction cost inflation indices to reflect current market conditions.

The modeled roof area (2,055 ft²) was derived from BIM-based gable roof geometries typical of single-family dwellings in the region. Costs were aggregated cumulatively across tiers, resulting in total retrofit estimates of $5,151 (Tier 1), $6,759 (Tier 2), and $10,803 (Tier 3). Tier 1 costs are primarily associated with enhanced roof deck attachment, sealed decking, and underlayment improvements. Tier 2 introduces incremental structural reinforcement of gable ends, soffit fastening improvements, and garage door upgrades. Tier 3 includes wind-rated shingles (ASTM D7158 Class H), gable overhang retrofits, and chimney bracing.

To validate the RSMeans-based estimates, representative retrofit components, including Class H shingles, gable-end reinforcement, and rated garage door installations, were cross-checked against publicly available 2025 contractor pricing and supplier data in Kentucky and Tennessee. Market pricing ranges were consistent with the modeled tier increments, though variability may occur depending on attic accessibility, roof pitch, contractor overhead, and site-specific conditions.

Recognizing potential market fluctuations, a ±20% cost sensitivity analysis was conducted. Under a +20% cost escalation scenario, Tier 1 and Tier 2 retrofits remained cost-effective in Base and High EAL conditions, indicating that the economic findings are robust to reasonable cost variability. Tier 3 cost-effectiveness remains sensitive to hazard intensity assumptions and insurance incentive levels.

Table 2. Tiered Retrofit Cost.

Ties #	Cost
Tier 1	$5,151.39
Tier 2	$6,758.88
Tier 3	$10,803.30

Insurance premium savings were modeled using representative annual homeowner premiums of $1,200, $1,800, and $2,400 to reflect variability across counties and risk classifications in Kentucky and Tennessee. Incentive levels of 5%, 15%, and 25% were applied based on mitigation credit ranges documented in IBHS FORTIFIED adoption guidance and related insurer wind-resilience discount programs (IBHS, 2020). While premium levels and discount availability vary by carrier and verification requirements, these modeled ranges are consistent with observed wind-mitigation incentives in comparable hazard-prone states. Sensitivity analysis across premium and discount levels ensures that the economic results are not dependent on a single assumed premium or discount structure.

Analysis of Retrofit Effectiveness

The combined cost and benefit analysis is summarized in Table 3. Results show that Tier 1 is the most robust option, with NBCR values ranging from 1.21 to 2.95, ensuring positive returns under all but the lowest EAL scenario. Tier 2 delivers strong results in Base and High cases (NBCR from 1.56 to 2.52), but narrowly underperforms under Low EAL (NB = –$138), illustrating the importance of hazard context in decision-making. Tier 3, though the most expensive, becomes viable under higher hazard assumptions (NBCR = 1.75, NB = $8,091) but is less attractive in lower-risk environments. These findings highlight that incremental retrofits can achieve disproportionately high returns, and that aligning retrofit choice with local hazard frequency is essential.

$$\text{Annual Avoided Loss} = V \times EAL \times R \qquad \text{(Equation 1)}$$

$$\text{PV Avoided Loss} = \text{Annual Avoided Loss} \times AF \qquad \text{(Equation 2)}$$

$$\text{Total PV Benefit} = \text{PV Avoided Loss} + \text{PV Insurance Savings} \qquad \text{(Equation 3)}$$

$$\text{Net Benefit (NB)} = \text{Total PV Benefit} - C \qquad \text{(Equation 4)}$$

$$\text{NBCR} = \text{Total PV Benefit} / C \qquad \text{(Equation 5)}$$

where V = structure value ($250,000); EAL = Expected Annual Loss (0.2%, 0.5%, 1.0%); R = TELR reduction (Tier 1: 30%, Tier 2: 35%, Tier 3: 40%); C = retrofit cost (from Table 1); AF = present value annuity factor (20 yrs, 3%).

Table 3. Present Value Benefits, Costs, and Ratios by Tier Under the Base Insurance and EAL Scenarios.

Tier	EAL Scenario	Retrofit Cost ($)	PV Avoided Loss ($)	PV Insurance Savings ($)	Total PV Benefit ($)	Net Benefit ($)	NBCR
Tier 1	Low (0.2%)	5151.39	2232.0	4017.0	6249.0	1097.0	1.21
Tier 1	Base (0.5%)	5151.39	5579.0	4017.0	9596.0	4445.0	1.86
Tier 1	High (1.0%)	5151.39	11158.0	4017.0	15175.0	10024.0	2.95
Tier 2	Low (0.2%)	6758.88	2604.0	4017.0	6620.0	-138.0	0.98
Tier 2	Base (0.5%)	6758.88	6509.0	4017.0	10526.0	3767.0	1.56
Tier 2	High (1.0%)	6758.88	13018.0	4017.0	17035.0	10276.0	2.52
Tier 3	Low (0.2%)	10803.3	2975.0	4017.0	6992.0	-3811.0	0.65
Tier 3	Base (0.5%)	10803.3	7439.0	4017.0	11456.0	652.0	1.06
Tier 3	High (1.0%)	10803.3	14877.0	4017.0	18894.0	8091.0	1.75

Financial Impacts and Sensitivity

Insurance incentives play a pivotal role in shaping cost-effectiveness. As shown in Table 4, even minimal discounts (5% on a $1,200 premium) recover nearly 30% of Tier 1 costs over 20 years. Under higher premiums and discount levels, savings become substantial; for instance, a 15% discount on a $2,400 premium yields $5,356 in PV savings. When these savings are combined with avoided structural losses from Hazus-MH modeling, Tier 1 and Tier 2 become compelling resilience investments even in moderate hazard regions, while Tier 3 is justified in high-risk zones or when paired with generous insurance incentives. These findings confirm that insurance incentives not only improve household-level affordability but also encourage broader adoption, producing community-scale resilience benefits through reduced aggregate claims.

$$\text{Annual Insurance Savings} = P \times d \qquad \text{(Equation 6)}$$

$$\text{PV Insurance Savings} = \text{Annual Insurance Savings} \times AF \qquad \text{(Equation 7)}$$

where P = annual premium ($1,200, $1,800, $2,400); d = discount rate (5%, 15%, 25%); AF = present value annuity factor (20 yrs, 3%).

Table 4. Insurance Premium Savings Sensitivity (present values) over 20 Years at 3%.

Discount	Annual Premium	Annual Savings ($)	PV over 20 yrs @ 3% ($)
Low (5%)	$1,200	60.0	893.0
Low (5%)	$1,800	90.0	1339.0
Low (5%)	$2,400	120.0	1785.0
Mid (15%)	$1,200	180.0	2678.0
Mid (15%)	$1,800	270.0	4017.0
Mid (15%)	$2,400	360.0	5356.0
High (25%)	$1,200	300.0	4463.0
High (25%)	$1,800	450.0	6695.0
High (25%)	$2,400	600.0	8926.0

DISCUSSION

Integrating roof-focused retrofits into the 20–25-year reroofing cycle offers both practical and economic advantages for households in Kentucky and Tennessee. The cost–benefit analysis demonstrates that, under reasonable assumptions for Expected Annual Loss (EAL) and insurance incentives, even the least costly retrofit tier yields positive net benefits and benefit–cost ratios greater than one. These findings align with empirical evidence that most residential tornado losses stem from EF0–EF2 events, and that relatively modest improvements—such as sealed decks and enhanced fastening—can interrupt progressive roof failures (FEMA, 2021; FEMA, 2023a). The modular, tiered framework further allows jurisdictions and homeowners to scale measures according to local hazard profiles, budgets, and maintenance schedules.

Policy and market incentives are critical for widespread adoption. The experience of Moore, Oklahoma, illustrates that enhanced building codes can deliver community-scale economic returns, achieving a 3:1 benefit–cost ratio after repeated tornado events (Simmons et al., 2015). Similarly, IBHS FORTIFIED adoption has been linked to lower claim frequencies and more stable premiums (IBHS, 2020). In Kentucky and Tennessee, municipalities could leverage reroofing permits to encourage sealed decks, improved fastening, and gable reinforcement, while

insurers can accelerate uptake by standardizing discounts for verifiable measures, such as ASTM D7158 Class H shingles and certified gable retrofits.

Several limitations must be acknowledged. Retrofit benefits vary across regions and housing stock, and enforcement of installation practices remains inconsistent—some jurisdictions lack residential inspection requirements (Kentucky Department of Housing, Buildings, and Construction, n.d.). While roof retrofits can substantially reduce Tornado Event Loss Ratios (TELR), other building envelope components—doors, windows, and walls—remain potential points of failure. Moreover, retrofitting may not always be feasible for older homes, where engineered solutions may be required but cost-prohibitive.

Future research should extend this framework by coupling roof-focused interventions with full-envelope retrofits, integrating parcel-scale surface roughness and building inventory data (WBID) for more precise TELR calibration. Additional work is also needed to evaluate the long-term durability of insurance incentives and to better understand homeowner decision-making when resilience investments are aligned with major maintenance cycles.

CONCLUSION

Research on wind-resistant gable roofing is well established in hurricane-prone regions of the United States; this paper extends that body of knowledge by developing a regional variant tailored to the tornado and wind risks of Kentucky and Tennessee. The integration of BIM not only enables homeowners and builders to visualize retrofit sequencing but also supports informed planning, permitting, and decision-making at the household level.

The cost–benefit analysis confirms that Tier 1 and Tier 2 retrofits deliver consistently strong financial returns, with net benefit–cost ratios exceeding one even under conservative assumptions. Tier 3, while more capital-intensive, becomes cost-effective in higher hazard settings or when paired with robust insurance incentives. These results demonstrate that roof-focused retrofits are both technically effective and financially sound, offering households a clear pathway to risk reduction.

Ultimately, the combination of hazard modeling, economic evaluation, and BIM-based visualization establishes a replicable framework that can guide policy development, insurer incentive programs, and homeowner adoption. By aligning retrofit measures with the natural reroofing cycle, Kentucky and Tennessee can progress toward a more resilient, economically efficient, and risk-informed housing stock—and the framework developed here can be adapted for other hazard-prone regions facing similar challenges.

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Design of Resilient, Economical, Affordable and Multidimensional (DREAM) Housing Solutions in Rural Appalachia

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ABSTRACT

Rural Appalachian communities face compounding challenges from climate disasters, economic instability, and housing insecurity. The DREAM (Designing Resilient, Economical, Appropriate, and Multidimensional) Housing project proposes a scalable solution: a 3D-printed, hurricane-resilient transitional housing model paired with a community-based social support program. This project, centered in Charleston, West Virginia, integrates flood-resilient structural design with cost-effective construction methods. Three structural models—a flat slab, crawl space with flood vents, and stilted design—were analyzed using SolidWorks for CFD and FEA simulations. Results showed that elevating homes on stilts significantly reduced hydrodynamic forces and structural stress, making it the preferred configuration. Revit modeling and physical prototypes demonstrated layout feasibility and community arrangement. Additionally, a website was developed to communicate research on social recovery programs and housing policy. The project concludes that additive manufacturing, combined with targeted social programming, offers a resilient and humane pathway for addressing transitional housing needs in disaster-prone regions.

An Exploration of the Building Code Process and Its Relationship to Building Resilience in The Bahamas

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ABSTRACT

Building codes seek to assure building resilience and life safety for building occupants. Despite an adopted building code, and government employees whose role it is to ensure code minimums are met, buildings continue to perform poorly during tropical storms and hurricanes. This study investigates building code implementation and adherence in the Bahamas through qualitative research, conducting interviews with Ministry of Works officials and experienced general contractors. The research explores what drives code updates, safety verification processes, and enforcement mechanisms. Findings reveal that while the Bahamas has adopted appropriate international building standards tailored to their hurricane-prone environment, significant challenges exist in code enforcement rather than code adequacy. Two primary themes emerged as impediments to effective implementation: resource limitations and personal relationships. Resource constraints include inadequate transportation for inspectors, lack of concrete testing protocols, and insufficient environmental studies for flood mitigation planning. The influence of personal relationships manifests when contractors utilize preferred inspectors or provide transportation for inspectors, potentially compromising the integrity of the inspection process. The research concludes that while the codes adopted in the Bahamas are likely sufficient for natural disaster resilience, enforcement remains problematic due to resource constraints and deployment issues.

INTRODUCTION

The Commonwealth of The Bahamas is an archipelago occupying 5,382 sq. mi (slightly smaller than the state of Connecticut), between southeast Florida and northern Hispaniola. The Bahamas' capital city, Nassau is located in the center of the island group. The islands are generally flat and low-lying. As such, natural disasters like hurricanes, and the flooding that typically accompany them, have particularly detrimental effects. The Bahamas were struck by

Hurricane Salley in 2020, Hurricane Nicole in 2022, and Hurricane Oscar in 2024. These storms resulted in minor or no damages and no loss of life. However, Hurricane Dorian in 2019 was a category five storm that caused serious destruction to the islands of Abaco and Grand Bahama. According to the Inter-American Development Bank, Dorian caused $3.4 billion in damages, one-quarter of The Bahamas' GDP, and resulted in the deaths of at least 74 people (Avila, Stewart, Berg, and Hagen, 2020).

Every hurricane season, citizens of The Bahamas suffer with the possibility of facing a storm that could be highly destructive. Both the psychological and physical rebuilding are daunting challenges. This study sought to explore the adoption, application, and enforcement of building codes in The Bahamas. The uniform building codes have their roots in the preservation of human life. However, it is unclear in The Bahamas if storm damages, in the form of lives lost and building damages, can be connected to a lack of codes, outdated codes, poor code enforcement, or potential contractor negligence. As such this study seeks to explore these issues and the potential relationship between building codes and storm resilience.

With the hypothesis that building code adherence could improve hurricane resilience, the study sought to identify if damage could be reduced, thus lives preserved, through enforcement or updating of building codes. More specifically this research sought to explore the following questions:

1. What drives new updates to building codes in The Bahamas?

2. How does the government ensure a building is safe for occupation?

3. What is the process of ensuring building codes are being enforced in The Bahamas?

To address these questions, interviews with various stakeholders were conducted, to gain a holistic view of the question.

LITERATURE REVIEW

Hurricane damage across the U.S. Gulf and Atlantic Coasts has left politicians, as well as locals lobbying for changes in outdated construction systems (Park, 2021). As documented in Puerto Rico, outdated building codes, mixed with a lack of code enforcement, can be disastrous for citizens and the economy (Nonko, 2017). With the volume of severe storms increasing (2024 Atlantic Hurricane Season n.d.), the need to mitigate damages is increasingly important given the substantial economic loss (Park, 2021; Burrus, Dumas, Graham, 2000) and evidence suggests that there are common deficiencies based on building types that are reoccurring. Mitigation of some of these deficiencies could be addressed through code updates and or enforcement (Yazdani, Dowgul, Manzur, 2010).

Hurricanes have the highest average event cost, highest number of fatalities, and the largest economic losses among all natural disasters (Park, 2021). The fatalities and economic losses are

likely to increase as the number of storms increases. The number of natural disasters that occur every year is increasing as time goes on, the annual average number of events for the past five years is 17.2 events where the 1980-2021 annual average was only 7.4 events (Gawlik, 2022; 2024 Atlantic Hurricane Season n.d). Further, significant portions of the population are found in coastal areas, where storm impacts are most severe (Park, 2021). In New York City, for example, Mayor Michael Bloomberg, realized after hurricane Sandy, in 2013, that something had to be done about their infrastructure's lack of resilience. The mayor, along with the City Council, formed a task force that would make changes to new construction as well as enforce precautions in existing residential buildings, including co-ops, condominiums, rental apartments and public housing (Navarro, 2013). Similar to New York, along the gulf coast, the aftermath of hurricanes Katrina and Rita led to scrutiny of code adherence as the relationship between damages and building codes (and code adherence) became evident. The damages from those storms, the relationship to codes, and the expectation of more extreme weather led to updated codes and are expected to accelerate future code adoption and improve code enforcement (Bowen, 2005).

The International Building Code (IBC) and the International Residential Code (IRC), contain specific provisions for hurricanes resilience through wind-resistant roofs and doors, and high-impact glass on upper floors (Bowen, 2005). The impacts of building codes and their ability to limit damages were well documented by Bowen (2005), primarily through a post-mortem of storm damage. Beyond codes, there is further evidence for building standards as a means to reduce storm damages. The Insurance Institute for Business and Home Safety has the Fortified Home program, which requires construction materials and methods that exceed minimum code requirements and has been shown, in the laboratory and through post mortem storm inspections, to reduce damages from storms (Alabama Department of Insurance and Center for Risk and Insurance Research, 2025; Ghosh, Bigelow, Smith, and Omole, 2023). While Fortified Home goes above and beyond the code now, as codes progress, the requirements in the Fortified program may be included in future versions of the code.

Nossiter (2006) reported that the damages from Hurricanes Katrina and Rita were amplified by a lack of construction standards as well as shoddy building practices, suggesting the onus for improvements in construction should lie with the contractors as well as the codes. Gawlik (2022) similarly believes that contractors and engineers need to take responsibility as they have an opportunity to improve building envelopes to mitigate the damage natural disasters do to communities. Inspections following Hurricanes Katrina and Rita found: collapsed brick walls that lacked correct anchoring and reinforcing, shingles that blew off roofs because they had been put in place incorrectly or did not have enough fasteners, and windows were shattered on high-rise buildings because nearby buildings were roofed with gravel (a practice forbidden in high-wind areas in the building codes) (Nossiter, 2006). All of these issues could have been ameliorated through code adherence and/or enforcement.

In contrast to the Gulf Coast, places like Puerto Rico have adopted some of the strictest building codes in the world in terms of hurricane resistance. However, the issue faced in Puerto Rico is solidifying a process for code certification as approximately 55% of all structures in Puerto Rico are built without code enforcement because they lack resources to ensure code adherence during

the building process (Nonko, 2017). Nonko (2017) further reports that, without inspectors to check on the progress of construction there is no accountability. Local governments in Puerto Rico do not have inspectors to approve documents or visit construction sites, nor are they licensed.

The issues found in Puerto Rico, relating to a lack of code enforcement, are common throughout the Caribbean (Nonko, 2017). The regulation of building codes in the Bahamas is a demanding thing as it is comprised of 700 islands and 30 inhabited cays. According to Kijewski-Correa (2022), The Bahamas suffers from the same challenges as Puerto Rico on its outer islands, where the Ministry of Works lacks the capacity to enforce code requirements. In more populated and thus government regulated islands like New Providence, however, building codes are enforced. Compounding the challenges in the Bahamas is the fact that the Bahamian Building Code (BBC) is based on U.S. building codes from over 30 years ago. As such they are missing the latest guidance regarding resistance to wind and coastal hazards. Bahamian residential construction consists mostly of load bearing masonry (76%) but wood-frame (15%) and reinforced concrete (9%) are also used. As such, structures should be able to withstand up to a category three or four hurricane (Kijewski-Correa, Roueche, Kennedy, Allen, Marshall, Kaihatu, Wood, Smith, Lester, Lochhead, Copp, McCarthy, Prevatt, and Robertson, 2022).

Building Codes protect the built environment by setting minimum safety requirements. With hurricanes and natural disasters becoming more frequent and more destructive code implementation and enforcement are more important. As seen in places like Puerto Rico and the Gulf Coast, poor building practices and/or a lack of code enforcement can lead to significant life and property losses.

METHODOLOGY

This study used qualitative research, collecting and analyzing interview data to explore how building codes are applied, enforced, and could improve severe storm resilience in the Bahamas. Through interviews with people working in the government and the construction industry in The Bahamas, this study provides insight into the governmental permitting and inspection processes that regulate the compliance of building codes.

Data were primarily collected on the island of New Providence, interviewing relevant personnel at the Ministry of Works, as well as local general contractors. Professionals on both sides of the building codes (government officials tasked with enforcing codes and contractors who oversee their application on projects) were interviewed to provide insights into local attitudes about building codes and to mitigate bias from one side of the issue or the other.

Interviews were conducted both in person and via Zoom. These were structured interviews that were recorded and then transcribed for analysis. Participants were identified through the professional network of the researchers and through a snowball technique, as participants were asked to connect the researchers to other relevant participants.

Interviews were conducted with seven individuals all of whom had formal education in architecture or engineering. All were considered to have extensive knowledge of the permitting, construction and inspection processes. Interviewees included: two officials from the Ministry of Works and five who worked as general contractors. The two who worked in the Ministry of Works were with the Building Control Department, each in a differing role, but each with many years of experience working in the ministry. The five interviewees who worked as general contractors, all had over 15 years of experience. They included different sizes of companies and each had different backgrounds but all were owners of construction companies.

Analysis was conducted using a modified version of Strauss and Corbin's (1998) coding method. Through the process of open and selective coding, common themes were identified in the interviews and reported.

ANALYSIS AND DISCUSSION

The results of the interviews provided consensus regarding certain aspects of building codes enforcement in the Bahamas. Other themes did not achieve consensus, but represented valid context and explanation relating to code adoption and enforcement in the Bahamas. However, enforcement of the codes is an underlying problem. These findings are representative of only a small sample, and were not all reported by the entire sample so they should be viewed as anecdotal with limited ability to be generalized. However, they represent the lived experiences of participants and thus merit documentation, particularly as this topic, in The Bahamas has not been explored in published literature.

Building Permit Process

An initial question to all participants was to describe the process of applying for permits and the process for inspections as construction progresses. All of the contractors interviewed as well the ministry officials were consistent in their description of the materials required to obtain a permit and the process associated with that. Further all respondents were consistent in their responses about the inspections required at different stages of the construction process. One general contractor reported that "all plans are submitted here in Nassau to Town Planning, and it goes through The Ministry of Works here in Nassau…everything goes straight to ground zero." However, some participants also noted that beyond the prescriptive code requirements, the process can vary when a licensed professional engineer is involved. In general, the involvement of a licensed professional engineer can change the inspection considerably, potentially rendering inspection by a Ministry official unnecessary. According to one respondent: "the process can change based on the structural drawings because your structural engineer will be responsible for going to the site, to investigate what the environmental conditions are…" Another respondent stated: "…depending on the job you are working on, in addition to the Ministry of Works inspectors, you can have an engineer who can sign off and his signature trumps any inspector. A licensed engineer can certify a project and all the phases going through even if the inspector does not get on site." In these cases, the licensed professional engineer is effectively the inspector. There was clear consensus on the procedures and processes for permitting and inspections, even when a professional engineer is involved and changes those procedures and processes. This

consensus suggests that knowledge of the laws and policies surrounding building codes in the Bahamas are not a problem. It further suggests that contractors typically follow the procedures.

Given that knowledge of these laws and policies is not lacking, the data suggests that the government has regulated construction sufficiently to ensure that contractor's expectations and knowledge of the requirements were consistent with the expectations of Ministry officials. Further it is clear from the responses of Ministry officials that a great deal of effort and resources have been expended to ensure appropriate codes have been adopted in the Bahamas. One Ministry of Works official reported that because it is a hurricane environment, it is of the utmost importance that building designs be able to stave off or provide resilience when there is a major disaster. He said simply "[that is] the main criteria for what determines code has to do with our local environment." The official further reported that the building codes put in place were adopted from the best jurisdictions around the world. He said: "We collate the American standard for Civil Engineers, and we use for electrical the Canadian Electrical code. So, we borrow the best from each jurisdiction that would serve as a minimum standard for us." Suggesting Ministry officials are focused on adopting appropriate safeguards for Bahamian structures in the event of natural disasters. These responses suggest the Bahamian government is expending resources to identify and adopt codes that will minimize loss in the event of natural disasters. However, these results conflict with Kijewski-Correa et. al.'s (2022) conclusion that the dated codes are a weakness in the Bahamian defense against natural disasters.

Although the data suggests efforts and resources are expended to adopt appropriate codes, the data also suggests that the challenge in the Bahamas lies not in adoption, but in enforcement of code compliance. Responses to additional questions in the interviews, suggested various constraints in the system that work against code compliance and thus the safeguarding of Bahamian citizens in the event of natural disasters. Two broad themes emerged as shortcomings in the system. First a lack of resources and second personal relationships, with some overlap occurring between the issues identified under these two themes.

Lack of Resources

Within the theme of "lack of resources" three issues emerged: concrete testing, environmental study, and transportation. Within the theme of "personal relationships," two issues emerged: friendship and transportation. It should be noted that most participants did not explicitly note any shortcomings in the Bahamian system. However, because these issues represent illegal activities that could impact participant's personal security or welfare, the researchers did not expect all participants to share them.

Participants were asked about verification of concrete strength and the concrete testing process. All of the contractors reported that the strength of the concrete used has no verification process. It was unclear if the codes adopted did not specify concrete testing or if it was simply not happening. One contractor said, "…The Ministry of Works does not test the concrete; they just enforce the structural law. If you do not personally purchase your tester to test that concrete, there is no way of telling if that concrete's PSI is accurate." Another contractor reported, "The strength of the concrete is normally tested by the supplier…the concrete companies that we

purchase our concrete from are required to do testing to make sure that we are at the required PSI for whatever the structural drawings stipulate." Third-party testing of concrete, a standard practice in other countries, does not occur in the Bahamas and the supplier is trusted to supply the appropriate strength of the concrete. Whether this is because concrete testing is perceived as unnecessary to avoid the additional cost of testing, because there are no resources for third-party testing in the Bahamas, or something else entirely, it represents a weak point in the Bahamian process for building inspections. Although not testing concrete strength does not appear to be a violation of code, it is a perilous practice given the recent collapse of the tower in Bangkok, Thailand during the Myanmar earthquake, as it has been attributed to substandard steel used to reinforce the structure (Dasgupta, 2025).

Another challenge identified in the safety of projects and homes in the Bahamas is the use of environmental studies prior to approval, to manage or plan for flood waters. The Bahamas is a low-lying country, compounded by the narrow width of the islands. So, nearly the whole of every island has the exposure of a coastal area. This leaves most of the island(s) at risk during a storm, but some areas are even more susceptible to damage from flooding. This is due to how areas are developed. One participant described it saying; "Most of those areas were built without any consideration for flood mitigation, there are also areas that were once wetlands that were demucked and filled in, which is a natural attenuation spot for runoff from the higher land, which is why those areas are more susceptible to flooding." With a growing population, houses are being built in areas that perhaps they should not, because they fall within the flood plain of those areas. This only causes the issue to worsen with climate change. The participant further stated; "with sea levels rising we have experienced that in those areas where they have filled in, all they have done now is basically redirected the normal hydrology of the water table in the area to areas that were not prone to flooding. These are now becoming more prone to flooding because of decisions that were made not keeping pace with the natural environment. That is one of the primary reasons why we are experiencing flooding in areas that are becoming more prone than others." Although this issue falls outside of the normal permitting and inspection process, it is reported here because it is something that in many places is required before a permit can be applied for. Further, environmental studies have a direct effect on the resilience of buildings in the Bahamas. It was coded under lack of resources because an environmental study appears to be a resource that is not being brought to bear in Bahamian construction. Unfortunately, this study did not identify why environmental studies are not occurring or are not effective in mitigating flood water impacts from development and construction.

The third issue that emerged in the theme of "lack of resources" was transportation. It was reported that often inspectors lack vehicles to get to a job site and conduct inspections when contractors call for them. One participant simply said; "the only problem the Ministry has is that they don't have sufficient vehicles." He shared that in some instances, inspectors would have to share government vehicles and carpool to jobsites in order to cover all the projects. But in other cases the contractors would pick up the inspector and bring him to the job to perform the inspection. This supports Nonko's (2017) conclusion that a lack of resources occurs throughout the Caribbean, however while it is a lack of man power on some islands, in the Bahamas it is a lack of transportation.

Personal Relationships

The issue of a lack of vehicles overlaps the theme of "lack of resources" with the theme of "personal relationships." If an inspector knows they have to rely on the contractor to give them a ride they are certainly influenced to pass the inspection or go easy on the contractor. Beyond capacity, the lack of vehicles for inspectors likely contributes to the view that contractors may simply forego inspections. One participant stated he would only call inspectors for major stages of work but not necessarily the smaller stages. This sentiment that inspections are optional, that a contractor may simply choose to forego an inspection if the inspector cannot get to the job site is justifiably reinforced by the Ministry. Particularly if they fail to provide adequate resources for inspections to be conducted. Further, if a contractor could, without concern, simply choose not to have some inspections done (not just when an engineer is involved and acts as the inspector), suggests that the impact of personal relationships is profound. This was only reported by one contractor, which indicates it could be a rare occurrence. But it could also be a result of other contractors fearing to share that they do something illegal. Either way, personal relationships are likely the only way a contractor could get away with behaving like this.

Further supporting the theme of "personal relationships" was the response of another participant who pointed out, "…our major impediment in this country is because everyone knows each other, sometimes the building process is skewed because you are my friend and you aren't necessarily coming out to check if I did everything right." This response suggests that as Bahamian contractors establish personal relationships with inspectors, the inspectors will treat those contractors differently, or as the contractor put it they will "scratch their back" when needed. There was no specific mention of quid pro quo, but it seems whether casually or intentionally, if all of the players are friends and at times the contractors have to provide transportation for inspectors, conflicts of interest are unavoidable and to the detriment of public safety.

Despite these challenges and threats to public safety in the event of a natural disaster, all participants indicated that they believed the codes in place would protect Bahamians. However, some participant responses point out specific shortcomings in the process suggesting there are issues with policy requirements (concrete testing and environmental studies) as well as in the process (transportation and friendships). These results suggest that while there is known consistency in the permit and code process, that may not be an accurate depiction of actual code application in the Bahamas.

The data confirms that the Bahamian Ministry of Works has a challenging task and while they may have the manpower, they lack other resources (transportation). There are appropriate building codes that are evaluated and updated as necessary, as well as a clear understanding of the permit and inspection process, even when there are variations from the involvement of a licensed professional engineer. However, the process can become skewed because of contractors using a preferred inspector, which can be exacerbated by contractors providing transportation for the inspectors. In addition, there are little to no regulations on concrete testing, leaving contractors to trust suppliers for mix designs, a potential conflict of interest. These issues and the

threats they present to the Bahamian public are exacerbated by rising water levels and increased incidences of natural disasters that are presumed to be the effect of climate change.

CONCLUSION

Building codes are only one consideration in analyzing the effects of natural disasters in the Bahamas, or any island or coastal area. The Bahamian Ministry of Works, which oversees building code adoption and adherence is challenged, particularly as it relates to code adherence through inspection. The challenges are a result of their responsibility for many different islands, but even with adequate manpower and transportation, personal relationships can make code adherence inconsistent. Of the five contractors interviewed, two reported how they had gained approvals outside of the Ministry of Work's policies. The researcher also noted that early in the interview process all of the contractors knew the correct answers about how the codes are applied and inspections conducted, however it was not until later in the interviews that respondents were willing to share these breaches in policy, likely once they felt comfortable that there was no threat in being open with the researcher. The researchers conclude that these behaviors, while only reported by 40% of respondents, are likely occurring more broadly, but other participants simply did not share them.

The data gathered leads the researchers to conclude that, building codes adopted in the Bahamas are likely adequate for resilience to natural disasters. However, it is the enforcement of the codes (not the adoption of them) that presents a problem. The fundamental problem facing the Ministry of Works is resources and how they are deployed. Whether there is simply a lack of resources provided to the Ministry or an inappropriate distribution of resources is beyond the scope of this research.

The researchers suggest future study on this subject in the following forms: Exploration of the use of environmental studies in the development stages of Caribbean and Bahamian construction. Impacts of non-conforming concrete in natural disasters. Contractor knowledge of practices that avoid or circumvent objective inspections. Replication of this study to provide additional data point and/or site observations triangulated to interview data.

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Model-to-Data Validation of Flood Damage Models for Buildings in Coastal Regions: A Case Study of Hurricane Ian (2022)

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ABSTRACT

This paper presents a data-driven validation of two benchmark coastal flood damage models: (1) HAZUS, developed by the Federal Emergency Management Agency (FEMA), and (2) North Atlantic Coast Comprehensive Study (NACCS), developed by the U.S. Army Corps of Engineers. The validation was conducted using a hindcast study of damage to buildings in Fort Myers Beach, FL, impacted by Hurricane Ian (2022). The hindcast data comprised the component-based damage state (DS0-DS6) and first-floor elevation estimates for 3,408 buildings. A hazard layer was developed based on the High-Water Marks (HWMs) measured after the event. The results show that the NACCS damage functions better capture the damage gradient than HAZUS damage functions, particularly near the shoreline with high wave effects. The HAZUS damage functions yield more conservative results for buildings by the shoreline and overestimate for buildings inland. The USACE model has an overall accuracy of 25%, and the HAZUS model has one of 27%. Such findings can eventually lead to more precise models and simulations, enabling engineers and emergency managers to better estimate damage from future hurricanes.

Keywords: Coastal Buildings; Damage Models; HAZUS Damage Function, Hurricane Ian; Structural Damage, NACCS Damage Function.

INTRODUCTION

Flood damage models often lack validation due to insufficient data. A model with insufficient validation decreases its reliability, which makes it so that communities are unable to trust it (Molinari et al., 2019). The goal of validation is to have enough confidence that the model can

perform its intended purpose with sufficient accuracy (Sargent, 2011). A validated model can be used to reliably predict the level of damage to buildings or determine if they survive or collapse under what hazard intensity. This information can be used to improve building codes and better prepare homeowners for flooding (Molinari et al., 2019).

Molinari et al. (2019) define a flood risk model as a model that predicts the expected damage in a given area and for a specific flood event. This type of model is rarely validated because it relies on a large amount of historical data that is not frequently available. Flood risk models often have three main components: hazard, exposure, and vulnerability. The hazard represents the potential flood intensity at a location, which may be defined deterministically (e.g., design flood level) or probabilistically (e.g., likelihood of exceeding a given flood level). The exposure is the community (e.g., buildings) that will be exposed to the hazard. The vulnerability, in this case, is defined as a damage function that shows the relationship between the hazard and damage to the building inventory in terms of percentage loss (Nofal and van de Lindt, 2020c). There are three main validation methods used for flood risk models. The first method is comparing a model's results to observe damage from past events. The second method, when observation is unavailable, is comparing model-to-model results. This method is suitable when both models are intended for similar building inventories and hazards. The third option is used when there is a lack of validated models and observed data. It relies on expert judgment to assess if models' outputs are logical (Molinari et al., 2019).

This paper aims to conduct data-driven validation of existing flood damage models for buildings in coastal regions. The validation is conducted using an existing Virtual Damage Assessment (VDA) dataset that contains component-based damage states (DS0-DS6), estimates of the buildings' first-floor elevations, and foundation type for 3,408 buildings in Fort Myers Beach, FL, impacted by Hurricane Ian (2022) (Amini et al., 2024; Figueira et al., 2025). It also contains a flood hazard layer that was created based on High-Water Marks (HWMs) observed after the storm. Flood damage models validated in this paper are (1) HAZUS, developed by the Federal Emergency Management Agency (FEMA, 2009), and (2) North Atlantic Coast Comprehensive Study (NACCS), developed by the U.S. Army Corps of Engineers (USACE, 2015). This type of dataset allows researchers to find the level of uncertainty in their models and what causes it. For each model, confusion matrices and spatial damage maps were made to compare its results to the VDA dataset. The following literature review will discuss HAZUS and USACE flood damage models and validation methods used for them.

EXISTING FLOOD DAMAGE MODELS AND VALIDATION

HAZUS (FEMA, 2009) and USACE (USACE, 2015) models are two widespread deterministic flood damage models, which employ depth-damage functions to estimate structural and content damage to buildings in terms of loss percentage of the total replacement cost. The HAZUS flood module is composed of depth-damage curves from multiple sources: FEMA Benefit-Cost Analysis Re-engineering (BCAR) report (2011), the Federal Insurance and Mitigation Administration (FIMA) FIA credibility-weighted damages, the U.S. Army Corps of Engineers (USACE) Chicago District, Galveston District, and Institute for Water Resources (IWR). The

curves have been developed for different building occupancies, distinguishing between coastal and riverine flooding. The model requires a surge depth above the FFE or the lowest horizontal structural member (LHSM) as the input. While depth-damage functions are straightforward to use, they do not account for uncertainty in damage prediction that can limit their suitability for a reliable flood risk assessment (e.g., de Moel and Aerts, 2011; Omar et al., 2020a).

The USACE depth-damage curves in this paper are from the North Atlantic Coastal Comprehensive Study (NACCS), conducted after Hurricane Sandy to address coastal flooding and risk. The curves were developed by an expert panel and compared to data collected after Hurricane Sandy. They are organized by pre-defined prototypes that distinguish between building foundation, building type, and occupancy type. They offer slightly more detail than the HAZUS curves because each prototype has a curve to predict both inundation and wave damage. Within these specific hazard curves, there are minimum, most likely, and maximum curves to determine the level of uncertainty in the prediction. Like HAZUS curves, they require a surge depth relative to the FFE as well (USACE, 2015).

VIRTUAL DAMAGE ASSESSMENT

This work uses a dataset compiled by a virtual damage assessment (VDA) on about 3,408 structures impacted by Hurricane Ian (2022) in Fort Myers Beach, Florida (Figueira et al., 2025). The study involved a component-based damage assessment, categorized by damage states (DS). Ranging from no damage (DS0) to complete damage (DS6), including roof, walls, elevated floors, windows, doors, attachments, and foundations, to estimate overall damage to a building. The VDA has been conducted by trained students using publicly available imagery, including satellite, StEER street-view, and drone footage (Ceferino et al., 2025). The dataset is publicly available on DesignSafe (Amini et al., 2024). Table 1 shows a VDA spatial map of the damage to buildings across Fort Myers Beach. Table 1 presents a breakdown of the number of structures by building type, categorized by damage state. The virtual damage assessment was conducted mostly using pre- and post-storm street-level and aerial imagery data. The process was performed by engineering students, who were trained in the established methodology. To validate the VDA results, 30 buildings were selected for all the students to evaluate, along with a group of experts. The validation process showed that their results were within one damage state of another.

Table 1. Building Type Counts with the Structural Damage State Amount from the Original VDA Dataset.

Building Type	DS0	DS1	DS2	DS3	DS4	DS5	DS6
Wood	558	545	325	391	101	122	544
Masonry	74	77	58	40	21	7	29
Concrete	23	19	14	21	6	13	22
Steel	3	6	4	1	4	4	25
Manufactured	-	1	-	-	-	-	62
Total	658	648	401	453	132	146	682

The VDA dataset also contains the foundation type and first floor elevation (FFE) of the buildings. This was done using Google Street View and Google Earth imagery by students as well. The primary methodology used was as follows: First, in Google Street View, students assigned the buildings FEMA diagram and foundation type (FEMA, 2019). Then, a section of the roof, the FFE, the next highest floor (NHF), and the lowest horizontal structural member (LHSM) were measured in pixels. In Google Earth, that same section of the roof can be measured in feet, essentially creating a ratio between pixels and feet to convert the other measurements to feet. The dataset contains FFE estimates for 3,110 buildings, from which 3,067 used the methodology discussed.

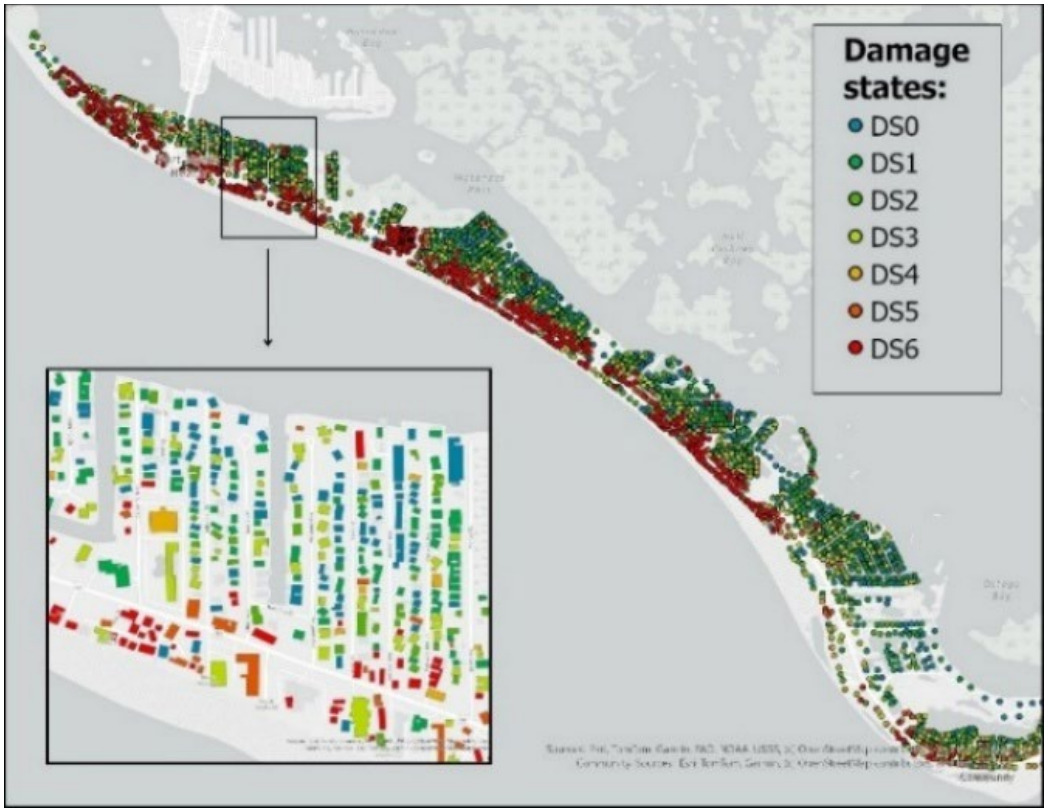

Figure 1. Map of Fort Myers Beach, FL, with structural damage state.

METHODOLOGY

Hazard

Hurricane Ian was a Category 4 hurricane that made landfall in Florida near the city of Cape Coral on September 28, 2022 (NHC, 2022). Fort Myers Beach, the focus of this paper, is about 14 miles southwest of Cape Coral on Estero Island. The maximum storm surge was 3-4.5 m above ground in Fort Myers Beach, resulting in most of the structural damage being due to storm surge and waves (NHC, 2022, Prevatt et al., 2023). This is also due to the maximum wind speed

being below the design level of the buildings (Cortes et al., 2022). In Lee County, about 52,514 structures were affected, of which 5,369 structures were destroyed and 14,245 were severely damaged. In Fort Myers Beach, about 900 structures were destroyed and 2,200 were damaged (NHC, 2022).

High water marks (HWM) were collected by Structural Engineering Extreme Event Reconnaissance (StEER) and the United States Geological Survey (USGS) during reconnaissance after the storm. This can be seen in Figure 2. USGS focused mainly on HWMs caused by surge, while StEER separated them as surge only and surge plus wave observation. Surge plus wave observations do have a higher level of uncertainty, specifically for locations less than 200 m from the shoreline (McCann et al., 2024). For the VDA dataset, the surge-only data were fitted with a linear function, and the surge plus wave was fitted with a power function, both as functions of the distance from the shoreline. This created a hazard layer that is a part of the VDA dataset and was used in this research.

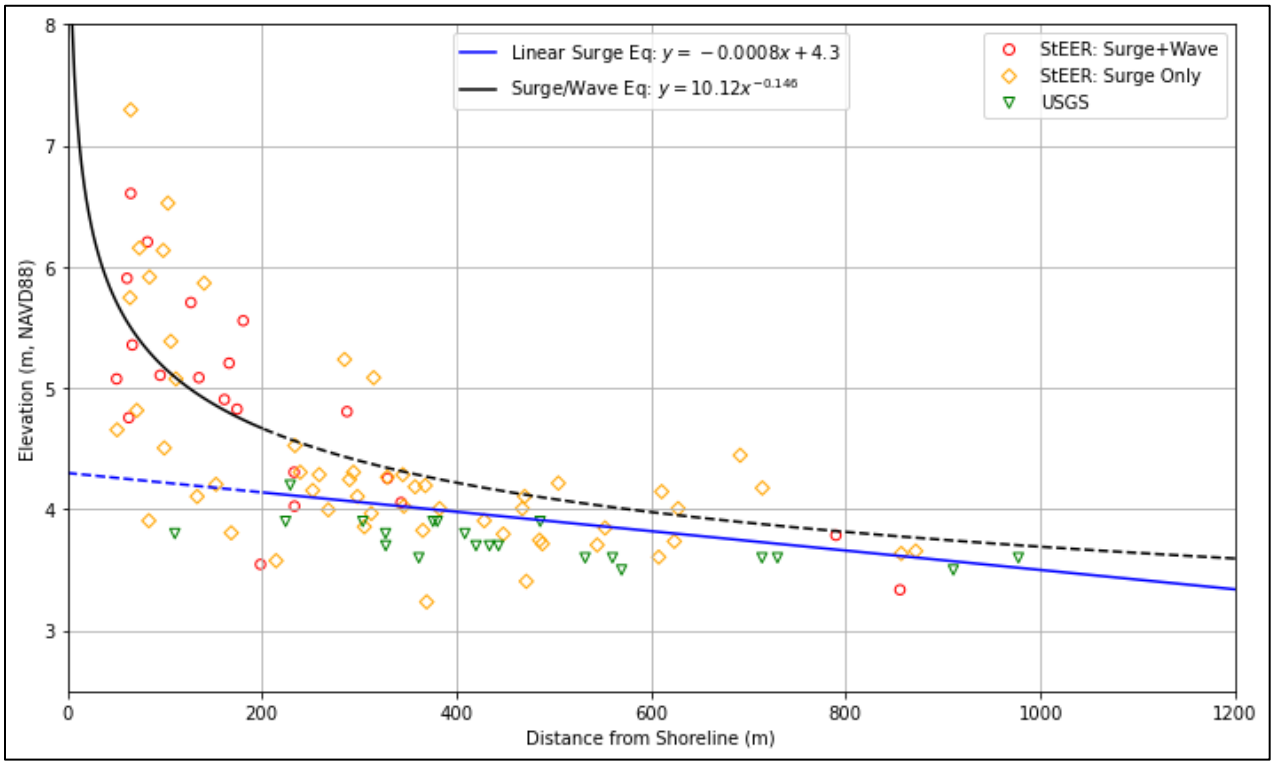

Figure 2. Water elevation based on high water marks taken across Estero Island.

Exposure

The VDA dataset contains building parameters from the National Structure Inventory (NSI) and Lee County Open Data, combined with the assigned FFE values and foundation types of

structures recorded by students. From the NSI, the occupancy type, building type, and flood zone were used for evaluating structure damage. From the Lee County data, the number of stories and the year built were utilized. Examples of this can be seen in Table 2 and 3.

Table 2. Number of Buildings for Specific VDA Parameters: Diagram Type, Number of Floors, and the FFE.

Diagram type (VDA*)		# of buildings	# of floors (TA**)			FFE relative to grade (ft) (VDA)		
			1	2 & 3	> 3	< 2.4 m (8 ft)	Between 2.4 & 3.7 m (8 & 12 ft)	> 3.7 m (12 ft)
1A	slab-on-grade	1024	873	129	15	1024	0	0
1B	raised slab-on-grade	272	230	37	2	262	8	1
5	elevated on piles	91	55	30	5	27	54	9
6	elevated on piles with an enclosure	810	601	115	87	300	437	61
7	wall foundation	704	488	184	17	186	432	78
8	crawlspace	238	198	29	0	224	10	1
Total		3139	2445	524	126	2023	941	150

*VDA = parameter from the Virtual damage assessment
**TA = parameter from the Tax Assessor

Table 3. Number of Buildings for Specific VDA Parameters: Diagram Type, Flood Zone, and Occupancy Type.

Diagram type (VDA)		# of buildings	Flood zone (NSI*)		Occupancy type (NSI)			
			A-zone	V-zone	commercial	single-family res	multi-family res	mobile home
1A	slab-on-grade	1024	818	173	107	831	86	0
1B	raised slab-on-grade	272	229	33	36	185	49	2
5	elevated on piles	91	46	41	7	58	26	0
6	elevated on piles with an enclosure	810	510	270	18	626	166	0
7	wall foundation	704	534	132	23	607	73	1
8	crawlspace	238	143	75	36	160	40	2
Total:		3139	2280	724	227	2467	440	5

*NSI = parameter from the National Structure Inventory

Vulnerability

This work adopted depth-damage curves from HAZUS and USACE coastal damage models. The damage curves for the HAZUS model were adopted from the SimCenter Damage and Loss Model Library (FEMA, 2009; Zsarnóczay et al., 2025b). The damage curves for the USACE model were digitized from the report (USACE, 2015).

To use the USACE model, each building in Fort Myers Beach needs to be assigned a specific prototype. The study establishes the prototype's foundation type, the number of stories, the building use, and its design level. From the dataset, the parameters that best aligned with the required inputs were the occupancy type from the NSI, the building diagram and foundation type from the VDA study, and the number of stories from the tax assessor (TA) data. Utilizing these parameters, prototypes were assigned; this mapping can be seen in Table 4.

The one parameter that was unavailable in the dataset was the building design level. This was needed to differentiate between commercial prototypes. The National Academies of Sciences, Engineering, and Medicine (1994) defines the level of engineering for structures based on building usage. Using the occupancy type (NSI) and the number of stories (TA), the design level is defined for each building. The details can be seen in Table 5.

Table 4. USACE NACCS Prototype Assignments Used in Fort Myers Beach, FL.

		Parameters					
		Foundation Type	**Foundation**	**Design Level***	**Building Diagram**	**Occupancy Type****	**Number of Stories**
Prototypes	**2**	shallow	slab-on-grade raised/non-raised	E, ME	1A, 1B	Com	2
	3	shallow	slab-on-grade raised/non-raised, crawlspace	NE, PE	1A, 1B, 8	Com	1
	5A	shallow	slab-on-grade raised/non-raised, crawlspace	-	1A, 1B, 8	Res1-1SNB	1
	5B	shallow	slab-on-grade raised/non-raised, crawlspace	-	1A, 1B, 8	Res1-2SNB, Res1-3SNB	2+
	7A	deep	piles	-	5	-	1+
	7B	deep	piles - enclosed	-	6	-	1+

*Design level: E = Engineered; ME = Marginally Engineered; NE = Non-engineered; PE = Partially Engineered.
**Occupancy type: Com = commercial building; Res1-1SNB = Single family residential, 1 story, no basement; Res1-2SNB = Single Family Residential, 2 story, no basement; Res1-3SNB = Single Family Residential, 3 story, no basement.

The HAZUS flood loss estimation model was developed by FEMA to be used by officials to support flood mitigation efforts (FEMA, 2009; Zsarnoczay et al., 2025a). The HAZUS depth-damage functions were designed based on flood zone, and this is the defining factor for whether the curve includes surge or wave damage. The functions similar to the USACE model use a hazard value relative to the FFE of a building. The FEMA flood loss model uses only surge levels, without factoring in wave height or wave effect. It is also important to emphasize that the functions come from multiple sources as shown in Table 5. The main parameters used to assign a damage function are the flood zone and the occupancy type.

The flood zone is the primary parameter and should be prioritized. FEMA acknowledges the difference between riverine and coastal flooding but only has well-documented and tested damage functions for single-family homes. The reasoning is that most coastal communities are made up of single-family homes. HAZUS advises prioritizing the use of the function for the correct flood zone, and if not available, use the next best one. In this case, the priority would be the A-zone, then the V-zone, and lastly a riverine flood zone function. In the case of Fort Myers,

this was only an issue with non-residential homes, which are evaluated to be using riverine functions as directed in the HAZUS Technical Manual. HAZUS describes functions mainly based on occupancy type, and for a residential building, this parameter also dictates the number of stories for the building.

Table 5. HAZUS Damage Function Properties and Parameters.

Damage function source*	Number of functions	Flood zone			Occupancy type			
		A-zone	V-zone	Riverine	Single-family res	Multi-family res	Mobile home	Commercial
FIA	6	4	2	-	6	-	1	-
BCAR - Jan 2011	4	-	4	-	1	2	1	-
USACE - Chicago	1	-	-	1	-	-	-	1
USACE - Galveston	18	-	-	18	-	-	-	18
Total	29	7	10	27	11	4	4	25

*Damage functions: BCAR = Benefit-Cost Analysis Re-engineering; FIA = Federal Insurance and Mitigation Administration; USACE = U.S. Army Corps of Engineers.

To compare the coastal flood models and the VDA damage results, damage states (DS) were converted to loss ratios and damage percentages. The scale was used to assign damage states for the VDA dataset, as seen in Table 6 from Tomiczek et al. (2017). Since the scale was developed to assign damage states based on imagery and in-person analysis, there is no predefined conversion to convert the damage states to a damage ratio or percent. To address this, a scale from Nofal et al. (2020) was used because the descriptions of damage closely matched the ones defined by Tomiczek et al. (2017). Table 6 shows the damage state ratio and conversion used in this study.

Table 6. Damage State Scale Used for VDA and Converted for Models.

VDA Tomiczek et al. (2017)			Damage scale Nofal et al. (2020a)			
Damage state	**Count**	**Description**	**Damage State**	**Count**	**Description**	**Damage Ratio**
DS0	658	No damage	DS0	658	Insignificant	0.0 - 0.03
DS1	648	Minor	DS1	648	Slight	0.03 - 0.15
DS2	401	Moderate	DS2	854	Moderate	0.15 - 0.5
DS3	453	Moderate				
DS4	132	Major	DS3	132	Extensive	0.5 - 0.7
DS5	146	Complete	DS4	828	Complete	0.7 - 1.0
DS6	682	Complete				

RESULTS

For Fort Myers Beach, the structural damage was evaluated using the USACE NACCS and FEMA HAZUS models. Figure 3 shows spatial maps comparing the results. As shown in Figure 3(B), the USACE model shows a better representation of evaluating damage to the buildings near the shore. The comparison shows that the USACE model better captures the gradient of damage compared to HAZUS. As shown in Figure 3(C), the HAZUS map shows it underestimating damage to buildings by the shoreline and overestimating for the buildings further inland.

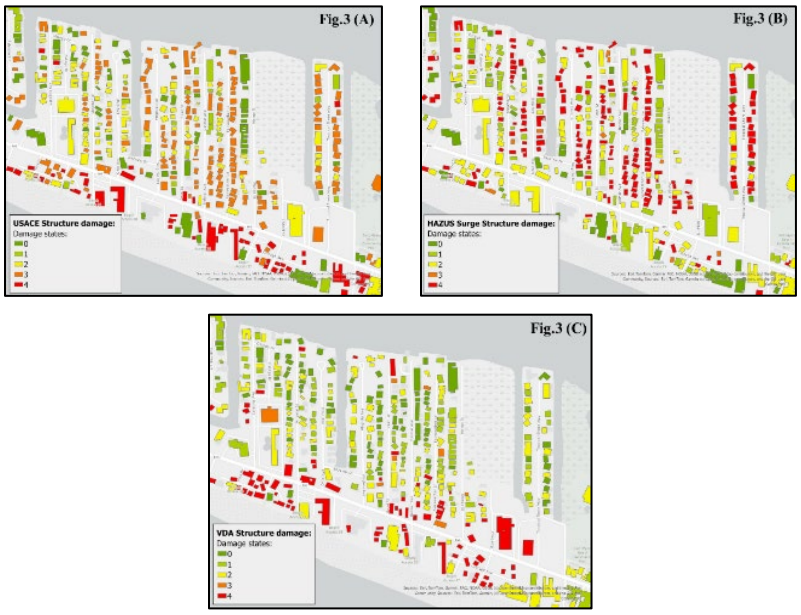

Figure 1. Structural damage spatial maps: (a) USACE (b) HAZUS (c) VDA.

Figure 4 shows the confusion matrices for each model. Overall, the results for USACE and HAZUS are similar when compared at the community level. For DS4, though, USACE has a higher accuracy and is significantly better at predicting DS3 than HAZUS. For DS3, HAZUS has low accuracy. Also, the accuracy of the models considering plus/minus one DS shows that USACE has lower uncertainty. For example, looking at DS2, USACE now has the accuracy rate of 0.72, while HAZUS has one of 0.42. This could be because of a few reasons. First, converting damage state to loss ratios can impose uncertainty in the results. Second, DS3 specifically is the start of structural damage and can be hard to identify in the field. This leads to a lower number of buildings observed and labeled DS3, and this, coupled with the uncertainty of converting the loss ratios, could be an explanation for what is seen in the results. Another aspect is that HAZUS does not factor in the wave effect like the USACE model. Higher levels of damage usually impact the houses affected by waves. This means that the absence of the wave effect in the HAZUS model results in fewer houses being accurately identified for those higher damage states.

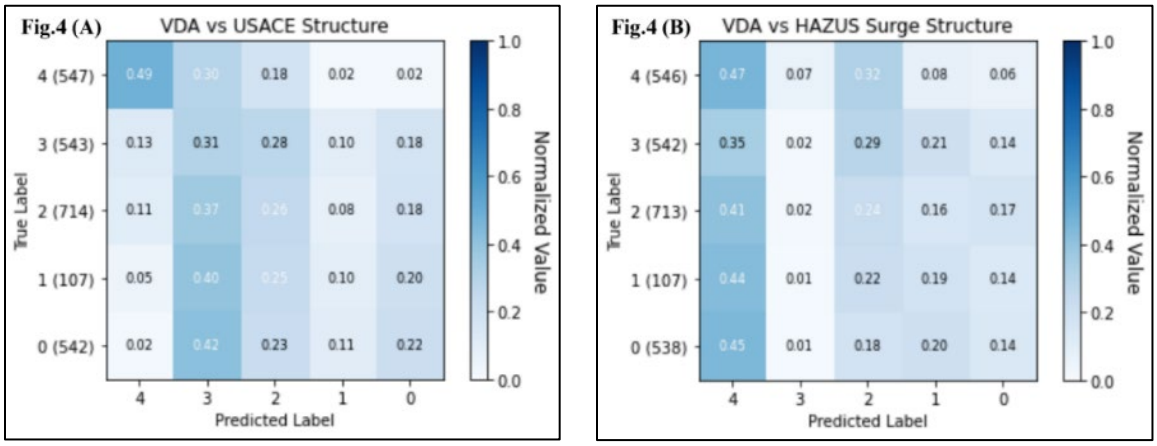

Figure 2. Structural damage confusion matrices: (A) USACE. (B) HAZUS.

In Table 7, the precision, recall, F1, and accuracy scores are similar across both models except for a few instances. For DS0, the USACE shows a higher recall and F1 score. A higher recall means the model can identify the correct damage state more often. This is different from the precision score, which tells U.S. how often a specific damage state was predicted compared to how often it actually occurred. The F1 score is the balance between precision and recall and should be a number between precision and recall (Grandini et al., 2020). An F1 score is beneficial in identifying an imbalanced dataset. For DS0, this means USACE predicted the correct DS more often, and the precision and recall values are closer together compared to HAZUS. For DS4, a higher accuracy is seen for USACE. This makes sense given that most houses that received DS4 were affected by waves and not just the surge. The other metric that stands out is the values for DS3. The values for both models are lower compared to the results

for other DS. This is true except for the USACE recall value. This can be attributed to having fewer observations of DS3 (132 houses).

Table 7. Metrics for Models Based on Structural Damage.

		Precision (%)	Recall (%)	F1 (%)	Accuracy (%)
DS0	HAZUS	24	14	18	-
	USACE	31	22	26	
DS1	HAZUS	26	19	22	
	USACE	28	10	15	
DS2	HAZUS	29	24	26	
	USACE	32	26	29	
DS3	HAZUS	3	2	2	
	USACE	4	31	7	
DS4	HAZUS	24	47	31	
	USACE	68	49	56	
Overall	HAZUS	21	21	20	25
	USACE	32	28	26	27

CONCLUSIONS AND FUTURE WORK

This paper conducted a data-driven validation of existing flood damage models for buildings in coastal regions. The validation was conducted using an existing Virtual Damage Assessment (VDA) dataset for 3,408 buildings in Fort Myers Beach, FL, impacted by Hurricane Ian (2022) (Amini et al., 2024; Figueira et al., 2025). This data was key in validating the flood damage models: 1) HAZUS, developed by the Federal Emergency Management Agency (FEMA) (FEMA, 2009), and 2) North Atlantic Coast Comprehensive Study (NACCS), developed by the U.S. Army Corps of Engineers (USACE, 2015). The results showed that the overall accuracy of the two models was similar. However, USACE more accurately predicted damage to buildings near the shoreline, which are often DS4. This is demonstrated by the model's performance for DS4, with precision (0.68), recall (0.49), and F1 (0.56), compared to the HAZUS model values of precision (0.24), recall (0.47), and F1 (0.31). USACE's higher accuracy for DS4 may be attributed to the inclusion of wave effect and foundation type as parameters in their damage curves. HAZUS only uses surge levels, and the parameters considered are occupancy type and flood zone. Another key takeaway is that converting the damage ratios to damage states creates a large level of uncertainty. This was seen in the inconsistencies for DS3 and the accuracy values when considering plus/minus one DS. The conclusion of this work is the importance of considering a hazard layer that includes the wave effect, and for damage curves to factor in building foundation type and flood zone. Future work can involve improving the understanding of uncertainty in FFE estimation, DS conversion, and establishing a standardized method for converting DS to loss ratios across a range of building types. Future work will also include

validating other flood models from the literature and performing sensitivity analysis to identify the source of uncertainty.

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Innovative and Sustainable Construction Technologies | Issues, Materials, and Methods

Advancing Sustainable Housing Through Innovative Construction Materials and Methods

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ABSTRACT

The growing global emphasis on environmental responsibility has intensified the demand for sustainable housing within the residential construction industry. Traditional construction practices contribute significantly to carbon emissions, material waste, and excessive energy consumption, creating challenges in meeting sustainability goals while maintaining durability, cost efficiency, and compliance with evolving building codes. As housing demand continues to rise, the construction industry must adopt innovative materials and modern construction methods that enhance environmental performance without compromising structural integrity or constructability.

This paper examines the integration of advanced construction materials and contemporary building methods to improve sustainability in residential housing. Innovative materials—including laminated veneer lumber (LVL), fiber cement siding, and advanced insulation composites are evaluated for their environmental benefits, structural performance, and contribution to energy efficiency. Modern construction approaches, such as modular construction, panelized systems, and lean construction techniques are analyzed for their effectiveness in reducing material waste, improving quality control, enhancing labor productivity, and shortening project timelines.

Life Cycle Assessment (LCA) and embodied carbon analysis are used to evaluate environmental impacts throughout the construction process, from material selection through execution. Case studies demonstrate how the integration of innovative materials and construction methods supports resilient residential design, improves project performance, and aligns with regulatory and sustainability standards. The findings provide practical insights for construction managers, builders, designers, and educators seeking to align residential construction practices with industry expectations and sustainability benchmarks.

INTRODUCTION

Sustainable construction has become a central objective in residential housing development due to increasing concerns over environmental degradation, climate change, and rising energy costs. Residential construction accounts for a significant share of greenhouse gas emissions and material waste, prompting builders, designers, and researchers to explore environmentally responsible alternatives to conventional practices. Traditional materials and construction

methods often rely on resource-intensive processes that contribute to high-embodied carbon, inefficiencies, and long-term environmental impact.

In response to growing public awareness and regulatory pressure, the residential construction sector is undergoing a transformation that prioritizes sustainable material selection and efficient building methods. The objective is to reduce environmental

harm, minimize reliance on finite resources, and create durable, energy-efficient, and resilient housing for a growing population. This paper investigates how the integration of innovative construction materials and modern building techniques can address these challenges and improve sustainability outcomes in residential housing.

LITERATURE REVIEW

Sustainability has evolved from a niche consideration into a foundational principle of modern residential construction. Residential buildings account for approximately 21% of total energy consumption in the United States, highlighting the critical role housing plays in achieving sustainability goals (U.S. Department of Energy, 2020).

Research consistently shows that sustainable construction strategies can reduce carbon emissions, enhance durability, improve energy efficiency, and promote occupant health, while also increasing long-term housing value (Residential Construction, 2025).

A key theme in sustainable housing literature is environmentally responsible material selection. Engineered wood products such as laminated veneer lumber (LVL) offer high strength-to-weight ratios, dimensional stability, and reduced waste while storing carbon when sourced from sustainably managed forests. Fiber cement siding provides durability, resistance to moisture and fire, and reduced maintenance requirements, contributing to longer service life. Advanced insulation composites improve thermal performance and reduce operational energy demands.
In addition to materials, modern construction methods play a critical role in sustainability.

Figure 1. Engineered wood (LVL) used in structural framing, demonstrating uniform, high-strength components used in modern sustainable residential construction.

Modular and panelized construction techniques improve efficiency by reducing waste, shortening construction timelines, and enhancing quality control through factory-based fabrication. Lean construction principles further support sustainability by minimizing inefficiencies and maximizing value through improved planning and collaboration (Kibert, 2016). The literature emphasizes that the combined use of innovative materials and modern construction methods yields environmental, economic, and social benefits that exceed those achieved by isolated strategies.

Figure 2. Examples of modular construction units and factory assembly lines, highlighting controlled, efficient off-site housing production.

This study employs a qualitative and analytical methodology that integrates material performance analysis, construction method evaluation, sustainability assessment tools, and case study review. The materials analyzed include laminated veneer lumber (LVL), fiber cement siding, and advanced insulation composites due to their potential to reduce embodied carbon, enhance durability, and improve building performance. Modern construction methods evaluated include modular construction, panelized systems, and lean construction practices. These methods are assessed based on construction efficiency, waste reduction, energy performance, and quality control.

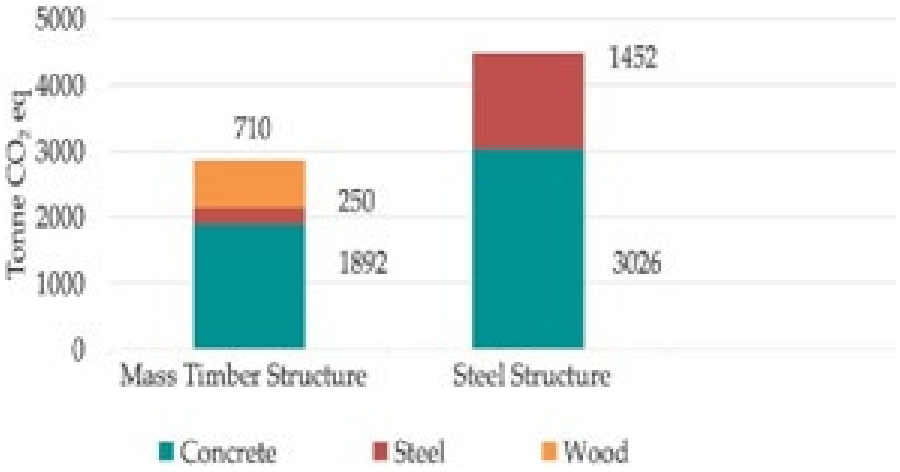

Figure 3. Embodied carbon comparison charts between timber and traditional structural materials, showing lower carbon impact potential for engineered wood systems.

METHODOLOGY

Life Cycle Assessment (LCA) is used to evaluate environmental impacts across the entire life cycle of materials and construction processes, from raw material extraction to end-of-life considerations. Embodied carbon analysis tools, including EC3, are applied to compare carbon emissions associated with material production, transportation, and installation. Case studies are incorporated to demonstrate real-world applications and outcomes of sustainable residential construction strategies.

RESULTS

Material Performance

The evaluation of laminated veneer lumber (LVL) revealed significant environmental and structural advantages over conventional solid-sawn lumber and carbon-intensive materials such as steel and concrete. LVL demonstrated high strength-to-weight ratios, dimensional stability, and reduced material waste due to efficient use of wood fiber. Its compatibility with prefabrication enhanced construction precision and reduced on-site waste.

Fiber cement siding exhibited strong durability and lifecycle performance. Although its initial embodied energy was higher than some traditional cladding materials, its resistance to fire, moisture, pests, and weathering reduced maintenance and replacement frequency, resulting in improved long-term environmental performance.

Advanced insulation composites achieved higher thermal resistance than conventional insulation materials while requiring less thickness. These materials contributed to reduced heating and cooling energy demand, improved indoor air quality, and enhanced overall building envelope performance.

Construction Method Efficiency

Modular construction significantly reduced construction time and material waste by utilizing factory-controlled environments. Projects incorporating modular methods demonstrated improved energy efficiency due to precise insulation installation and airtight construction practices (Modular Building Institute, 2025). Panelized construction systems produced similar benefits, including improved quality control, reduced waste, and enhanced thermal performance. The integration of LVL framing and advanced insulation composites within panelized assemblies further improved structural and energy efficiency. Lean construction practices enhanced efficiency across modular and panelized projects by improving workflow coordination, reducing labor inefficiencies, and minimizing material overuse.

Case Study Analysis

A multi-family residential development in Portland, Oregon utilized cross-laminated timber (CLT) panels as the primary structural system. The project achieved a 30% reduction in construction time and an estimated 50% reduction in embodied carbon compared to conventional concrete construction. LVL was used for beams and floor framing, improving structural consistency and reducing waste.

A modular housing project in Atlanta, Georgia achieved a 25% reduction in construction costs. It was completed two months ahead of schedule. Energy modeling indicated a 40% reduction in energy consumption, attributed to advanced insulation composites and enhanced air-sealing techniques. An affordable housing initiative in Chicago implemented LVL framing and fiber cement siding, resulting in reduced material waste, improved durability, and long-term cost efficiency.

DISCUSSION

The findings demonstrate that innovative materials and modern construction methods significantly advance sustainability in residential housing. Engineered wood products such as LVL and CLT reduce embodied carbon while maintaining structural integrity and compatibility with off-site construction. Fiber cement siding contributes to building durability and resilience, while advanced insulation composites improve operational energy efficiency.

Modular, panelized, and lean construction methods enhance sustainability by reducing waste, improving quality control, and shortening construction timelines. The use of Life Cycle Assessment and embodied carbon analysis highlights the importance of considering full lifecycle impacts rather than focusing solely on operational energy performance. Early design decisions that related to material selection and construction strategy were shown to have a substantial influence on overall environmental impact.

Viewed through advanced construction management concepts presented in this course, the integration of LVL framing systems and modular construction aligns closely with real-world jobsite priorities. These approaches improve schedule reliability and enhance trade coordination by reducing on-site variability and construction inefficiencies. At the same time, they support sustainable performance goals without compromising constructability or project delivery.

CONCLUSION

This study demonstrates that innovative construction materials and modern building methods play a critical role in advancing sustainable residential housing. Materials such as laminated veneer lumber, fiber cement siding, and advanced insulation composites reduce embodied carbon, enhance durability, and improve energy efficiency. Construction methods including modular, panelized, and lean construction further support sustainability by minimizing waste, improving construction quality, and reducing project timelines.

The integration of lifecycle-based assessment tools enables informed decision-making that supports long-term environmental performance. While challenges such as cost, regulatory barriers, and workforce familiarity remain, continued innovation, education, and policy development can accelerate the adoption of sustainable housing practices. As environmental pressures and housing demand increase, the combined use of innovative materials and construction methods are essential for creating resilient, energy-efficient, and sustainable residential environments.

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Effect of Reinforced Masonry Beams' Creep on the Unreinforced Masonry Walls' Arching

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ABSTRACT

Unreinforced masonry walls supported by reinforced masonry beams will be affected by the additional deflections caused by increasing strain under sustained load. Eliminating the continuous support provided to the wall leads to arching mechanism. This can result in increased stress on the wall and a higher risk of failure, especially if the wall is subjected to out-of-plane loads like earthquakes or wind.

In this paper, besides considering the reinforced masonry beam short-term deflection (caused by self-weight, dead and live load), the time dependent deflection (long term) caused by creep will be calculated and the effect of this additional deflection on the unreinforced masonry wall arching will be discussed. To be able to calculate the long-term CMU beam deflection, a simplified method has been created and used in this paper. In addition, the effect of compression rebar on the CMU (simply supported) beams' creep has been calculated. At the end a CMU beam example, along with tabulated results for different compression bars at mid top of the beam, is presented to show the effect of compression bar on the CMU beam's deflection for minimizing the wall arching supported by the beam.

INTRODUCTION

Masonry beams deflection, like reinforced concrete (RC) beams, has two parts—short and long-term deflections. Short term deflection is that part of deflection that will happen almost as soon as external loads are applied to the beam. Long term deflection will occur by creep and has to do with compressive stress acting on the element. Calculating long term deflection in reinforced concrete beams has a simplified method in ACI, and based on that the total (short plus long term) deflection of a RC beam can be determined. To calculate the CMU beams' creep deflection, a simplified method has been created and used in this paper to find the importance of the creep on the CMU beams' deflection. Adding a compression bar at the top mid span of RC and CMU beams will reduce the long-term deflection, and with this new method that is provided in this paper, we will be able to calculate the percentage of deflection reductions for different compression bars. In this method, the ACI strength method's stress distribution (compression and tension stresses) for beams is adopted but with allowable stress design (ASD) stresses.

CREEP DEFLECTION

Figure 1 is used to calculate a masonry beam deflection caused by creep. The CMU

beam might be with or without mid span top compression bar (A's).

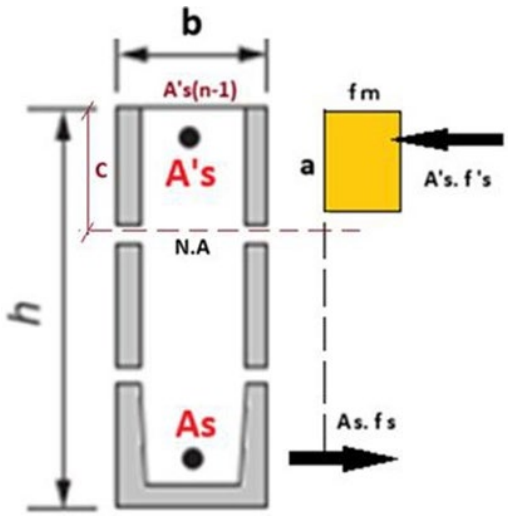

Figure 1. Masonry beam.

Creep deformation can be determined by Equation 1, and it can be used for concrete masonry unit (CMU) and clay masonry unit by using corresponding coefficient of creep in that equation.

$$dcreep = Kc.\ L.\ fm\ /2 \qquad (1)$$

where:

$Kc = Coefficient\ of\ creep$
$fm = Unfactored\ comressive\ stress\ on\ the\ element\ (psi)$
$L = Length\ of\ the\ elemet\ (in)$

Due to the compressive stress acting on the top part of a simply supported masonry beam, the maximum would be at mid length of the beam, and at both supports there would be no compressive stress, so half of the beam length will be considered for this calculation under maximum compressive stress.

Unfactored compressive stress is considered $fm = 0.45f'm$ in this paper, and if a compression bar is applied at the top mid span of the beam, then fm can be determined from Equation 2. Equation 2 can be used for masonry beams with or without a compression bar.

$$fm = 0.45f'\ [1 - (n - 1)\ A's\ /(a.\ b)] \qquad (2)$$

where:

$n = Es/Em$
$Es, Em = Modulus\ of\ elastisities\ of\ steel\ bar\ and\ masonry\ beams$
$a = Height\ of\ compression\ block\ as\ shown\ in\ Figure\ 1\ (in)$
$b = Beam's\ width\ (in)$
$A's = Copression\ bar\ cross\ secion\ (in2)$

Equation 2 is created by simple assumptions and for no compression bar at top middle length of masonry beam by using ($A's = 0$) the unfactored compression stress would be

$$f_m = 0.45f' . m$$

In order to show the effect of creep on masonry beams' deflection, first we need to calculate the beam deflection based on self-weight, dead, and live loads acting on the beam considering uncracked and cracked sections.

The compression zone is just at the top part of the simply supported beam, so creep will be anticipated within height "A" as shown in Figure 1. The bottom part of the beam would be in tension and will be elongated, and the neutral axis will stay without any deformation. So, length of the beam along the neutral axis would be "L" and the top of the beam (that has creep deformation) will be compressed and changed to $L - dcreep$. Figure 2 illustrates angle, length and depth of the neutral axis that are used for creep deflection calculations of a simply supported masonry beam.

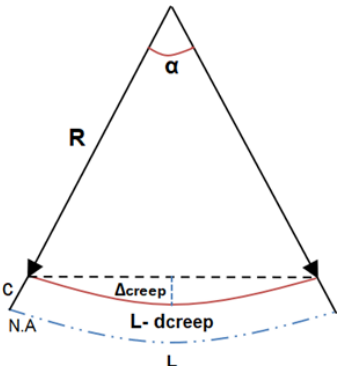

Figure 2. Simply supported masonry beam's creep deflection.

Based on Figure 2 amount of "α" and "$\Delta creep$" can be evaluated by the Equations 3 and 4.

$$\alpha = dcreep\ /c \qquad (3)$$

where:

$$c = Neutral\ axis\ distance\ from\ top\ of\ the\ beam$$

Note: In this paper amount of "c" is adopted from the LRFD method for masonry beam design ($c = a/0.8$).

$$R = (L - dcreep)/\ \alpha \qquad (4)$$

Creep deflection can be obtained from Equation 5, and minimizing this deflection would be our goal.

$$\Delta creep = R[1 - COS(\alpha\ /2)] \qquad (5)$$

EFFECT OF COMPESSION BAR ON THE CREEP DEFLECTION

Now, by using equations 1 through 5 we can calculate the effect of creep deflection on the simply supported masonry beams. As an example, a simply supported concrete masonry (CMU) beam with following information is considered.

$L = 12\ ft = 144\ inches$
$b = 7.63\ inches$ (8" $nominal$) $h = 24\ inches$
$d = 20\ inches$
$f'm = 2\ ksi$
$Es = 29000\ ksi$
$Em = 900f'm = 1800\ ksi$
$Kc = 2.5 \times 10{-}7\ /psi$

Notes:

- The compressive stress fm will be calculated from Equation 2.
- "A" can be determined from $a = As.fy/\ (b.f'm) = 3.932\ in.$
- The neutral axis can be calculated from $c = a/0.8 = 4.915$".
- $n = \ Es\ = 16.111\ Em.$
- Just the self-weight, dead and live load deflection results are shown here.
- For clay masonry beam $Em = 700f'm = 1400\ ksi$ and $Kc = 0.7 \times 10{-}7\ /psi.$

By assuming different compression bars at the top mid span of the CMU beam, the effect of the

compression bar on the beam's creep deflection can be calculated and the results are presented in Table 1.

Table 1. Effect of Compression Bar on Creep and Total Deflection.

Case	$A's$ $(in2)$	fm (psi)	d_{creep} (in)	α (rad)	$R\ (ft)$	Δ_{creep} (in)	Δ_{total} (in)	$\frac{\Delta_{creep}}{\Delta_{total}}$ (%)
I	0	0.9	0.0162	0.003296	43682.28	0.059324	0.35432	16.74
II	0.2	0.81	0.0146	0.002964	48576.40	0.053348	0.31885	16.73
III	0.31	0.76	0.0137	0.002782	51766.26	0.050062	0.31556	15.86
IV	0.44	0.7	0.0126	0.002566	56121.58	0.046177	0.31168	14.82
V	0.60	0.63	0.0113	0.0023	62604.13	0.041397	0.30690	13.49
VI	0.79	0.54	0.00975	0.00199	72556.26	0.035719	0.30122	11.86
VII	1	0.45	0.00804	0.00164	88021.53	0.029444	0.29494	9.98
VIII	1.2	0.36	0.00641	0.00130	110440.3	0.023468	0.28889	8.12
IX	1.4	0.27	0.00478	0.00097	148180.3	0.017491	0.28299	6.18
X	1.6	0.18	0.00314	0.00064	225100.9	0.011514	0.27701	4.16
XI	1.8	0.08	0.00151	0.00031	468072.2	0.005538	0.27104	2.04

Figure 3 shows the relation between the CMU beam's compression bar and $\Delta creep$ ratio $\Delta total$ (percentage), also Figure 4 is illustrating the CMU beam's creep deflection reduction by increasing the top mid span compression bar for different "$f'm$".

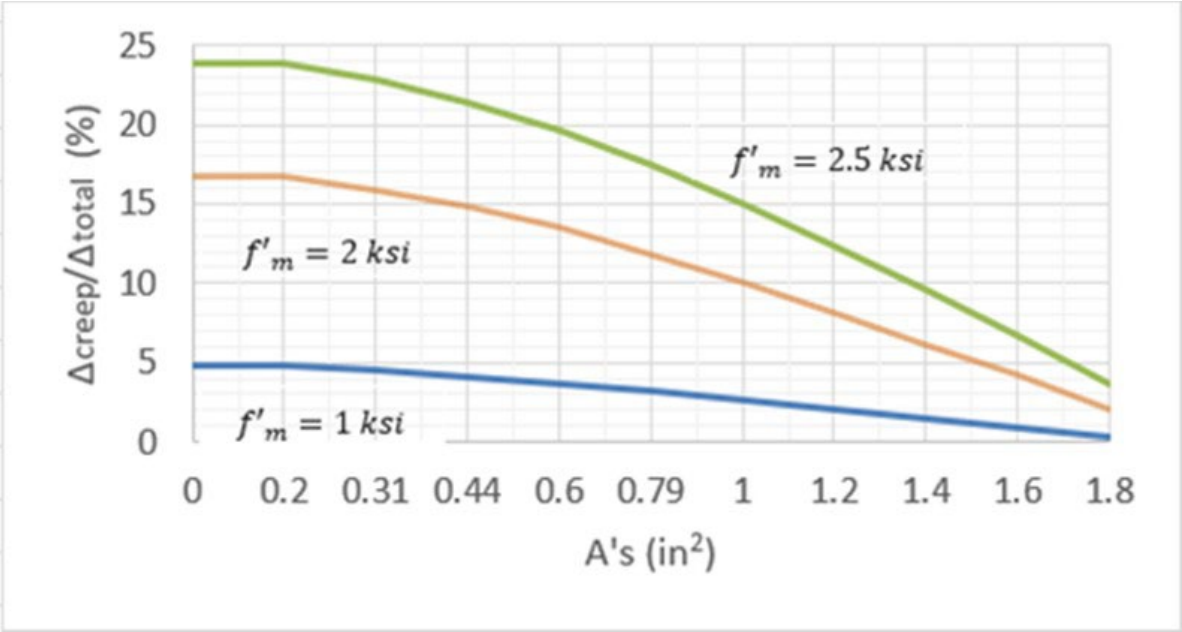

Figure 3. Compression bar versus deflection percentage.

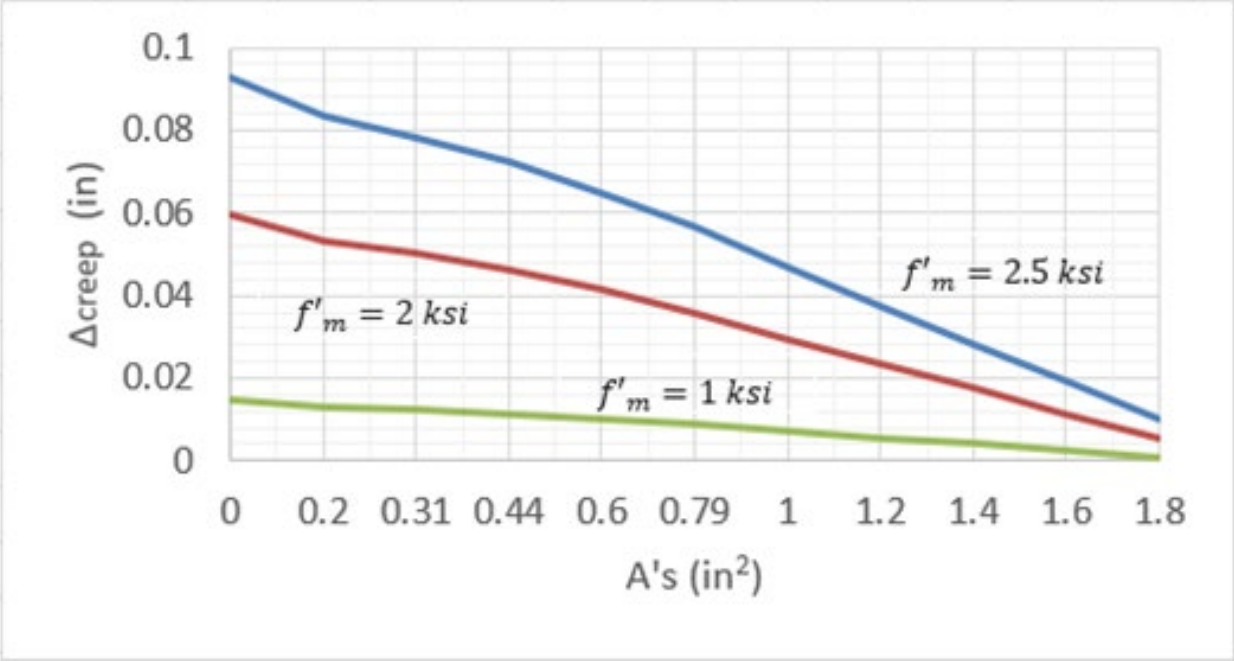

Figure 4. Compression bar versus creep deflection.

Beams' deflection that are supporting walls can contribute and intensify arching in those walls. Beam deflection can even cause separation in a wall, and Figure 5 shows wall arching sitting on a beam with significant deflection. Long term deflection might be dangerous for walls/buildings' stability, especially during an earthquake or high-speed wind conditions, and in general, minimizing deflection might improve the walls/buildings' stability.

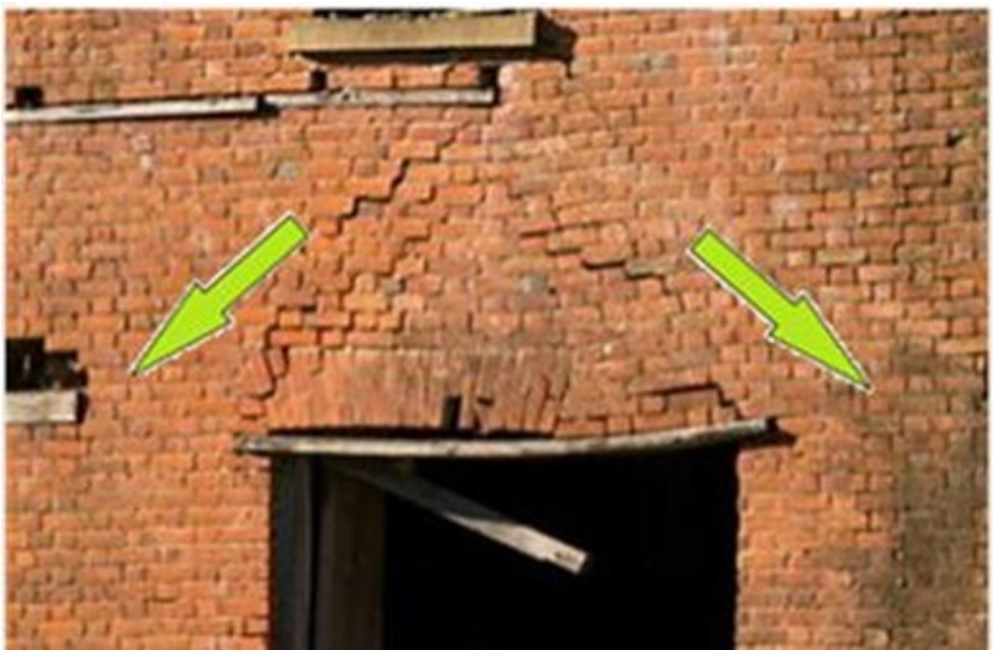

Figure 5. Arching caused by big beam deflection.

CONCLUSIONS

Based on the Example, Table 1, and Figures 3 and 4 the following conclusions have been made:

1. Using higher quality masonry units "$f'm$" will increase the CMU beam creep deflection.

2. Adding compression bar at top mid span of a masonry beam will reduce the masonry beam creep deflection that is almost 20% relative to beams without compression bar.

3. Using reinforced masonry walls sitting on reinforced masonry beams will reduce the arching problems.

4. There is no need to extend the compression top rebar to the supports.

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Going Beyond the Hype: Lessons Learned from Forensic Analysis of Proprietary Cladding Material Failures

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ABSTRACT

This paper examines failures of proprietary cladding systems through forensic analysis and offers lessons for design and installation. Due to the desire for more sustainable construction practices, there are a variety of proprietary cladding materials used in single-family and multi-family residences that are being marketed as more sustainable. Proprietary claddings comprised of polyvinyl chloride (PVC), fiber cement, wood flour, and other proprietary materials may be used to substitute non-proprietary materials like wood, masonry, stucco, and aluminum. Substitute claddings have some reported benefits and drawbacks. Composite materials used in proprietary products may be more durable, easier to maintain, and less expensive, with claims of lower environmental impacts. However, composite cladding products can contain a mix of materials, such as petroleum-based products, which complicate recycling and reuse efforts. Further, proprietary cladding material standards are not as uniform as those used for more traditional non-proprietary materials.

As a result, proprietary cladding products often rely on manufacturer-specific standards and installation requirements. Lack of industry-wide standardization makes it challenging for designers to evaluate and compare products, and for contractors to meet manufacturer-specific installation requirements. Proprietary products also tend to rely on lab-based testing, with limited in-situ product history. Accelerated long-term testing in a lab does not necessarily reflect actual long-term exposure. This paper briefly discusses some of the advantages, then offers a wider discussion of the disadvantages, of proprietary cladding products. Presented as well are case studies of cladding failures that resulted from various factors, including expectations of performance based on comparisons with traditional, non-proprietary materials or quality control issues during manufacturing. General lessons learned and key takeaways are presented to assist in evaluating products to be used in single- and multi-family housing projects. Recommendations are made to assess product claims and evaluate durability and resiliency for long-term service conditions.

INTRODUCTION

The desire in industry to build more sustainably has resulted in an interest in developing materials with smaller environmental impact. In the construction of modern single-family and multi-family housing, there are a variety of substitute cladding products that can be used in place of traditional wood, masonry, stucco, or aluminum materials, which are marketed as being more sustainable than those traditional materials. Modern cladding materials may be comprised of polyvinyl chloride (PVC), fiber cement board, or other proprietary materials such as composites using wood flour or other cellulose materials combined in a matrix that may include PVC. A term that encompasses many of these types of materials is wood polymer composites (WPC). These substitute materials have a variety of reported benefits and potential drawbacks in practice. In some cases, composite cladding materials may be more durable, easier to maintain, and less expensive when compared to traditional materials. Further, newer composite cladding materials incorporating bio-based materials may result in a reduced environmental impact where wood-based materials are used. However, those same composite cladding materials may also include petroleum-based ingredients, such as PVC, in their composition that complicate efforts to recycle or reuse those materials. Additionally, while traditional materials follow well-understood material standards, such as categorization of properties by species and grading for wood, or specific ASTM standards for masonry and mortar materials, standards for modern substitute cladding materials are less uniform and more dependent on proprietary, manufacturer-specific product representations. These representations or claims can periodically change if the constituent ingredients or processes change, such as if a substitute ingredient becomes more cost effective in the formulation.

Thus, proprietary modern claddings are often provided as a full product system that relies on manufacturer-defined standards for product formulation and installation quality. This can make it more challenging for designers to evaluate products for their quality and durability, and for contractors to properly implement manufacturer-specific installation requirements. Further, newer products demonstrate their performance and quality primarily through lab testing, with limited product history for in-service conditions and therefore the claimed lifespans may not be achieved in practice. Long-term testing is difficult to accomplish in a laboratory because time is not available to evaluate a product subjected only to natural conditions, and accelerated testing may not accurately represent actual long-term exposure.

CURRENT STATE OF THE INDUSTRY

When selecting a cladding material for a project, there are several criteria a designer or builder will consider. In general, designers select on behalf of their clients or homeowners cladding materials that are aesthetically pleasing, low cost, and easy to maintain. Tertiary considerations may include the ease of installation, durability, and sustainability.

Innovative Material Challenges

There are several challenges when considering the properties and life cycle of proprietary

cladding materials, which often tend to be a composite of several materials. The composite nature of these materials presents challenges. One challenge with proprietary materials is that they can be very manufacturer-specific, and there are no common testing or industry standards specific to these materials. Traditional materials, however, have better established standards such as through ASTM International (ASTM), American Wood Council (AWC), Brick Industry Association (BIA), and the Vinyl Siding Institute (VSI) among others.

Another challenge concerns the properties of various proprietary products. Cladding products containing PVC have very high thermal expansion coefficients relative to other cladding materials, as much as 20 times higher, as summarized in Table 1. If a cladding product with high thermal expansion is overly constrained during installation, there is a risk of damage to the cladding materials and an early need for replacement. The thermal expansion coefficient can be especially problematic when dark colors are used, because the temperature of the material is more affected by the solar incidence as well as the surrounding air temperature. The authors have measured cladding surface temperatures of 140 degrees F on days where the air temperature was less than 80 degrees in New England. For example, if PVC siding was cut to length and installed on a day that was 40 degrees F, this means that a 12-foot-long length of siding would regularly need to accommodate nearly a 1/2 inch of thermal expansion. For products combining cellulose and PVC the moisture-related expansion would be additive to thermal expansion.

The daily and seasonal thermal expansion of cladding products with high thermal expansion coefficients will also subject sealants used in conjunction with these products to additional bond stresses that can cause the sealants to fail adhesively or cohesively. Failure of these sealants can result in additional bulk water reaching the moisture control layer of the wall.

Table 1. Linear Coefficients of Thermal Expansion for Various Cladding Materials (Pace, 2011; Forest Products Society, 2010; Lardner and Archer, 1994).

Material	Linear Coefficient of Thermal Expansion 10-6 in/(in F)
Rigid PVC (siding)	32
Cellular PVC (trim)	36
Wood (parallel to grain)	1.7
Brick Masonry	3
Aluminum	13

Other challenging properties of proprietary materials concern their performance in a fire. Although traditional materials must consider fire performance as well, for example wood cladding is a combustible material, composite proprietary cladding products that include PVC or wood polymer composites typically contain ingredients that can release toxic fumes and chemicals during a fire, presenting risks to the environment and to human health. The composite nature of those PVC or wood polymer materials can thus lead to higher fire hazards and risks as

compared to homogeneous wood cladding alone (Renner et al., 2021). Further, flame retardants that may sometimes be used to improve the fire performance of wood polymer composites can also release toxic fumes during a fire (Ramesh et al., 2022).

Finally, proprietary composite cladding products tend to rely on manufacturer-dependent quality control measures. However, the more ingredients used to create a composite product, the more difficult it becomes to assess the quality of the raw ingredients and to ensure there are no undesirable interactions. Further, products that are relatively new and based off proprietary formulations often have limited long-term project history and therefore limited in-service performance. Note that early replacement due to failures caused by quality control or poor installation guidance can significantly reduce the potential environmental benefits of using proprietary composite cladding products.

General Product Sustainability

Some manufacturers heavily market their newer or proprietary cladding products as being sustainable and therefore good for the environment. Sustainability is a broad concept that can have different meanings for different groups or stakeholders. Often in industry, products are compared based on their global warming potential, which is commonly reported in a product's environmental product declaration (EPD) as equivalent greenhouse gas emissions. An EPD is a standardized and verified document that provides transparent and comparable information about the environmental impact of a product throughout its life cycle. Having an EPD for a product does not necessarily mean that product is environmentally better than others but rather is a means of comparing a product to others that also have an EPD. EPDs are produced by a third-party agency and typically follow reporting requirements per the ISO 14040/14044, ISO 14025, EN 15804, or ISO 21930 standards (Zacharia, 2025). More work needs to be performed to understand whether the third parties themselves become biased through the process of being engaged to generate an EPD on behalf of their client. EPDs vary in the extent of emissions data they provide, with some covering all life cycle stages and others focusing solely on product stage emissions, also known as the cradle to factory gate stage (A1 to A3). The product stage (A1 to A3) includes extraction, transport to the manufacturing facility, and manufacturing processes, and is often the basis for product comparison.

However, because many of the products marketed as sustainable are relatively new, an EPD is not always available, as product development may still be ongoing and the manufacturer may elect to start selling a product before spending money on an EPD certificate. A missing EPD makes it challenging to compare a product to others on the market, as the potential sustainable benefits have not been quantified. Even when an EPD is available, it may make assumptions about lifespan or material content that do not consistently match actual product composition or actual in-service lifespan.

There are some EPDs available for proprietary products, though, and a study published by Dovetail Partners, Inc. presented an environmental comparison of a variety of non-proprietary and proprietary cladding materials, including but not limited to brick and mortar, stucco, PVC, fiber cement, and engineered wood. The analysis includes a baseline assumption of a 60-year

lifespan equally for all products and found that PVC and solid wood-based siding products had the lowest environmental impact. The authors note that this assumption significantly favors inexpensive materials like PVC and discounts obvious differences in longevity (Bowyer, et al., 2019). Organizations like the Fannie Mae provides more realistic service lives of 20 years for wood siding, 25 years for vinyl siding, 45 years for cement-board siding, and "50+" years for brick veneer (Fannie Mae, 2019). Additionally, the authors also note that brick and mortar can have a 200-year lifespan, stucco can have a 100-year lifespan, and aluminum can have an 80-year lifespan. Although a 60-year lifespan is assumed in their analysis, the Dovetail Partners study cautions that poor installation and application of materials can significantly decrease the lifespan of the materials, such that replacement is required earlier than expected (Bowyer, et al., 2019). As previously noted, early replacement will certainly increase the environmental impact of a building. For example, the PVC cladding in the Dovetail Partners study may not have the lowest environmental impact of the studied cladding materials if only a 25-year lifespan is achieved, rather than the assumed 60-year lifespan.

Looking at the environmental impact of products more specifically, composite materials tend to be very proprietary and have a variety of ingredients used and proportions of different materials that can significantly affect global warming potential. For example, during the A1-A3 product stages, wood polymer composites may use either recycled materials, virgin materials, or a blend of both, and those using recycled materials will have a lower environmental impact than those using virgin materials (Ramesh, et al., 2022). Some wood polymer composites even use mineral fiber, including either mineral wool or fiberglass, as an ingredient; however, a study found significant reductions in environmental impact when using reprocessed mineral wool instead of glass fiber (Ramesh, et al., 2022).

In one last example, fiber cement cladding makes use of cement, which can be energy and water intensive in its production process (Read, 2022). Apart from the proportions of cementitious materials used in the product, the authors also note that the types and proportions of cementitious materials are also important. For example, portland cement has a greater global warming potential than supplementary cementitious materials like fly ash or blast furnace slag.

Recyclability of Composite Cladding Materials

Other than the global warming potential reported in product EPDs, many newer products are marketed as being recyclable. However, many products may be challenging to recycle due to their mixed composition or may only be recycled into lower quality materials. For example, bio-based materials may contain petroleum-based ingredients in their composition that complicate efforts to recycle or reuse these materials.

In general, composite materials tend to be more difficult to recycle than single-ingredient materials because they are heterogeneous (Ozaltay, Gunoz, and Kara, 2013). While recycling technologies for composite materials are in development across a range of industries, including construction, automotive, marine, and aerospace, these technologies are currently expensive and result in recycled materials that are of a lower quality than the original product and its ingredients (Yang, et al., 2012; Krauklis, Karl, Gagani, and Jorgensen, 2021). Recycling

technologies in other industries focus on recycling composites such as carbon fiber reinforced polymers and glass fiber reinforced polymers, and even though the materials are different than those used in construction, the concepts are similar for products that include a matrix of binders and fibers. In most fiber-reinforced materials, the recycling process will essentially involve chopping up longer fibers into shorter fibers. Where wood flour fibers are used, these fibers are already extremely short and therefore the drawbacks of the recycling process are reduced. However, with any fiber-reinforced materials, there is the additional challenge of collecting and returning used materials to the factory. Further, any functional chemicals applied to the fibers to improve properties, such as binding capacity within the resin matrix, will not have the same benefit in the recycled product.

In one study, wood polymer composites tested in a lab after multiple rounds of reprocessing found no adverse effects on mechanical properties, despite multiple rounds of reprocessing via extrusion which shortens the fibers. However, the study cautions that more research is needed to understand the effects of long-term in-situ aging of materials on material properties when recycled at the end of life (Burgstaller and Renner, 2023). Further, it is typically easiest to recycle a wood polymer composite into another composite material, rather than breaking the product materials down to their individual components (Ramesh, et al., 2022). Based on the current knowledge, the recycling of wood polymer composites has limited applications for reuse. Further, useful recycling applications are likely best suited for handling offcuts and waste during manufacturer.

Of additional note, demolition at the end of a life of a building can result in a significant amount of mixed demolition debris. It can be challenging to sort this material properly to direct different materials to the proper recycling facilities, or to send material back to specific manufacturers. Materials may also become contaminated during the demolition process or may have been contaminated over time due to site conditions (Guberman, 2022; Dahlbo et al., 2015). A clear plan with a focused effort is required to successfully recycle cladding materials at the end of a building's lifespan.

There is potential for recycling technologies to improve over time as they are further developed, but it is possible that nature of proprietary composite cladding materials means they will always be more challenging to recycle and reuse as compared to traditional materials.

Effects on Human Health

Further to the environmental impact of cladding materials, there is great interest in the use of materials that do not degrade human health. Composite construction materials have historically used ingredients that were eventually found to be harmful, such as Polychlorinated Biphenyls (PCBs) in sealants and coatings, and asbestos in fiber cement panels. While these specific materials are no longer used in newly manufactured cladding materials, other substituted materials can have their own drawbacks. For example, composite cladding materials that contain PVC can be hazardous to human health at various stages of its life cycle, including during building fires that may happen internally or through spread of wildfires. The chemicals used to make PVC include known carcinogens, and stabilizers historically used in PVC manufacturing

included heavy metals used as recently as 2015 (Petrovic, 2018). Newer organic stabilizers used in PVC manufacturing have not been thoroughly vetted for their safety (Petrovic, 2018). PVC is also a combustible material and, when burned, PVC releases several toxic chemicals that are hazardous to human health if breathed in, and which can affect drinking water quality if released into the environment (Chong, Abdulramoni, Patterson, and Brown, 2019).

Some products also may present hazards during handling and installation. For example, fiber cement cladding releases silica dust when cut on site. Installers must wear proper personal protective equipment (PPE) during cutting because long-term exposure to silica dust can cause lung damage, silicosis, and cancer with long-term exposure (Read, 2022).

Further, the use of plastics in proprietary cladding materials, such as in wood plastic composites, can contribute to the spread of microplastics in the environment. Wood plastic composites can release microparticles during cutting in the field and through weathering over time (Kuka et al., 2023). Microparticles then break down in the environment into microplastics which are hazardous to human health and the environment. Microparticles are not typically well-controlled during cladding cutting and installation in single- and multi-family residential construction.

CASE STUDIES

The following case studies document forensic investigations conducted by the authors involving proprietary cladding failures in residential and multi-family buildings in the northeastern United States. Each investigation involved field observation, material sampling, and laboratory analysis including petrographic testing to determine root causes of premature material degradation. For confidentiality reasons related to ongoing litigation and client privacy, specific project locations and detailed failure extent have been generalized while preserving the technical findings.
The durability and service life of cladding materials are generally understood to depend on intrinsic material properties and the level of maintenance performed by the owner. However, the case studies presented below do not involve maintenance neglect or extreme weather events. Rather, they document failures in properly maintained buildings where materials inadequately accommodated normal environmental conditions including thermal expansion, or where product formulation varied from manufacturer representations. These cases illustrate the gap between laboratory testing, product marketing claims, and actual field performance under typical service conditions.

Fiber Cement Lapped Siding

Fiber cement lapped siding is a material that is intended to appear similar to wood clapboards, sometimes even with a surface that appears to mimic the grain of wood, but is comprised of fly ash (a byproduct of coal-fired power plants), portland cement, cellulose fiber, and fine aggregate. Fiber cement siding is marketed as being more durable than wood, in that it is more decay resistant, and is non-combustible as compared to PVC or wood.

Various class actions have been filed, alleging that manufacturing defects resulted in cracking of the siding that can result in it becoming detached from the building. The cracking was so severe

that the siding required replacement sooner than reasonably expected. Figure 1 shows cracking of a representative fiber cement clapboard. Figure 2 shows displacement due to cracking of a fiber cement clapboard.

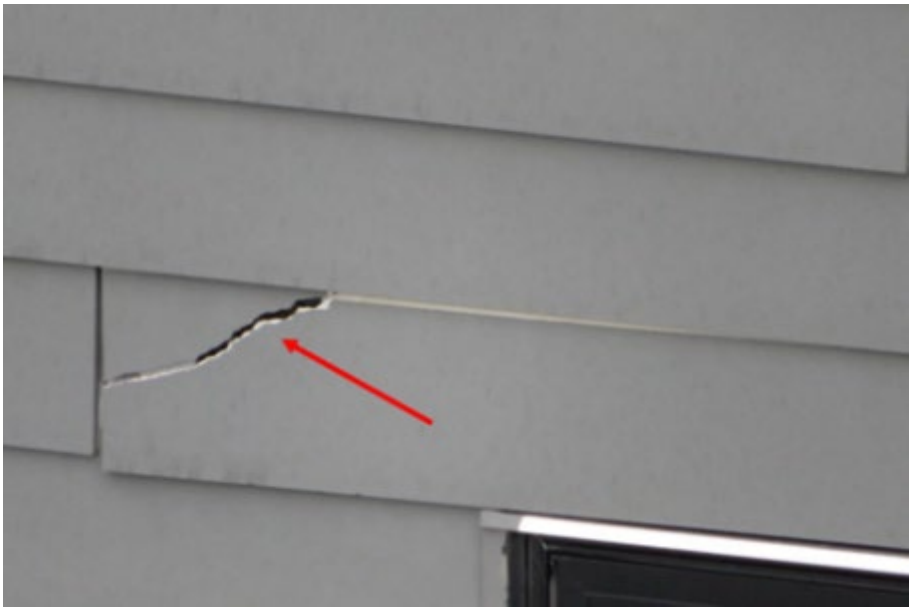

Figure 1. Cracking of fiber cement clapboard cladding.

Figure 2. Displacement due to cracking of fiber cement clapboard cladding.

Fiber cement siding, due to its properties as a material that is much more brittle than wood or PVC has exacting requirements for installation including strict adherence to edge distances. Fiber-cement siding manufacturers often claim that installation deficiencies alone are responsible for member cracking, even when there is no observable correlation between boards with cracking and boards that are not installed in accordance with the manufacturer's instructions.

Fly ash is commonly subject to supply constraints as demand for supplemental cementitious products with a lower carbon equivalent than portland cement has increased while coal-fired power plants have substantially decreased. In one project, siding with extensive cracking was removed from a building that was constructed in 2015. A siding sample was obtained from a lot known to have been manufactured in 2020. A comparison was made amongst the EPD from around the time the building was constructed in 2014 and the compositions determined through petrographic analysis and petrographic point sampling. Table 2 presents the results of that comparison.

Table 2. Comparison of Fiber Cement Siding Constituents Between EPD and Samples from Different Production Dates, with Values Outside Stated Ranges in Bold.

Constituents	Proportion (%) by Weight			
	2014 EPD	2015 Sample A	2015 Sample B	2020 Sample
Portland Cement	28-40 %	34 %	38 %	50 %
Fly Ash	22-32 %	20 %	20 %	0 %
Cellulose Fibers	5-10 %	19 %	20 %	11 %
Sand (quartz)	25-35 %	27 %	22 %	39 %

The authors note that fly ash was eliminated from the product produced in 2020, and the amount of portland cement necessary to bind the material together was increased. It is expected that this change was made due to availability of the materials at the time of production. Drying shrinkage of cementitious materials occurs over the course of one or more years, with most of this shrinkage occurring at an early age. The increase in coarse aggregate and the decrease in cellulose fiber was likely an attempt to control this shrinkage as the volume change of the material is largely related to the amount of cement paste.

Although there were no changes in the product name or representations made of the product made by the manufacturer, not only had its mechanical properties significantly changed, but so too had its carbon equivalence, due to the increased proportion of portland cement.

PVC-Cellulose Composites

PVC-cellulose composites have been used for decking materials as well as for trim boards. They are now more frequently being marketed and used as a replacement for clapboards or other siding materials. The cellulose fibers contained in these products can be obtained from various sources, including waste products of agricultural production. When the cellulose is obtained from this type of source, manufacturers claim that this offsets a difficult to degrade product from the waste stream and provides an alternative to wood.

Because of the relatively large coefficient of thermal expansion compared with other cladding materials, manufacturers state that the boards should be acclimatized to the temperature they will be installed at prior to installation and provide details for scarfed joints to conceal the effects of expansion and contraction.

The authors have performed several investigations where, due to the coefficient of thermal expansion, the siding becomes bowed in warm temperatures, especially when installed during cooler temperatures. Figure 3 shows displacement of the top edge of the cladding due to thermal changes subsequent to installation. Figure 4 shows bowing of cladding due to restraint of the thermal expansion. Due to the short lengths of the cellulose fibers compared to wood, and the low fiber volume fraction, these products are significantly less stiff than wood. This compliance exacerbates problems with bowing and warping. Typically, the bowing exhibits itself as a series of projections from the wall where the siding remains tight to the sheathing or furring at the attachment points and projects outwards to a maximum in between the attachment points.

Figure 3. Gap due to thermal change of vertically-oriented PVC-cellulose composite cladding.

Figure 4. Bowing due to thermal change of vertically-oriented PVC-cellulose composite cladding.

When observed during cold weather, large gaps can occur that are inconsistent with the amount of displacement that most types of sealant joints can accommodate. This is not only an aesthetic issue. If there are also deficiencies in the water control layer behind the cladding, they may become exposed to a greater amount of water than if the cladding is able to shed most of the bulk water, thus increasing the risk of water infiltration.

DISCUSSION AND CONCLUSIONS

Although proprietary and newer innovative cladding materials can have some benefits related to low environmental impact, durability, and aesthetics, the benefits may be overstated by manufacturer product manufacturing and rely largely on manufacturer-specific quality control and proper installation. Among case studies of fiber cement lapped siding, severe cracking was observed due to inconsistences in the proportions of material constituents, including the elimination of fly ash altogether from more recent samples. Case studies of PVC-cellulose composite cladding found severe warping of siding boards due to the large coefficient of thermal expansion of the material.

Although there are many challenges to using proprietary cladding materials, they can be appropriate choices for specific projects if carefully considered during design. In general, a manufacturer's marketing is often insufficient to fully assess a cladding product. It is often necessary to research a product further to understand all constituents of the materials and available performance test data. Designers can evaluate a product by reviewing available test results on product data sheets including reports containing the test data, requesting case studies of in-situ projects from manufacturers, and by requesting any additional testing data the manufacturer may not have on their website. Given sufficient time in a project's schedule, it may be helpful in large-scale multi-family residential projects to consider additional product testing to further evaluate material performance. Additional testing will depend on client buy-in or manufacturer support, with the caveat that laboratory testing still will not be a perfect predictor of long-term in-situ performance. Always be wary of new products, products that do not have a track record of use in your region, and instances where the product being used is installed in a novel way or is used in a larger size or length than ever before.

Further, in selecting a cladding product during design, it is important to use the right material for the right climate and building type. For example, PVC cladding may not be appropriate in climates or regions with severe weather conditions that can cause damage to the PVC, such as large temperature swings, excessive heat or cold, hail, or high winds. In some cases, it may be more appropriate to use more traditional or non-proprietary materials, such as on institutional projects expected to have a longer lifespan, historic building retrofits, high-end single- or multi-family projects expected to have a longer-than-average lifespan, or in climates and regions with more severe weather conditions. Periodic inspection and maintenance are always beneficial to achieving the full lifespan of any cladding product. Products with a known maintenance track record are generally preferable to products whose required maintenance is not known or if the manufacturer understates the need for maintenance of their product or adjoining conditions, like coatings or sealants.

During design of multi-family projects that include architectural specifications, designers can include robust requirements for the cladding to encourage best practices are followed. Project specifications for proprietary claddings may include installation review or inspection requirements, as well as a list of specific pre-vetted manufacturers and products, with clear limitations on substitution requests. As a project transitions to occupancy, owners can mitigate risks to their cladding by performing regular inspections, consistent maintenance as required by the manufacturer, and by addressing early signs of material failure quickly. These steps can be highly formalized in larger multi-family residential projects, or more informal when taken on by a single-family homeowner. Homeowners can protect their cladding investment by reporting any issues to the builder or installer in a timely manner to access any warranty coverage and benefits they may have.

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Improvement of Compressive Strength of Hempcrete by Promoting Pozzolanic Effects

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ABSTRACT

Growing environmental concerns regarding construction industry emissions have accelerated the search for sustainable building materials, with hempcrete showing promise as a bio-based solution despite limitations in compressive strength for structural applications.

This study investigates systematic approaches to improve the compressive strength of hempcrete through advanced mixture design optimization, alternative binder selection, and strategic additive incorporation. The experimental program examined the substitution of conventional hydrated lime with magnesium oxide (MgO) binders and the integration of pozzolanic additives including fly ash and ground granulated blast furnace slag (GGBS) at varying dosages (6% and 20% by binder weight). Ten distinct mixture designs were evaluated to quantify the individual and synergistic effects of these components on mechanical performance after seven-day curing periods.

The results demonstrate substantial enhancement in compressive strength, with specimen 2BGGBS20 achieving the highest value of 167.61 psi (1.14 MPa), representing a 469% improvement over the baseline hempcrete formulation (29.43 psi). This optimal formulation combined 40% MgO binder with 20% GGBS addition and 15% hemp content, demonstrating the effectiveness of high-dosage pozzolanic enhancement. MgO-based specimens consistently outperformed lime-based counterparts, with fly ash incorporation also yielding significant strength improvements (166.78 psi). The analysis revealed clear dosage-response relationships for GGBS incorporation, with 20% addition achieving 14.7% higher strength than 6% dosage.

The investigation demonstrates that strategic mixture optimization combining MgO binders with elevated pozzolanic additive content can produce hempcrete formulations suitable for load-bearing applications, advancing sustainable construction material development while preserving hemp-based composites' inherent environmental advantages.

Keywords: Hempcrete, Biobased Material, Fly Ash, Magnesium Oxide, GGBS, Mechanical Properties, Sustainable Construction.

INTRODUCTION

Hempcrete represents a revolutionary approach to sustainable construction, emerging as a promising alternative to conventional building materials in response to growing environmental concerns and the construction industry's significant carbon footprint (Asghari and Memari, 2024). As a bio-composite material primarily composed of hemp hurds (shiv), lime-based binders, and water, hempcrete addresses the urgent need for environmentally responsible building solutions while offering unique functional properties (Lupu, Isopescu et al., 2022; Asghari and Memari, 2024).

The development of hempcrete stems from the construction sector's responsibility for substantial greenhouse gas emissions and the pressing need to reduce the environmental impact of building materials (Bas, Kamal et al., 2022; Parashar, Sistla et al., 2022). Hemp cultivation can be completed within less than four months, ensuring rapid carbon absorption during production and deployment (Asghari and Memari, 2024; Tong and Memari, 2025). This material has been successfully used in France since the 1990s for non-weight bearing insulating infill walls (Asghari and Memari, 2024; Tong and Memari, 2025).

Research Gap

Despite recent advances in hempcrete formulation, a systematic investigation of combined binder substitution and high-dosage pozzolanic additives remains unexplored. Previous studies have independently examined lime alternatives or additive incorporation, but the synergistic effects of magnesium oxide (MgO) binders with optimized pozzolan dosages (up to 20% by weight) have not been comprehensively evaluated.

Research Objective

This study presents a systematic evaluation of strategies to enhance hempcrete's compressive strength by: (1) substituting traditional hydrated lime with reactive MgO cement, (2) incorporating pozzolanic additives (ground granulated blast furnace slag and Class F fly ash) at varying dosages (6-20% by binder weight), and (3) evaluating sand integration for matrix densification. Employing Design of Experiments methodology, the investigation aims to transition hempcrete from a non-structural infill material toward a viable load-bearing option in sustainable construction.

Experimental Program

Research into the optimization of hempcrete's mechanical properties is essential for advancing its use as a sustainable building material. This experimental program details the materials and methodologies employed to enhance the compressive strength and overall performance of hempcrete through systematic investigation of binder alternatives and pozzolanic additives. The study explores magnesium oxide cement (MgO) as a novel alternative to traditional hydrated lime, alongside pozzolanic additives including ground granulated blast-furnace slag (GGBS) and Class F fly ash. Additionally, the role of sand as a fine aggregate was investigated to understand its impact on density and compressive strength development.

Materials
Materials for the study consisted of hemp hurds, hydrated lime, magnesium oxide (MgO), and pozzolanic additives (fly ash and GGBS), selected for their established roles in improving hempcrete mechanical performance and sustainability.

Hemp Hurds
Industrial hemp (Cannabis sativa L., KANABAT brand) hurds were procured from Americhanvre (https://americhanvre.com/) that markets hemp and lime products from La Chanvriere de l'Aube with "GRANULAT CHANVRE BÂTIMENT" certification for building standards compliance. Air-dried hurds were sieved to 5-25 mm particle size. Measured bulk densities: loose (112.4 ± 2.2 kg/m³), vibrated (170.5 ± 2.0 kg/m³), and layered (165.8 ± 4.5 kg/m³), consistent with literature (Delhomme, Hajimohammadi et al., 2020).

Binders
Hydrated Lime (CL90s) conforming to EN 459-1 was sourced from Sarl Lisbonis Chaux Grasses (LCG), selected for its high calcium oxide content (>90%) and progressive carbonation capability under ambient conditions. The carbonation process involves atmospheric CO_2 assimilation into the binder matrix, converting $Ca(OH)_2$ to $CaCO_3$ through the lime cycle, partially offsetting production emissions (Jami, 2016).

Light-burned Magnesium Oxide (reactivity grade) was obtained from Premier Magnesia's Magox XL brand as an innovative alternative to hydrated lime. MgO was selected due to its lower calcination temperature (700-1000°C), reduced energy demand, and enhanced early strength development through faster carbonation kinetics (Zhou and Li, 2012; Haik, Meir et al., 2023). MgO's crystal structure evolves with calcination temperature, affecting surface area and reactivity critical for binder applications, with 500–600°C calcined MgO demonstrating optimal reactivity for construction use.

Pozzolanic Additives
Class F Fly Ash was sourced from Diversified Minerals Inc. and R-E-D Industrial Products. This low-calcium pozzolan ($SiO_2 + Al_2O_3 > 70\%$, $CaO < 6\%$) was incorporated at 6% by binder weight to enhance matrix packing and long-term strength through secondary pozzolanic reactions (Walker, Pavia et al., 2014, O'Flaherty, Khalaf et al., 2023). Its primarily siliceous composition requires external alkaline activation to form cementitious compounds.

Ground Granulated Blast-furnace Slag (GGBS) was obtained from BURGESS OPTIPOZZ and R-E-D Industrial Products to evaluate supplier variations. GGBS was incorporated at 6% and 20% by binder weight. This rapidly quenched slag exhibits high specific surface area and forms calcium silicate hydrate (C-S-H) gel through hydration and pozzolanic reactions, contributing to long-term strength development and durability enhancement (Walker and Pavía, 2011).

Fine Aggregate

Sand was incorporated at 40% by total mix weight in selected formulations to enhance packing density, reduce voids, and improve compressive strength through improved particle size distribution.

Mixture Design

Ten mixture designs were developed to evaluate the individual and synergistic effects of binder type (hydrated lime vs. magnesium oxide), pozzolanic additives (fly ash and GGBS at 6% or 20% by binder weight), and sand incorporation (40% by total weight) on compressive strength performance (Table 1).

Table 1. Mixture Design Matrix.

Mixture Name	Sand	Binder Types		Hemp (% Total Weight)	Additives	
		Lime (% Total Weight)	MgO (% Total Weight)		Fly Ash (% Binder Weight)	GGBS (% Binder Weight)
H1	-	33.33	-	33.33	-	-
1E		40	-	15	6	-
2E		-	40	15	6	-
2T		-	40	15	-	6
1BOG	-	40	-	15	-	-
2BOGS	40	-	40	15	-	-
2BGGBS6	-	-	40	15	-	6
2BGGBS6S40	40	-	40	15	-	6
2BGGBS20	-	-	40	15	-	20
2BGGBS20S40	40	-	40	15	-	20

Specimen H1 served as the baseline control with equal proportions of hemp hurds, hydrated lime, and water (33.33% each). Binder performance was compared through specimens 1E vs. 2E (lime vs. MgO with 6% fly ash) and 1BOG vs. 2BOGS (lime vs. MgO without additives, 2BOGS with sand). Additive effectiveness was evaluated through 2E vs. 2T (fly ash vs. GGBS at 6%), while dosage optimization compared 2BGGBS6 and 2BGGBS20 (6% vs. 20% GGBS). Sand effects were assessed in specimens 2BOGS, 2BGGBS6S40, and 2BGGBS20S40. Water-to-binder ratios were optimized between 0.45-0.55 based on binder reactivity and workability requirements.

Specimen Preparation

Specimens were prepared using a standardized protocol: dry materials (hemp hurds, binder, additives) were homogeneously mixed in a Hobart mixer for 3 minutes, followed by gradual water addition with 3 additional minutes of mixing. Fresh mixtures were cast into 50mm (2×2×2 inch) cubic molds in 3-4 layers, with each layer tamped 10-15 times to eliminate voids and ensure uniform density. Specimens underwent two-phase curing: 24-48 hours sealed at 23°C (wrapped in damp towels and plastic), followed by 7 days at 100% relative humidity and 23°C to optimize hydration while preventing premature drying.

Testing Methodology

Density Measurement

Specimen density was calculated from measured mass and dimensions after the curing period, with three replicates per mixture design ensuring statistical reliability.

Compressive Strength Testing

Compressive strength tests were conducted using an MTS testing apparatus following adapted ASTM C109 procedures. A loading rate of 20 lb/s was applied until failure, with ultimate strength determined at the transition from linear to non-linear stress-strain behavior. Three specimens per mixture were tested to ensure result reproducibility.

RESULTS AND DISCUSSION

The experimental results demonstrate significant improvements in hempcrete performance through systematic optimization of binder selection, pozzolanic additives, and mixture composition. This section presents the density and compressive strength findings, analyzing the mechanisms responsible for performance enhancement and comparing results with the baseline H1 specimen and existing literature.

Density Analysis

Densities ranged from 536.75 kg/m³ (H1 control) to 1353.27 kg/m³ (2BGGBS20S40), a 152% increase through strategic material optimization (Table 2). These values significantly exceed typical hempcrete densities of 270-850 kg/m³ (Asghari and Memari, 2024), demonstrating the effectiveness of the compaction methodology and material selection employed.

MgO substitution consistently increased densities compared to lime-based formulations. Specimen 2E (MgO + fly ash: 1050.88 kg/m³) achieved 15.1% higher density than specimen 1E (lime + fly ash: 912.81 kg/m³), attributed to MgO's superior packing characteristics and rapid hydration kinetics (Haik, Bar-Nes et al., 2020, Asghari and Memari, 2024).

Pozzolanic additives enhanced matrix densification through combined physical and chemical mechanisms. Fly ash improved packing efficiency via fine particle size and spherical morphology, while GGBS contributed through pozzolanic reactions (O'Flaherty, Khalaf et al., 2023). Increasing GGBS dosage from 6% to 20% yielded modest density gains of 2.4% (1122.84 vs. 1149.28 kg/m³, Table 2).

Sand incorporation at 40% by total weight consistently increased densities across formulations, with 2BGGBS20S40 achieving maximum density (1353.27 kg/m³). Sand particles bridge the size gap between hemp hurds and binder particles, optimizing packing density and reducing porosity (Delhomme, Hajimohammadi et al., 2020).

Table 2. Average Density of Hempcrete Mixture Designs.

Mixture	Cube	Weight (grams)	Average Density (kg/m3)	Average Density (lb/ft3)
H1	1	67.7	536.75	33.51
	2	72.9		
	3	70.5		
1E	1	119.4	912.81	56.97
	2	118		
	3	121.6		
2E	1	136.2	1050.88	65.61
	2	139.1		
	3	138		
2T	1	134.3	1050.63	65.59
	2	141.3		
	3	137.6		
1BOG	1	120.9	914.85	57.11
	2	120.6		
	3	118.3		
2BOGS	1	149.4	1168.61	72.96
	2	151.4		
	3	158.8		
2BGGBS6	1	145.4	1122.84	70.10
	2	147.7		
	3	148.5		
2BGGBS6S40	1	174.8	1308.21	81.67
	2	164.2		
	3	175.5		
2BGGBS20	1	142.3	1149.285	71.75
	2	157.4		
	3	152.3		
2BGGBS20S40	1	176.2	1353.27	84.48
	2	178.1		
	3	177.9		

The systematic tamping compaction achieved 35-60% higher densities than natural compaction methods (Nguyen, Picandet et al., 2010), demonstrating compaction's critical role in hempcrete optimization. The 7-day curing period enabled initial hydration and pozzolanic reactions, with lime-pozzolan systems reaching 60-70% of the ultimate strength (Walker, Pavia et al,. 2014).

Compressive Strength Analysis

Performance Enhancement Over Baseline

All optimized formulations demonstrated substantial compressive strength improvements over the H1 control specimen (29.43 psi). The performance enhancements ranged from 230% (1BOG: 97.23 psi) to 469% (2BGGBS20: 167.61 psi), validating the effectiveness of the systematic optimization approach (Table 3).

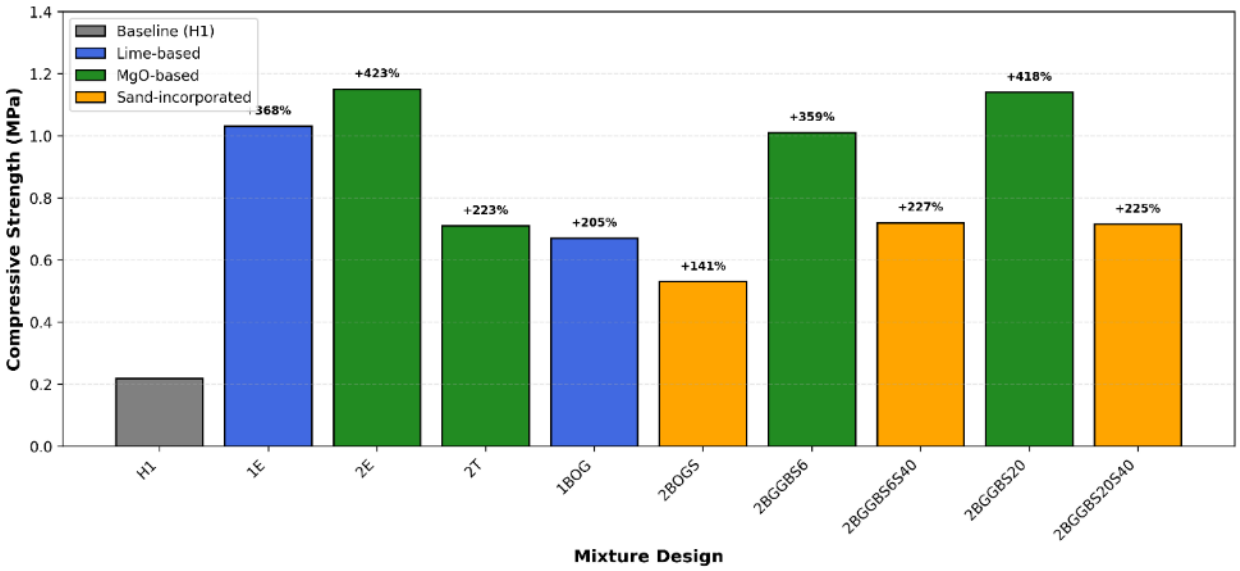

Figure 1. Compressive strength performance of hempcrete mixture designs. Error bars represent standard deviation (n=3). Percentage improvements relative to baseline control (H1, shown in gray) are indicated above bars. Color coding: blue = lime-based binders, green = MgO-based binders, orange = sand-incorporated formulations (40% by total weight).

Binder Performance Comparison

MgO-based formulations consistently outperformed lime-based counterparts in direct comparisons. Specimen 2E (MgO + fly ash: 166.78 psi) achieved 11.4% higher strength than specimen 1E (lime + fly ash: 149.68 psi), despite similar density profiles (Table 3.). This superior performance stems from MgO's enhanced pozzolanic reactivity and faster carbonation kinetics, forming stronger binding matrices within the 7-day curing period (Zhou and Li 2012, Haik, Meir et al., 2023).

The comparison between 1BOG (lime only: 97.23 psi) and 2BOGS (MgO + sand: 77.41 psi) requires careful interpretation, as the latter includes sand modification that alters the matrix composition significantly.

Table 3. Compressive Strength Performance of Hempcrete Mixture Designs.

Mixture	Load (lb)	Average Stress-psi	Average Stress-MPa
H1	126.3	29.43	0.22
	108.3		
	118.6		
1E	610.22	149.68	1.03
	578.1		
	607.85		
2E	661.31	166.78	1.15
	663.97		
	676.15		
2T	408.05	101.75	0.71
	410.3		
	402.71		
1BOG	396.2	97.23	0.67
	382.85		
	387.74		
2BOGS	307.09	77.41	0.53
	317.37		
	304.44		
2BGGBS6	586.87	146.11	1.01
	578.02		
	588.42		
2BGGBS6S40	410.63	103.86	0.72
	415.47		
	420.28		
2BGGBS20	671.16	167.61	1.14
	674.79		
	665.38		
2BGGBS20S40	417.04	103.73	0.715
	412.56		
	415.21		

Additive Effectiveness Analysis

Fly Ash Performance: Specimens incorporating fly ash (1E: 149.68 psi, 2E: 166.78 psi) demonstrated superior strength development compared to GGBS formulations at equivalent dosages. The enhanced performance of fly ash stems from its optimal particle size distribution and high silica content, promoting efficient pozzolanic reactions with both lime and MgO binders (O'Flaherty, Khalaf et al., 2023).

GGBS Dosage Optimization: A clear dosage-response relationship emerged for GGBS incorporation. Specimen 2BGGBS20 (20% GGBS: 167.61 psi) achieved 14.7% higher strength than 2BGGBS6 (6% GGBS: 146.11 psi), indicating that higher GGBS content enhances pozzolanic activity and matrix strengthening (Walker and Pavía, 2011). This aligns with literature findings suggesting optimal GGBS replacement levels of 15-25% for maximum strength development.

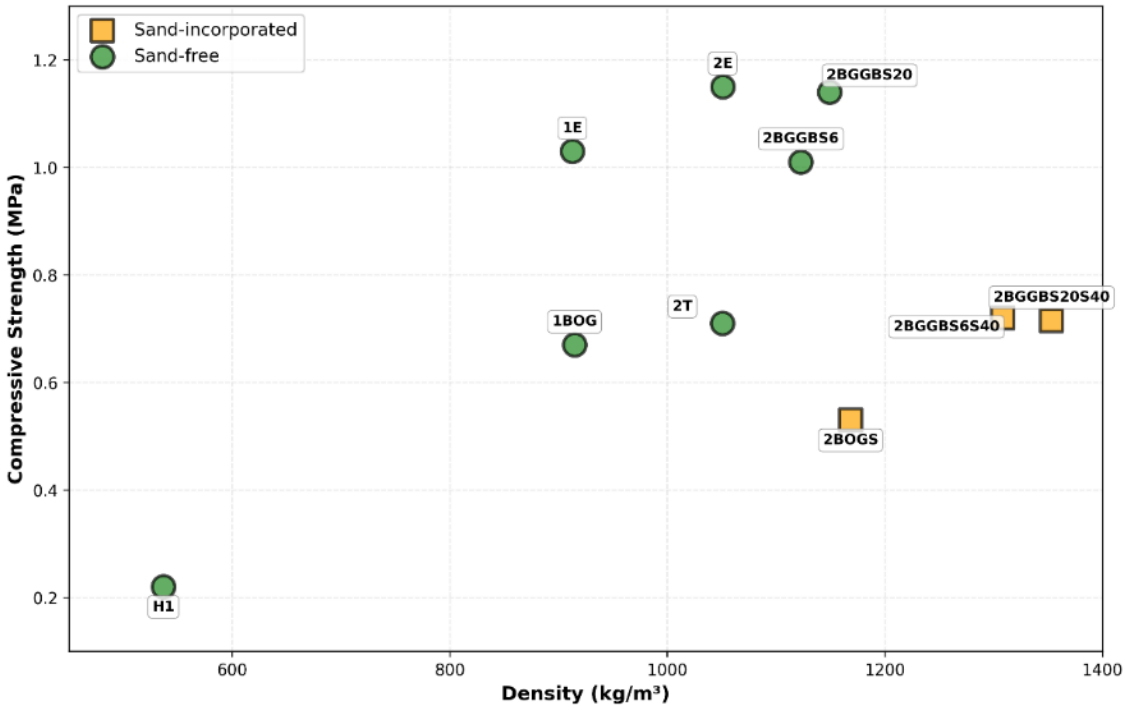

Figure 2. Relationship between density and compressive strength for hempcrete mixture designs. Sand-incorporated specimens (orange squares) demonstrate higher densities but reduced compressive strengths compared to sand-free formulations (green circles). Each data point is labeled with its mixture designation. The scatter plot reveals the density-strength paradox, where sand incorporation consistently increases density while reducing compressive strength.

Sand Addition Paradox

Contrary to density increases, sand incorporation reduced compressive strength across all formulations. Specimens 2BGGBS6S40 (103.86 psi) and 2BGGBS20S40 (103.73 psi) exhibited 28.9% and 38.1% strength reductions compared to sand-free counterparts, attributed to: (1) dilution effect—reduced volumetric concentration of hemp hurds and binder weakening the composite matrix, and (2) weak interfacial bonding between sand particles and lime/MgO matrix creating failure initiation points under loading.

MgO-based binders with high-dosage pozzolanic additives (particularly fly ash and 20% GGBS) represent the optimal pathway for hempcrete strength enhancement. Peak formulations (2E, 2BGGBS20) achieved 5.7-fold improvements over baseline while maintaining environmental benefits of hemp-based construction. Post-compression examination revealed distinct failure characteristics correlating with mixture composition (Figure 6).

Figure 3. Post-compression failure modes of representative hempcrete specimens. (A) Specimen 1E: controlled failure with surface spalling and visible carbonation layer. (B) Specimen 2E: ductile failure and intact fiber network. (C) Specimen 2BGGBS20: progressive failure with fiber pullout, peak-performing formulation. (D) Specimen 2BGGBS6S40: brittle failure, demonstrating reduced ductility from sand incorporation.

CONCLUSION

This systematic investigation into hempcrete compressive strength enhancement demonstrates significant potential for developing high-performance bio-based construction materials through strategic mixture optimization, achieving substantial mechanical improvements, while maintaining environmental benefits inherent to hemp-based composites.

The peak-performing formulation, specimen 2BGGBS20, achieved 167.61 psi (1.14 MPa) compressive strength, representing a 469% improvement over traditional hempcrete (29.43 psi). This optimal composition of 40% MgO binder, 20% GGBS, and 15% hemp content validates the effectiveness of combining reactive alternative binders with high-dosage pozzolanic additives. Binder Performance: MgO consistently outperformed hydrated lime across all formulations, demonstrating 11.4% higher strength in direct comparisons (specimen 2E vs. 1E). This superior performance stems from MgO's enhanced pozzolanic reactivity, faster carbonation kinetics, and improved particle packing characteristics.

Additive Optimization: Clear dose-response relationships emerged for pozzolanic additives, with GGBS showing optimal performance at 20% by binder weight. The comparison between 2BGGBS6 (146.11 psi) and 2BGGBS20 (167.61 psi) demonstrated 14.7% strength enhancement, indicating that higher pozzolanic content enhances matrix strengthening through improved chemical bonding.

Density-Strength Correlation: Mixture densities ranged from 536.75 kg/m³ to 1353.27 kg/m³, significantly exceeding literature values through systematic compaction. However, density increases did not directly correlate with strength improvements, particularly in sand-incorporated specimens, highlighting the complex interplay between matrix composition and mechanical performance.

The 469% improvement achieved represents a paradigm shift in hempcrete capabilities, positioning bio-based materials as credible alternatives for structural applications. The findings provide both scientific understanding of enhancement mechanisms and practical implementation guidance, contributing to sustainable construction technology advancement.

Future Research Directions

To advance optimized hempcrete toward structural applications, future investigations should address:

(1) long-term durability including freeze-thaw resistance and moisture cycling,

(2) thermal performance and hygrothermal behavior to ensure maintained insulation properties,

(3) scalability through full-scale testing and standardized construction specifications, and

(4) comprehensive life cycle assessment comparing environmental impacts with conventional materials.

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Indoor Environmental Quality of Homes: A Comparison of ICF and Traditional Construction

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ABSTRACT

Indoor Environmental Quality (IEQ) of single-family homes is critical for the health and well-being, yet IEQ considerations are frequently overlooked by homebuyers when comparing construction materials. This study examined Insulated Concrete Form (ICF) as an alternative to traditional wood framing for exterior walls of single-family homes. While existing literature documents ICF's energy efficiency benefits, limited research exists comparing IEQ performance between ICF and traditional construction. IEQ data was collected over 12 months from four single-family homes with comparable characteristics. Monitored parameters included temperature, humidity, carbon dioxide, formaldehyde, particulate matter (PM 1.0, 2.5, and 10.0), covering homes with floor areas of 1,900-2,000 square feet located within a half-mile radius. The sample consisted of two ICF homes and two traditional wood-framed homes.

The findings reveal a complex performance profile for ICF construction. ICF homes demonstrated superior humidity control, averaging 43.78% compared to 50.15% in traditional homes, and modest improvements in carbon dioxide management (1333 ppm vs 1419 ppm). However, ICF homes showed consistently elevated particulate matter concentrations across size fractions, with PM1.0 levels 194.5% higher (11.31 vs 3.84 μg/m³) and PM2.5 levels 123% higher (17.26 vs 7.74 μg/m³) than traditional homes. Formaldehyde concentrations were slightly higher in ICF homes (0.0446 vs 0.0320 ppb), while temperature performance was equivalent between construction types. Results varied significantly between home pairings, highlighting the complex interaction between construction methodology, HVAC system design, and occupant behaviors. The enhanced airtightness of ICF construction creates different indoor environmental dynamics requiring specialized mechanical systems. While ICF construction offers advantages in humidity control and energy efficiency, elevated particulate matter levels represent a significant concern requiring enhanced HVAC filtration systems and construction quality control protocols.

These findings demonstrate that optimized ventilation design and high-efficiency filtration are essential for ICF homes to realize their full IEQ potential.

INTRODUCTION

Indoor Environmental Quality (IEQ) is a critical factor influencing the health, well-being, and productivity of the occupants in any building, commercial and residential alike. The majority of Americans spend a considerable amount of their time in their homes, making the quality of IEQ in homes extremely important to public health outcomes. Existing studies demonstrate that better IEQ positively impacts occupants' comfort, reduces health risks, and enhances overall quality of life, while poor IEQ could contribute to sick building syndrome, respiratory issues, and reduced cognitive function (Frontczak and Wargocki, 2011). Despite this established relationship between IEQ and health outcomes, prospective homebuyers most often prioritize initial construction costs, energy efficiency, and material durability over indoor air quality considerations when evaluating available options for buying new homes.

The homebuilding industry has shown growing interest in alternative materials and construction methods that offer superior performance characteristics compared to conventional wood-framed (WF) construction. Insulated Concrete Form (ICF) is one such alternative that utilizes expanded polystyrene (EPS) foam forms filled with reinforced concrete to create wall systems that provide enhanced thermal performance, structural integrity, and increased airtightness (Ghosh and Bigelow, 2025). ICF has proven to provide significant energy savings, with studies reporting more than 40% energy efficiency compared to conventional wood-framed buildings, while also providing resistance against natural disasters and improved sound insulation (Ghosh and Bigelow, 2025).

Another reason to explore alternative construction materials arises from recent studies demonstrating that building materials significantly influence indoor formaldehyde concentrations, with conventional construction materials such as wood products and adhesives being primary sources of indoor air pollutants (EPA, n.d.; Salthammer et al. 2010).
Existing studies have well documented the advantages of ICF construction in terms of energy efficiency and structural performance. However, examination of the IEQ of ICF homes relative to conventional WF homes is limited. Previous studies have focused primarily on thermal performance, cost analysis, and durability characteristics of ICF, with limited investigation of IEQ parameters such as temperature, humidity, and pollutant concentrations. This research gap is significant given that ICF construction utilizes fundamentally different materials and assembly methods that may substantially affect indoor air quality through reduced air infiltration, alternative material compositions, and enhanced building envelope performance.

To bridge this gap, the purpose of this study was to conduct a comparative analysis of IEQ between ICF homes and conventional WF homes. Through systematic monitoring of multiple IEQ parameters over a 12-month period, this study quantified the differences in IEQ parameters such as temperature, humidity, and pollutant concentrations between homes with ICF exterior walls and conventional WF homes.

LITERATURE REVIEW

ICF construction offers various advantages over conventional wood-framed construction, particularly in energy efficiency and structural performance. The integration of EPS within ICF walls provides superior thermal insulation while eliminating the need for conventional wood formwork materials, contributing to natural resource conservation (Ngugi et al., 2017). ICF walls require simplified construction procedures and reduced water consumption, making them more sustainable than conventional wall assemblies. Experimental studies consistently demonstrate that ICF construction improves overall building comfort through enhanced thermal mass and thermal resistance advantages (Eman and Elsayed, 2019).

Multiple studies provide empirical evidence supporting ICF advantages. Saber et al. (2010) found ICF houses demonstrated about 20% better energy efficiency due to superior R-values when comparing houses with identical design parameters. A Tennessee study of seven similarly built houses found ICF walls reduced energy consumption by 7.5% compared to wood-framed houses, emphasizing thermal mass benefits in maintaining indoor thermal stability (Petrie et al., 2002). Simulation studies confirm these findings, with Ochsendorf et al. (2011) demonstrating that ICF construction adds less than 5% to lifecycle costs while providing considerable energy savings. Research by Mallay and Wiehagen (2014) found lower whole-house infiltration rates in ICF homes, while Gajda and VanGeem (2000) concluded that ICF walls saved the most energy across all tested U.S. locations compared to other thermally massive materials (Gajda 2001). While extensive research exists on ICF energy efficiency and structural benefits, limited studies have investigated indoor environmental quality implications compared to traditional construction. Existing research focuses primarily on thermal performance metrics (Cruz and Cunha, 2022; El-Maghraby et al., 2024; Mantesi et al., 2015; Maref et al., 2012) rather than comprehensive IEQ parameters including air quality, humidity control, and pollutant concentrations. This research gap is significant given that building materials and construction methods can substantially influence indoor air quality through material emissions, air infiltration rates, and moisture management. The enhanced airtightness characteristics of ICF construction may create different indoor environmental conditions compared to traditional construction, potentially affecting occupant exposure to various pollutants and overall comfort levels.

RESEARCH GOAL AND METHODOLOGY

The primary research goal was to understand if ICF homes have better IEQ compared to conventional wood-framed homes.

Research questions addressed

(1) How do construction types compare regarding key IEQ parameters?

(2) How do year-long monitoring data reflect seasonal exposure conditions?

(3) How might orientation contribute to observed IEQ variability across comparable home pairings?

The study hypothesized that ICF homes may impact air quality due to increased airtightness, however thermal performance would improve due to enhanced humidity control and thermal stability.

Significance

The findings provide evidence-based guidance for builders, designers, and homebuyers regarding health and comfort implications of different construction methods. This study contributes to knowledge about sustainable building practices and their impact on occupant well-being, presenting empirical data to support design decisions that prioritize both energy efficiency and indoor air quality. A quantitative research approach was employed to analyze and compare IEQ data from ICF and conventional WF homes through continuous monitoring of temperature, humidity, carbon dioxide, formaldehyde, and particulate matter over a 12-month period.

Sample Selection and Characteristics

For this study, data were collected from four single-family homes including two homes with ICF exterior walls and two homes utilizing WF construction exterior walls with conventional insulation systems as shown in Table 1. All homes were constructed in 2022 under the 2015 International Residential Code (IRC). The homes had comparable characteristics, with floor areas ranging from 1,900 to 2,000 square feet and similar floor plans between the two types of construction to ensure consistency in the comparisons.

Table 1: Home Characteristics and Specifications.

	Floor Plan Type	Insulation Type		Orientation
		Walls	Attic	
ICF_1	Floor Plan Type B	ICF	R-30 blown FG	East Entry
ICF_2	Floor Plan Type A	ICF	Foam Attic	East Entry
WF_1	Floor Plan Type B	R-15 blown FG	R-30 blown FG	South Entry
WF_2	Floor Plan Type A	R-15 blown FG	Foam Attic	South Entry

Location and Environmental Controls

All study homes were located within a half-mile radius of each other in the same neighborhood to minimize variability in external environmental conditions such as outdoor air quality, temperature, humidity, and solar exposure patterns. This proximity ensured that observed differences in IEQ parameters could be attributed to construction methodology rather than environmental factors. The homes were occupied during the monitoring period to reflect real-world conditions and typical occupant behaviors that influence IEQ.

Data Collection Parameters and Monitoring Protocol

Data collection was conducted over a complete 12-month period from February of 2023 through January of 2024 to capture a full annual cycle and seasonal variations. Six primary indoor environmental quality parameters continuously monitored were temperature (°F) and relative

humidity (%) to evaluate thermal comfort and moisture control performance, carbon dioxide concentrations (ppm) as an indicator of ventilation effectiveness and air exchange characteristics, formaldehyde levels (ppb) and particulate matter through three size fractions (PM 1.0, PM 2.5, and PM 10.0 in $\mu g/m^3$) to assess airborne concentrations impacting respiratory health. Continuous monitoring ensured comprehensive data coverage to identify daily, weekly, and seasonal patterns, providing sufficient data for robust statistical comparison and identification of seasonal effects on building performance between construction types.

Quality Control and Data Management

Rigorous quality control procedures were implemented including instrument calibration according to manufacturer specifications, data validation checks to identify instrument malfunctions or transmission errors, and outlier identification methods to distinguish genuine extreme values from measurement errors while preserving valid readings. Data processing involved systematic aggregation of continuous measurements into daily, weekly, and monthly averages to facilitate statistical analysis and reduce short-term fluctuation influences on performance assessments.

Statistical Analysis Plan

Statistical analysis employed independent samples t-tests to compare IEQ parameters between ICF and traditional WF homes. The analysis included room-specific comparisons for two home pairs: ICF_2 vs WF_2 (Floor Plan Type A) and ICF_1 vs WF_1 (Floor Plan Type B), with data collected from both living rooms and bedrooms. Effect sizes were calculated using Cohen's d to assess practical significance of observed differences, with interpretations of small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) effects. Statistical significance was evaluated at $\alpha = 0.05$.

RESULTS

Data analysis was conducted comparing IEQ parameters between ICF and traditional WF homes using independent samples t-tests. The analysis combined data from both home pairings (ICF_1 vs WF_1 and ICF_2 vs WF_2) across all rooms over the 12-month study period to provide comprehensive performance comparisons between construction types.

While the study was designed to capture a complete annual monitoring period to account for seasonal variation, the primary focus of the analysis was on the aggregated year-long comparisons between construction types. Seasonal trends and orientation effects were controlled through the study design (12-month monitoring period and proximity of homes within the same neighborhood) but were not analyzed as independent variables due to the limited sample size. Future studies with larger datasets will enable more detailed seasonal and orientation-specific analyses.

Descriptive Statistics

Table 2: Combined Descriptive Statistics by Construction Type.

Parameter	ICF Homes	Traditional Homes	Difference of Means	Performance
	Mean (SD)	Mean (SD)	(ICF - Traditional)**	Indicator
Temperature (°F)	72.03 (1.92)	72.78 (2.92)	-0.75°F**	≈ Equivalent
Humidity (%)	43.78 (9.18)	50.15 (9.80)	-6.37%**	✓ ICF Advantage
CO_2 (ppm)	1333.15 (480.17)	1419.09 (656.53)	-85.94 ppm**	✓ ICF Advantage
Formaldehyde (ppb)	0.0446 (0.033)	0.0320 (0.039)	+0.0125 ppb**	✗ ICF Higher
PM1.0 (µg/m³)	11.31 (16.76)	3.84 (8.43)	+7.47 µg/m³**	✗ ICF Higher
PM2.5 (µg/m³)	17.26 (25.87)	7.74 (13.04)	+9.52 µg/m³**	✗ ICF Higher
PM10 (µg/m³)	18.92 (28.26)	18.31 (25.16)	+0.62 µg/m³**	≈ Equivalent*

* PM10 equivalence influenced by one anomalously high traditional home measurement.
** All differences statistically significant at $p < 0.001$.

Statistical Comparison Results

Table 3: Statistical Significance and Effect Sizes by Home Pairing.

Parameter	ICF_1 vs WF_1 (Floor Plan B)	ICF_2 vs WF_2 (Floor Plan A)
	Cohen's d	Cohen's d
Temperature (°F)	-0.083	-0.694
Humidity (%)	+0.279	-1.823
CO_2 (ppm)	-0.439	+0.149
Formaldehyde (ppb)	-0.169	+1.046
PM1.0 (µg/m³)	+0.700	+0.265
PM2.5 (µg/m³)	+0.671	+0.187
PM10 (µg/m³)	+0.676	-0.730

* All effect size above are statistically significant at $p < 0.001$.

Key Findings Summary

Particulate Matter - Consistent ICF Elevation: The most concerning finding was consistently elevated particulate matter concentrations in ICF homes across PM1.0 and PM2.5. ICF homes showed PM1.0 levels averaging 11.31 µg/m³ versus 3.84 µg/m³ in traditional homes (194.5% higher), and PM2.5 levels averaging 17.26 µg/m³ versus 7.74 µg/m³ (123% higher). For both PM1.0 and PM2.5 home pairings demonstrated this pattern, with ICF_1 vs WF_1 showing larger effect sizes than ICF_2 vs WF_2, but both reaching statistical significance ($p<0.001$).

Although PM10 concentrations exhibited statistically significant differences within individual home pairings, the combined analysis showed near-equivalent mean values between construction types (18.92 µg/m³ for ICF vs. 18.31 µg/m³ for traditional homes). This apparent equivalence reflects opposing effect directions across the two home pairings, which offset each other when aggregated. One anomalously high PM10 measurement in a traditional home further influenced the combined mean, reinforcing the importance of interpreting PM10 results at the pairing level.
Humidity Control - Variable Performance: Humidity control results showed significant variation between home pairings. The ICF_2 vs WF_2 comparison demonstrated a very large advantage for ICF construction (Cohen's $d = -1.823$, $p<0.001$), with ICF homes averaging 38.89% compared to 54.07% in traditional homes. However, the ICF_1 vs WF_1 comparison showed a small advantage for ICF homes (Cohen's $d = 0.279$, $p<0.001$), with ICF homes averaging 48.66% versus 46.29% in traditional homes. Overall, ICF homes averaged 43.78% humidity compared to 50.15% in traditional homes.

Carbon Dioxide Management

Mixed Results: CO_2 concentrations showed complex patterns that varied significantly between home pairings. The ICF_1 vs WF_1 comparison favored ICF homes with a medium effect size (1405 ppm vs 1653 ppm, Cohen's $d = -0.439$, $p<0.001$), while the ICF_2 vs WF_2 comparison showed a small advantage for traditional homes (1261 ppm vs 1182 ppm, Cohen's $d = 0.149$, $p<0.001$). Overall, ICF homes averaged slightly lower CO_2 concentrations (1333 ppm vs 1419 ppm), indicating modestly better air quality management.

Formaldehyde Concentrations

Variable Results: Formaldehyde results varied dramatically between home pairings. The ICF_1 vs WF_1 comparison showed slightly lower formaldehyde in ICF homes (0.044 ppb vs 0.051 ppb, Cohen's $d = -0.169$, $p<0.001$), while the ICF_2 vs WF_2 comparison showed substantially higher formaldehyde in ICF homes (0.045 ppb vs 0.013 ppb, Cohen's $d = 1.046$, $p<0.001$). Overall, ICF homes averaged slightly higher formaldehyde concentrations (0.0446 ppb vs 0.0320 ppb).

Temperature Performance

Slight ICF Advantage: ICF homes maintained slightly lower average temperatures (72.03°F vs 72.78°F), with the difference varying by home pairing. The ICF_2 vs WF_2 comparison showed a medium-large effect (Cohen's $d = -0.694$, $p<0.001$), while the ICF_1 vs WF_1 comparison showed minimal difference (Cohen's $d = -0.083$, $p<0.001$). Both construction types achieved

comfortable indoor temperatures while ICF homes demonstrated energy efficiency advantages through enhanced thermal mass.

Home Pairing Variations

The study revealed substantial performance variations between the two home pairings, even within the same construction types. The ICF_2 vs WF_2 comparison (Floor Plan A) showed more dramatic differences in humidity control, while the ICF_1 vs WF_1 comparison (Floor Plan B) showed larger particulate matter elevations and different CO_2 patterns. These variations highlight the importance of building orientation which can majorly impact temperature and humidity control, and occupant behaviors in determining IEQ outcomes.

DISCUSSION

This study provides the first comprehensive empirical comparison of IEQ between ICF and traditional WF single-family homes, revealing a complex performance profile with both significant advantages and important challenges.

The most significant finding was that ICF construction's enhanced airtightness creates fundamentally different indoor environmental dynamics. While ICF homes demonstrated superior humidity control (43.78% vs 50.15%) and modest CO_2 improvements (1333 vs 1419 ppm), they showed consistently elevated particulate matter concentrations with 194.5% higher PM1.0 and 123% higher PM2.5 levels than traditional WF homes.

Critical Airtightness Effects

The enhanced building envelope airtightness of ICF construction eliminates natural air infiltration that traditionally helps dilute indoor pollutants. This creates both opportunities for improved environmental control and challenges requiring specialized mechanical ventilation approaches. The elevated particulate matter levels demonstrate that conventional HVAC systems designed for leaky building envelopes are inadequate for ICF construction.

Additionally, ICF construction processes involving concrete mixing, EPS foam cutting, and specialized finishing techniques may generate different types of airborne particles that persist longer in the tighter building envelope. Since data collected started within a year after construction completion, the increased PM level could be due to that. The interaction between construction-related particulates and enhanced airtightness may create conditions requiring extended post-construction ventilation periods and enhanced cleaning protocols specifically designed for ICF projects.

Ventilation and Air Quality Management

ICF construction requires intentional, controlled ventilation with high-efficiency filtration to manage indoor air quality effectively. The mixed CO_2 results and variable formaldehyde concentrations (0.0446 vs 0.0320 ppb) makes controlled mechanical ventilation essential rather than optional. Energy recovery ventilators (ERVs) or heat recovery ventilators (HRVs) can become critical components in ICF homes to provide necessary fresh air exchange while

maintaining energy efficiency benefits. The ventilation system must be carefully sized and designed to account for the specific air exchange requirements of tighter building construction while considering occupancy patterns and room-specific needs.

Occupant Behavior Amplification

The substantial variations observed between home pairings within the same construction types highlight the critical influence of occupant behaviors on indoor environmental quality outcomes. These behavioral factors become more significant in ICF construction due to the enhanced airtightness that amplifies the impact of indoor pollution sources and activities.

CO_2 concentrations are directly influenced by occupancy density, duration, and activity levels. Family size, sleep schedules, home office usage, and entertaining patterns significantly influence CO_2 accumulation patterns, making proper ventilation system design and operation more critical in ICF construction given the air tightness.

Indoor particulate matter levels are substantially influenced by occupant activities including cooking methods, cleaning practices, candle or incense burning, fireplace usage, and pet ownership. ICF construction's enhanced airtightness means that particulate matter generated from these activities accumulates more readily without adequate ventilation and filtration. Occupant behaviors such as using range hoods during cooking, regular HVAC filter replacement, and avoiding high-particulate activities become more important in ICF homes.

Occupant choices regarding furniture, cleaning products, personal care items, and hobby materials significantly influence indoor formaldehyde concentrations. In ICF homes, the enhanced airtightness means that formaldehyde emissions from consumer products, new furniture, or renovation materials accumulate more readily. Occupant behaviors such as selecting low-emission products, allowing new items to off-gas before bringing them indoors, and maintaining adequate ventilation during activities that may generate formaldehyde become more critical.

Building Performance Integration Requirements

Realizing ICF construction's full potential requires integrated design approaches including appropriately sized controlled ventilation systems, enhanced filtration capabilities (MERV 13-16 or HEPA), integrated humidity control, and occupant education. Traditional HVAC approaches designed for conventional construction are inadequate for optimizing IEQ in ICF buildings, necessitating specialized mechanical systems and operational protocols.

The enhanced airtightness of ICF construction makes occupant education and behavior modification more critical for achieving optimal indoor environmental quality. Homeowners must understand how their activities and choices affect indoor air quality in tighter building envelopes and be provided with specific guidance on ventilation system operation, consumer product selection, and activity management.

LIMITATIONS

This study has several limitations that affect the generalizability of findings. The small sample size of four homes in a single geographic location limits applicability across climate zones and construction practices. All homes were occupied during monitoring, introducing variability from occupant behaviors, furnishing choices, and lifestyle factors that may confound construction-related effects. The study was conducted during the first year of occupancy when construction dust, material off-gassing patterns and building system performance may differ from long-term stabilized conditions. This study does not include seasonal analysis, and orientation effects cannot be isolated due to sample characteristics with both ICF homes having east-facing entries while traditional homes have south orientations.

IMPLICATION FOR PRACTICE

The findings have immediate implications requiring industry action. For builders and designers, ICF construction demands enhanced mechanical system design including controlled ventilation with energy recovery, high-efficiency particulate filtration, integrated humidity control, and construction quality control protocols specifically for dust management during and after construction. For homebuyers, ICF construction provides energy efficiency benefits but requires investment in enhanced HVAC systems and understanding that airtightness amplifies the impact of occupant behaviors on indoor air quality, necessitating modified operational protocols and maintenance commitments. For policymakers, these findings demonstrate the urgent need for updated building codes that include specific mechanical system requirements for high-performance construction methods, as ventilation standards designed for leaky traditional construction are inadequate for ICF buildings and require new approaches that address enhanced airtightness characteristics while maintaining energy efficiency benefits.

CONCLUSION

This study provides the first comprehensive empirical evidence comparing indoor environmental quality between ICF and traditional wood-framed single-family homes, revealing a complex performance profile that challenges conventional assumptions about the relationship between construction materials and indoor air quality. The findings demonstrate that ICF construction delivers both significant advantages and important challenges that must be carefully considered in design and construction practices.

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Mechanical and Structural Evaluation of Carbon Geocrete as an Alternative to Portland Cement Concrete

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ABSTRACT

The construction industry is a significant contributor to global CO_2 emissions, primarily due to the widespread use of ordinary portland cement (OPC) in concrete production. To address this environmental challenge, this study investigates the mechanical and structural performance of a novel geopolymer concrete (GPC) known as carbon geocrete. This material is developed by activating industrial byproducts engineered to sequester atmospheric CO_2, offering a sustainable and cement-free alternative for construction applications. A comprehensive experimental program was carried out to evaluate the mechanical properties of carbon geocrete—including compressive strength, tensile strength, flexural capacity, and bond strength—through both material-level testing and structural testing of reinforced components. The performance of carbon geocrete was systematically compared to that of conventional OPC concrete to assess its feasibility for standard structural use. The results demonstrate that carbon geocrete meets the mechanical and structural performance requirements for potential application in precast and cast-in-place building elements. The tested specimens exhibited adequate strength and durability characteristics, supporting their potential for use as a full replacement for OPC-based concrete. Overall, the findings highlight carbon geocrete as a viable, alternative to conventional cementitious materials, capable of significantly reducing the carbon footprint of concrete construction. Its successful performance at both component and structure scales underscores its promise for future widespread adoption in the construction industry.

Keywords: CO_2 Emission; Portland Cement; Carbon Geocrete; Sustainable Construction Materials; Structural Performance.

INTRODUCTION

Concrete is the most widely used construction material globally due to its high strength, long-term durability, and cost efficiency (Makul, 2020). It is the second most consumed substance on Earth after water, with global production approaching 30 billion tons annually. In the United States, although wood-frame construction predominates in low-rise residential housing, concrete

remains indispensable in numerous residential and multi-family applications. Beyond traditional uses—such as slab-on-grade floors, footings, and basement or foundation walls (Data, 2001; Jellen and Memari, 2019) — concrete is increasingly used in prefabricated wall and floor systems, including insulated concrete forms (ICFs) and precast insulated foundation panels such as Superior Walls systems (ACS, 2025), which provide enhanced energy efficiency, moisture resistance, and long-term structural reliability in residential and light-commercial buildings (Kosmatka et al., 2011).

Furthermore, the growing adoption of 3D concrete printing has introduced new possibilities for rapid, low-cost, and sustainable home construction, with several projects demonstrating its feasibility for single- and multi-family dwellings (Buswell et al., 2018; Wolfs et al., 2019). Collectively, these advancements illustrate that concrete plays a crucial role not only in conventional foundation systems but also in modern residential building envelopes and construction technologies.

Although concrete structures offer exceptional strength and durability, their production imposes substantial environmental burdens, including high energy consumption, elevated greenhouse gas emissions, and depletion of natural resources (Habert et al., 2020). The cement manufacturing process alone accounts for nearly 8% of global anthropogenic CO_2 emissions, mainly due to the calcination of limestone and fossil fuel combustion in kilns.

To address these challenges, researchers have explored incorporating waste-derived materials—such as recycled glass and reclaimed concrete aggregates—as partial replacements in concrete mixtures (Mohajerani et al., 2020; Vishwakarma and Ramachandran, 2018). This approach not only diverts industrial and municipal waste from landfills but also reduces the ecological footprint of construction materials. Consequently, the integration of waste by-products into concrete has gained recognition as a practical and sustainable strategy to address the environmental challenges associated with portland cement production (Gopinath et al., 2020).

Among the most promising waste-derived innovations are alkali-activated binders or geopolymer concretes (GPCs), which replace ordinary portland cement (OPC) entirely with industrial by-products such as fly ash (FA) and ground granulated blast-furnace slag (GGBFS) (Palomo et al., 1999; Provis and Van Deventer, 2014). When activated with alkaline solutions such as sodium hydroxide and sodium silicate, these precursors undergo polymerization to form an amorphous aluminosilicate network distinct from the calcium–silicate–hydrate gel characteristic of OPC systems (Davidovits, 2015; Meyer, 2009). The resulting materials exhibit significant environmental advantages: geopolymer binder production consumes approximately 40% less energy and emits up to 80–90% less CO_2 than conventional cement manufacturing (McLellan et al., 2011; Habert and Ouellet-Plamondon, 2016). The use of these binders therefore offers a dual benefit—reducing carbon emissions and reusing industrial waste materials (Mikulčić et al., 2016). Moreover, geopolymer technology supports the development of low-carbon housing solutions, particularly in regions seeking to combine energy-efficient construction with climate resilience and reduced lifecycle emissions.

Beyond environmental performance, fly ash and slag-based geopolymer concretes have demonstrated mechanical properties comparable to those of OPC concrete. Optimized geopolymer mixes commonly achieve 28-day compressive strengths of 40–60 MPa (Nath and Sarker, 2014), with the inclusion of GGBFS improving early-age strength and enabling ambient curing (Bernal et al., 2012; Ismail et al., 2014). Their tensile and flexural strengths typically range from 3 to 5 MPa and 7 to 9 MPa, respectively—values that align closely with structural-grade OPC concretes (Sarker et al., 2013; Yellaiah et al., 2018). The elastic modulus, typically between 20 and 30 GPa, also remains within the expected range for reinforced concrete design (Thomas and Peethamparan, 2015; Nath and Sarker, 2017). These findings confirm that design relationships used for OPC concrete can be adapted for geopolymer systems with appropriate calibration.

At the structural scale, experimental investigations on reinforced geopolymer concrete beams, columns, and bond behavior have confirmed that GPC members can achieve similar load capacity, stiffness, ductility, and cracking behavior as their OPC counterparts (Shaikh and Vimonsatit, 2015; Nath et al., 2018; Ojha et al., 2023). Studies on residential-scale elements—such as wall panels and slab systems—have also indicated the feasibility of geopolymer concretes for prefabricated housing and modular construction (Ngo et al., 2021). The compatibility of geopolymer mixtures with automated and additive manufacturing techniques strengthens their potential role in next-generation residential construction, particularly in the context of 3D-printed concrete housing (Buswell et al., 2018; Wolfs et al., 2019). In addition to structural reliability, geopolymer concretes exhibit improved fire resistance, lower permeability, and enhanced thermal stability—attributes that are increasingly valued in modern residential building codes emphasizing energy efficiency and resilience (Nath and Sarker, 2015; Kong et al., 2018).

Despite extensive research on fly ash and slag-based geopolymers, most studies focus on material-level properties under controlled conditions, with fewer addressing large-scale reinforced behavior or direct comparison with OPC systems in the context of residential or low-rise building applications. Additionally, only limited studies have investigated geopolymer concretes that actively sequester CO_2 during their production phase. This research gap constrains the practical adoption of cement-free concretes in mainstream housing construction.

The present study addresses this limitation by experimentally evaluating the mechanical and structural behavior of carbon geocrete, a novel geopolymer concrete formulated from carbonated industrial by-products designed to capture and store CO_2. Through comprehensive testing of compressive, tensile, flexural, and bond strength at both material and structural scales, this study benchmarks carbon geocrete against OPC concrete and provides key insights into its suitability for structural and residential construction applications, supporting the transition toward carbon-neutral and carbon-negative building materials for the next generation of sustainable housing.

EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate and compare the mechanical and structural performance of carbon geocrete and OPC concrete through a series of standardized laboratory tests. The study began with a mixture design phase aimed at optimizing the proportions of binders, aggregates, and activators to achieve the desired strength and workability. The OPC mix was proportioned according to conventional design procedures specified in ACI 211 (ACI, 2016), whereas the carbon geocrete mix incorporated geopolymeric binders and alkaline activators derived from industrial by-products to eliminate cement usage and reduce carbon emissions.

Material-level investigations included compressive strength, splitting tensile strength, and flexural tensile strength tests. Structural performance was further evaluated through flexural testing of reinforced beams under center-point loading and bond strength testing to assess the interaction between steel reinforcement and the concrete matrix. This comprehensive program provided a foundation for assessing the feasibility of carbon geocrete as a sustainable alternative to conventional cement-based materials.

Mixture Composition

The carbon geocrete mixture was designed to achieve strength and workability comparable to conventional OPC concrete while completely eliminating portland cement. The mixture proportions were established using a particle packing–based mixture design approach, following the Tarantula Curve concept to optimize aggregate gradation and minimize void content. This method aims to achieve dense packing through a continuous gradation, thereby reducing paste demand while maintaining adequate workability (Funk and Dinger, 2013).

The final carbon geocrete mixture comprised 62% aggregate, 32% paste, and 6% entrained air, yielding a slump of 165 mm—measured in accordance with ASTM C143/C143M (ASTM International, 2023a)—indicating high workability suitable for casting and consolidation. In contrast, the control OPC concrete—proportioned per ACI 211 (ACI, 2016) with a water-to-cement ratio of 0.50—contained 61% aggregate, 32% paste, and 7% entrained air, achieving a slump of 135 mm. Both mixtures were proportioned to attain equivalent 28-day compressive strength, allowing direct performance comparison between the two systems.

In the carbon geocrete mixture, carbonated fly ash (C. FA) served as the primary aluminosilicate precursor and was activated using a blended alkaline solution comprising sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The complete elimination of portland cement substantially reduced CO_2 emissions while preserving sufficient binder reactivity to ensure proper geopolymerization (Morsy et al., 2014). The detailed mixture proportions for both concretes are summarized in Table 1, highlighting the fundamental compositional differences between the geopolymeric and cementitious systems.

Table 1. Mix Proportions for Carbon Geocrete and OPC Concrete.

Material	Carbon Geocrete (kg/m³)	OPC Concrete (kg/m³)
Coarse Aggregate #8 (ASTM C33)	943	831
Fine Aggregate (ASTM C33)	691	923
Portland Cement (Type IL)	_	418
Carbonated Fly Ash (C. FA)	395	_
Sodium Silicate (Na2SiO3)	97	_
Sodium hydroxide (NaOH)	37	_
Water	91	209

Compressive Strength

The compressive strength test was performed to evaluate the fundamental mechanical performance of carbon geocrete in comparison with OPC concrete. The procedure followed the specifications of ASTM C39/C39M (ASTM International, 2023b), which defines the determination of compressive strength for cylindrical concrete specimens under axial loading. Cylinders were cast, cured, and tested at designated ages to measure their load-carrying capacity and assess the rate of strength development over time. These results provide critical insight into the hydration and geopolymerization kinetics that govern the mechanical behavior of both materials.

For each curing age—7, 14, and 28 days—three cylindrical specimens of both Carbon Geocrete and OPC concrete were prepared and tested. The measured compressive strengths are summarized in Table 2. At the target age of 28 days, both mixtures achieved comparable compressive strengths of approximately 30 MPa. However, the pattern of strength development differed significantly between the two materials. The OPC concrete exhibited rapid early-age strength gain, increasing from 22.5 MPa at 7 days to 27.8 MPa at 14 days, followed by a modest rise approaching its 28-day strength. In contrast, Carbon Geocrete displayed a delayed but more progressive strength evolution—beginning at 4.5 MPa at 7 days, rising to 17.5 MPa at 14 days, and ultimately reaching 30.6 MPa at 28 days.

This distinct trend, illustrated in Figure 1, underscores the fundamentally different binder development mechanisms in cementitious and geopolymeric systems. Whereas OPC concrete derives its early strength primarily from the hydration of clinker phases, the strength of carbon geocrete is governed by a gradual geopolymerization process that continues beyond the initial curing period. The nearly linear increase in compressive strength observed after 14 days suggests continued long-term polymeric network formation, indicating the potential for superior

mechanical performance and enhanced durability of carbon geocrete compared with conventional OPC concrete over extended curing durations.

Table 2. Compressive Strength Results for Carbon Geocrete and OPC Concrete.

Material	Time (Day)	Compressive Strength (MPa)	Std.
Carbon Geocrete	7	4.5	0.1
	14	17.5	0.4
	28	30.6	0.5
OPC Concrete	7	22.5	0.6
	14	27.8	0.5
	28	30.4	0.2

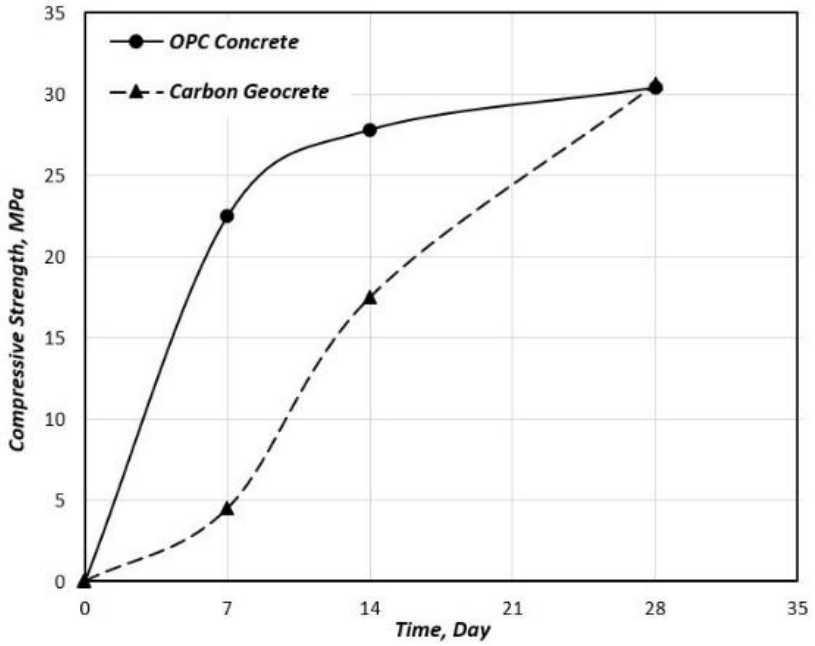

Figure 1. Variation of compressive strength with curing age for carbon geocrete compared with OPC concrete.

Tensile Strength

Tensile strength testing provides essential information about a material's cracking resistance, cohesion, and its ability to transfer stresses between aggregates and binder phases. In this study,

tensile performance was evaluated using two standardized methods: the splitting tensile strength test per ASTM C496/C496M (ASTM International, 2023c) and the flexural tensile strength test per ASTM C78/C78M (ASTM International, 2023d). These tests characterize the indirect and flexural tensile capacities of carbon geocrete and OPC concrete, which are critical for understanding their behavior under cracking and flexural loading in structural applications.

Splitting (or indirect) tensile strength tests were performed on cylindrical specimens following ASTM C496/C496M (ASTM International, 2023c). This test is particularly valuable for estimating the shear resistance of concrete and for determining parameters such as the development length of reinforcement in structural design. Three cylindrical specimens were tested for each material type after 28 days of curing, and the results are presented in Table 3.

Carbon geocrete exhibited an average splitting tensile strength of 3.2 ± 0.1 MPa, slightly higher than that of OPC concrete, which achieved 3.1 ± 0.1 MPa. The results demonstrate that carbon geocrete not only satisfied the requirement of achieving at least 10% of its compressive strength as tensile capacity but also slightly exceeded this threshold, exhibiting higher splitting tensile strength than OPC concrete. These findings confirm that the geopolymeric binder system in carbon geocrete can achieve tensile performance comparable to or exceeding that of conventional cementitious binders, supporting its suitability for structural applications.

Table 3. Splitting Tensile Strength Results for Carbon Geocrete and OPC Concrete.

Material	Specimen	Splitting Tensile Strength (MPa)	Avg. ± Std.
Carbon Geocrete	CG-1	3.3	3.2 ± 0.1
	CG-2	3.1	
	CG-3	3.0	
OPC Concrete	OPC-1	3.1	3.1 ± 0.1
	OPC-2	3.2	
	OPC-3	2.9	

Flexural tensile strength (or modulus of rupture) tests were conducted on prism specimens according to ASTM C78/C78M (ASTM International, 2023d) to evaluate the tensile capacity of the materials under bending stresses. Three carbon geocrete prisms were tested after 28 days of curing, and the results are summarized in Table 4. For comparison, OPC concrete specimens of the same geometry were tested under identical conditions.

Both carbon geocrete and OPC concrete achieved comparable flexural tensile strengths, with average modulus of rupture of 7.8 ± 0.9 MPa and 7.6 ± 0.8 MPa, respectively. As this test

represents the effective tensile stress developed at the bottom fiber of a beam or a slab under flexural loading, the results confirm that carbon geocrete exhibits flexural tensile performance comparable to or slightly superior to OPC concrete, validating its potential for structural applications where flexural behavior governs performance.

Table 4. Flexural Tensile Strength Test Results for Carbon Geocrete and OPC Concrete.

Material	Specimen	Modulus of Rupture (MPa)	Avg. ± Std.
Carbon Geocrete	CG-1	8.5	7.8 ± 0.9
	CG-2	8.4	
	CG-3	6.6	
OPC Concrete	OPC-1	6.8	7.6 ± 0.8
	OPC-2	7.2	
	OPC-3	8.7	

Flexural Strength

Although no specific standard exists for flexural testing of slender reinforced concrete beams, the present study adopted a center-point loading configuration following the general setup of ASTM C293/C293M (ASTM International, 2023e), which specifies procedures for determining the flexural strength of concrete specimens under center-point loading. In this test, each reinforced beam was simply supported at both ends and subjected to a concentrated load at midspan, allowing for evaluation of the overall moment capacity and flexural behavior of the reinforced members, as illustrated in Figure 2.

Half-scale reinforced concrete beams with dimensions of 50 × 75 × 600 mm were prepared using both carbon geocrete and conventional OPC concrete mixtures. Each beam was reinforced with a single #3 longitudinal steel rebar placed at the bottom. The applied midspan load was gradually increased until failure, and the corresponding ultimate moments were calculated based on the measured support span and applied load.

The moment capacities for the reinforced beams are summarized in Table 5, which indicates that the carbon geocrete beams achieved an average moment capacity of 1.5 kN.m, while the OPC concrete beams reached an average of 1.4 kN.m. These results reveal that carbon geocrete reinforced beams provided slightly higher flexural performance than their OPC counterparts, confirming the material's ability to develop effective composite action between the geopolymeric matrix and steel reinforcement. Overall, the flexural testing results demonstrate

that carbon geocrete can serve as a structurally competent and sustainable alternative to OPC concrete in reinforced flexural member.

A

B

Figure 2. Center-point loading test on (A) carbon geocrete and (B) OPC concrete slender reinforced beams.

Table 5. Flexural Moment Capacity of Reinforced Carbon Geocrete and OPC Concrete Beams Under Center-Point Loading.

Material	Specimen	Moment Capacity (KN.m)	Avg. ± Std.
Carbon Geocrete	CG-1	1.73	1.5± 0.2
	CG-2	1.30	
	CG-3	1.55	
OPC Concrete	OPC-1	1.28	1.4± 0.1
	OPC-2	1.57	
	OPC-3	1.46	

Bond Strength

The bond between reinforcing steel and the surrounding concrete is fundamental to the composite action of reinforced concrete members. This bond primarily consists of three mechanisms—chemical adhesion, friction, and mechanical interlocking—each contributing to stress transfer between steel and concrete (Nilson et al., 2010). The relative importance of these mechanisms depends on several factors, including concrete strength, bar surface geometry, casting orientation, bleeding behavior, confining stresses, and the presence of fibers or supplementary materials. Understanding this bond behavior is essential for evaluating the performance and reliability of reinforced concrete systems.

In this study, bond strength was evaluated using the pull-out test in accordance with the principles of ASTM A944 (ASTM International, 2023f), which outlines procedures for determining the bond strength of steel reinforcing bars embedded in concrete beam-end specimens. Each specimen consisted of a #3 steel rebar embedded in a 100 × 150 × 300 mm concrete block prepared from both carbon geocrete and OPC concrete, as illustrated in Figure 3. During testing, a controlled tensile load was applied along the axis of the rebar until bond failure occurred. The maximum pull-out load was recorded and used to calculate the bond strength (u) according to the following equation:

$$u = \frac{P}{\pi d_b L_b}$$

where P is the maximum pull-out load, d_b is the rebar diameter, and L_b is the embedment length. The test system was carefully designed to maintain the applied tensile load parallel to the rebar axis and to prevent yielding of the steel reinforcement, ensuring that the observed failure corresponded to bond failure rather than bar deformation.

The results, summarized in Table 6, indicate that carbon geocrete specimens achieved an average bond strength of 8.1 MPa, while OPC concrete specimens recorded an average of 7.8 MPa. The slightly higher bond strength of carbon geocrete suggests improved adhesion and interfacial interaction between the geopolymeric binder and steel surface.

The findings demonstrate that carbon geocrete provides bond performance comparable to that of OPC concrete, confirming its suitability for reinforced applications such as beam–column joints and lap splice zones.

(a) (b)

Figure 3. Bond strength testing on (A) carbon geocrete and (B) OPC concrete specimens conducted in accordance with ASTM A944 (ASTM International, 2023f).

Table 6. Bond Strength for Reinforcing Steel in Carbon Geocrete and OPC Concrete.

Material	Specimen	Bond Strength (MPa)	Avg. ± Std.
Carbon Geocrete	CG-1	9.5	8.1± 1.0
	CG-2	7.3	
	CG-3	7.6	
OPC Concrete	OPC-1	8.5	7.8± 0.6
	OPC-2	7.1	
	OPC-3	7.9	

CONCLUSION

This study evaluated the mechanical and structural performance of carbon geocrete, a portland-cement-free concrete, compared with conventional OPC concrete through standardized ASTM tests. Results showed that carbon geocrete achieved comparable properties, reaching a 28-day compressive strength of about 30 MPa. While OPC gained strength rapidly through hydration, carbon geocrete exhibited a gradual, continuous increase governed by geopolymerization, indicating superior long-term performance and durability. It also satisfied the expected tensile-to-compressive strength ratio for structural-grade concrete, confirming an effective binder–aggregate interface within the geopolymeric matrix.

At the structural scale, reinforced carbon geocrete beams demonstrated slightly higher flexural capacity than OPC beams, confirming effective composite action with steel reinforcement. Bond strength testing showed improved adhesion between the geopolymeric binder and steel, attributed to refined interfacial chemistry. Collectively, these results validate that carbon geocrete can be effectively used in reinforced concrete elements without compromising mechanical integrity or bond reliability.

Given the widespread use of reinforced concrete in residential and low-rise buildings, these findings have direct implications for sustainable housing. Replacing conventional cement-based concrete with carbon geocrete maintains structural reliability while reducing the embodied carbon footprint of residential and multi-family structures. This cement-free system supports carbon-neutral construction practices and offers a practical path to lower emissions in the built environment.

By eliminating portland cement and utilizing carbonated fly ash as the main binder, carbon geocrete reduces CO_2 emissions while preserving mechanical competence. These results demonstrate that carbon geocrete is a structurally sound and environmentally responsible

alternative to OPC concrete, enabling low-carbon reinforced concrete construction, especially in residential and light-commercial sectors. Its proven performance at both material and structural scales underscores its potential for reducing the carbon footprint of modern buildings.

Furthermore, beyond conventional cast-in-place and precast applications, the geopolymeric binder system of carbon geocrete presents promising opportunities for adaptation to emerging 3D concrete printing technologies through tailored mix design modifications aimed at achieving printability, buildability, and early-age stability, which could be explored in future research.

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Pneumatically Driven Wooden Nails in Light-Framed Construction and Determination of Appropriate End Grain Adjustment Factor

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ABSTRACT

Light-framed timber construction is one of the most common building styles for single-family homes in the United States. The main structural components of a wall are dimensional lumber, fasteners, and sheathing. LignoLoc® by Beck Fastening are wooden nails composed of 78 percent beech wood and 22 percent resin (Beck Fastening, 2020). They are pneumatically driven by the Fasco® LignoLoc® F60 which causes a lignin weld to occur between the outer surface of the wooden nail and the internal surface of the wood lumber being joined. The load path specifically examined in this paper includes a distributed lateral wind pressure that is collected by the external sheathing and distributed to the studs of the wall which then gets distributed as point loads to the connection of the top and bottom plate to the stud. All tests were conducted on pneumatically driven 2.25 x 0.185" wooden nails and 3 x 0.131" metal nails. The results of the test showed a withdrawal capacity of the wooden nails that was larger than the metal nails. The shear capacity of wooden nails was half the capacity of metal nails in side grain connections and 2/3 the capacity in end grain connections. Statistical analysis determined the wooden nail could have a replacement ratio of one-to-one due to the smaller coefficient of variance. Estimate ultimate shear capacities, allowable stress design lateral design values, end grain adjustment factors, and possible reductions due to failure modes are discussed. The initial results support the use of wooden nails as an alternative to metal nails in light-framed construction.

INTRODUCTION AND PURPOSE

Wood is a natural carbon sequestering material, and when used to make lumber for construction, the carbon consumed over the material lifecycle exceeds the carbon required to harvest and transport to job sites. Unfortunately, most construction waste of light-framed timber buildings will end up in landfills. This is primarily due to the thousands of metal fasteners that are used in light-framed construction which could cause damage to machinery and equipment if the wood was to be reused or recycled. A single-family dwelling needs to have end-of-life alternatives to landfills to utilize the full potential of wood as a building material. If metal fasteners were

replaced with wooden nails, then the floor, wall, and roof assemblies could be utilized as biomass or future engineered wood products such as strand board or alternative composites. Wood joinery and historic wood connections are still used today but on a much smaller scale in more custom projects. The densified wooden nails, LignoLoc®, created by Beck Fastening and driven by a nail gun, Fasco® LignoLoc® F60, are a new take on an old practice. Beck currently manufactures the wooden nails in Austria adjacent to the forest that produces the beech timber for an integrative process. The process densifies the beech wood with resin, heat, and compression to around 42.4 pounds per cubic feet. The pneumatic nail gun functions the same as a metal pneumatic nail gun. By integrating new building material into a system that is typically seen today on every construction site, Beck has created a system that could be widely adopted by industry without the demand for additional training to the skilled labor force.

SCOPE

This research tested entire assemblies to determine the ultimate capacity of withdrawal shear connections with two different fasteners. Specifically, top or bottom plate to stud were examined and referenced to Table R602.3(1) of the IRC (International Code Council, 2021). In order to confirm a datum for the testing machines being utilized, all tests were conducted on 3 x 0.131" metal nails and 2.25 x 0.185" wooden nails. The wooden nails used are LignoLoc® by Beck Fastening and they are pneumatically driven with a Fasco® LignoLoc® F60. This paper discusses if the LignoLoc® nails can be used as an alternative to metal nails with an acceptable replacement ratio dependent on available spacing, edge distance, and failure mode.

MATERIALS

- Douglas Fir-Larch (DFL) number one or number 2.
- 3 x 0.131" collated metal framing nails with pneumatic framing nail gun 2.25 x 0.185".
- Lignoloc® wooden nails with Beck FASCO 60 pneumatic nail gun.

The general density of DFL is around 31.2 pounds per cubic feet and a specific gravity of 0.5. For the following testing, all members are DFL, either number one or number two grade, kiln dried, and products of Western Wood Products Association. The NDS provides a table of reference lateral design values and withdrawal design values for pennyweight nails; common, box, and sinker (American Wood Council, 2018). It does not, however, list these values for one of the most common framing nails used in construction, the 3 x 0.131" nail that is used in pneumatic nail guns. This nail is however listed as an acceptable option in Table R602.3(1) Fastening Schedule in the IRC (International Code Council, 2021).

The shear capacity of Lignoloc® 2.25 x 0.185" wooden nails is around 120-150 pounds when driven with the Fasco® F60 (Deutsches Institut für Bautechnik, 2020). General Construction Technique Permit/ National Technical Approval for use of wooden nails in Europe for "wooden nails to produce stiffening and supporting wall panels, but not ceiling or roof panels" (Deutsches

Institut für Bautechnik, 2020). The details of the LignoLoc® wooden nails are shown in Figure 1 below. The density of the wooden nails is around 69 pounds per cubic foot which is a specific gravity of around 1.1 (Deutsches Institut für Bautechnik, 2020).

Figure 1. 2.25 x 0.185" LignoLoc® wooden nails.

METHODS

ASTM 1761-20, Standard Test Methods for Mechanical Fasteners in Wood and Wood Based Materials, is a testing guideline for how to examine the strength of fasteners within a given connection. This provision covers "mechanical fasteners, such as nails, screws, bolts, lag screws, and timber connectors" (ASTM International, 2020). ASTM 1761-20 provides experimental methods to determine the shear and withdrawal capacity of these fasteners. This ASTM standard gives a particular rate of loading for withdrawal and shear and general outlines for testing apparatus but still leaves room for interpretation.

Withdrawal Tension Testing End Grain Connections

ASTM 1761-20, Standard Test Methods for Mechanical Fasteners in Wood and Wood Based Materials, is a testing guideline for how to examine the strength of fasteners within a given connection. This provision covers "mechanical fasteners, such as nails, screws, bolts, lag screws, and timber connectors" (ASTM International, 2020). ASTM 1761-20 provides experimental methods to determine the shear and withdrawal capacity of these fasteners. This ASTM standard gives a particular rate of loading for withdrawal and shear and general outlines for testing apparatus but still leaves room for interpretation.

Wood is an anisotropic building material which means its capacity is dependent on the orientation of the wood. Specifically, the connections are dependent on the orientation. The internal stresses, from the wood member, are less when inserting a fastener into the end

grain of the wood than if inserted into the side grain of the wood. The withdrawal testing was conducted to evaluate the connection formed between a stud and a single top or bottom plate of a typical 2 x 4 stud wall. An assembly was designed and constructed following the minimal guidelines from the ASTM 1761-20 (ASTM International, 2020). The side member, plate, was an 8.5" 2 x 4 and was connected to a 5" 2 x 4 main member, stud, with three nails spaced at 0.75, 1.75, and 2.75 inches to meet the minimum spacing requirements outlined in the NDS in Table 12.5.1B Spacing Requirements for Fasteners in a Row (American Wood Council, 2018). Assembly shown in Figure 2 below.

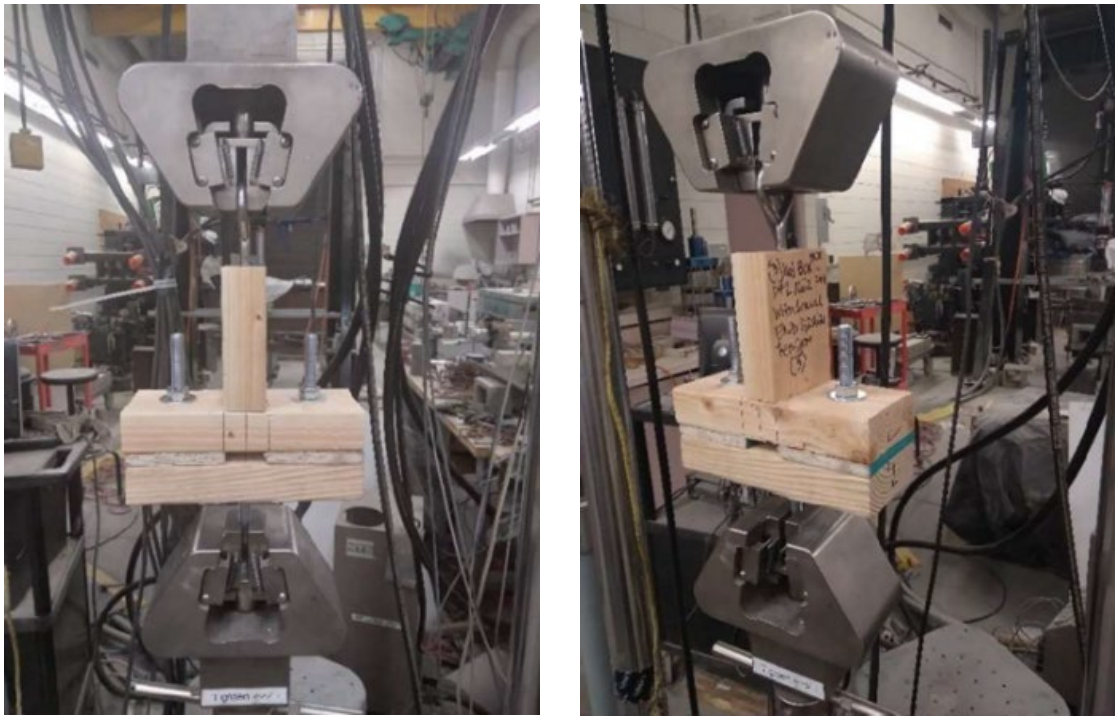

Figure 2. Front view of withdrawal assembly on the left and isometric view of assembly on the right.

SHEAR TENSION TESTING OF SIDE GRAIN CONNECTIONS

The shear tension testing was conducted to evaluate the connection formed between the double top plate of a typical 2 x 4 stud wall. This is a side grain connection where the load is perpendicular to the nail and parallel to the grain. An assembly in Figure 3 Below was designed following the guidelines from the ASTM 1761-20 (ASTM International, 2020). The assembly was constructed with a Simpson Strong-Tie BC40Z 4 x 4 Base, 5x½ inch zinc hex bolts, one inch nuts and washers, and 2x4 wood blocking (Simpson Strong-Tie, 2023). A 3/8" rigid steel plate with a ½" hole in the middle replaced the washer to give the Simpson Strong-Tie BC40Z 4 x 4 base the rigidity it needed to resist the higher loads (Simpson Strong-Tie, 2023).

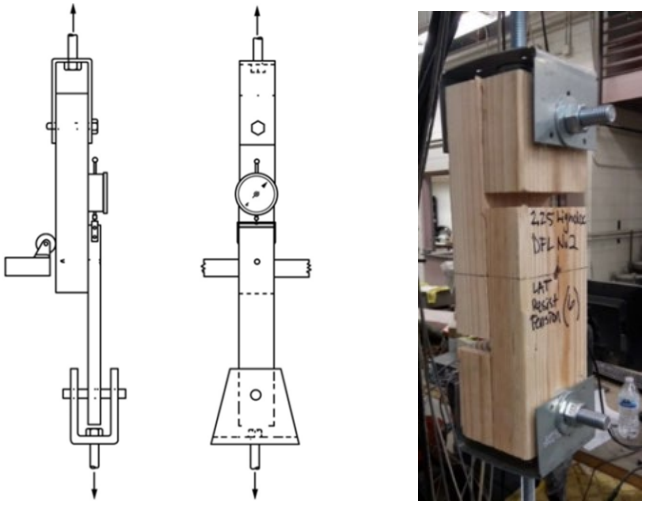

Figure 3. ASTM 1761-20 diagram of assembly on the left and photograph of actual assembly on the right.

SHEAR COMPRESSION TESTING OF SIDE GRAIN CONNECTIONS

The shear compression testing was conducted to evaluate the connection formed between the double top plate of a typical 2 x 4 stud wall. This is a side grain connection where the load is perpendicular to the nail and parallel to the grain. The two side members were 2 x 4 DFL number two and the middle main member was a 4 x 4 DFL number one. The 4 x 4 was needed to ensure the shear planes were independent and enough space was provided to avoid any double shear planes from occurring. All three members were oriented in the vertical direction with the grain parallel with the axial compression load. The configuration is shown in Figure 4 below.

Figure 4. Photograph of side grain shear connection.

SHEAR COMPRESSION TESTING OF END GRAIN CONNECTIONS

The shear compression testing of end grain was conducted to evaluate the connection formed between a top or bottom plate to a stud of a typical 2 x 6 stud wall. This is an end grain connection where the load is perpendicular to the nail and to the grain of the main member. Each of the assemblies, shown in Figure 5 below, had two shear planes to minimize eccentricity and eliminate the need for a roller support. All members were six inches long to eliminate the occurrence of splitting. The two side members were oriented with the grain vertical, parallel to load, and were in contact with the lower platen of the MTS. The main member was oriented with the grain perpendicular to load and was offset and only in contact with the upper platen of the MTS. Edge distance and spacing requirements informed the spacing and placement of the nails. Edge distance was one inch and spacing was around 0.75". This spacing is why the 2 x 8 size members were selected for the 12 total nail tests.

Figure 5. End grain shear connection assembly.

RESULTS

Withdrawal

The withdrawal capacity of the wooden nail is over two times the capacity of a metal nail with the same dimensions. Then if the 2.25 x 0.185" wooden nail is directly compared to the 3 x 0.131" nail, the wooden nail has over four times the withdrawal capacity per inch of penetration. While the NDS may mandate that nails are not to be loaded in withdrawal for end grain connections, that should not apply to wooden nails (American Wood Council, 2018). The 0.185" diameter wooden nail has similar withdrawal design values as a wood screw number seven in DFL connections. Below are the results of the withdrawal test in Table 1.

Table 1: Ultimate Withdrawal Loads Per Nail by Type.

Nail Type	Specific Gravity	Number of Nails	Ultimate Connection Load [lb]	Ultimate Divided by # of Nails [lb/nail]
3x0.131-inch Metal	0.5	3	330.55	110.18
3x0.131-inch Metal	0.5	3	290.75	96.92
3x0.131-inch Metal	0.5	3	290.95	96.98
2.25x0.185-inch Wooden	0.5	3	625.95	208.65
2.25x0.185-inch Wooden	0.5	3	645.73	215.24
2.25x0.185-inch Wooden	0.5	3	617.42	205.81
			Average	210

Shear

The capacity of the nails is determined by the cross-sectional area and the internal properties of the material. Connection yield modes are given in Figure I1 of the NDS (American Wood Council, 2018). Steel is ductile and the failure of 3 x 0.131" metal nails was primarily through bending of the nail, crushing of the wood member, and eventual withdrawal of the nail. Specifically, the metal nails failed in yield mode IIIm, which is where the "fastener yields in bending at one hinge point per shear plane and bearing yield of wood fiber in contact with fastener" (American Wood Council, 2018).

The wooden nails are brittle, so the failure mode was the fracture of the nail on either side of the shear plane with some wood crushing of the wood members and no withdrawal from either member. While this is not exactly yielding mode IV, it is the most similar in description which is when the "fastener yields in bending at two hinge points per shear plane and localized crushing of wood fibers near shear plane" (American Wood Council, 2018).

Metal Nails Side Grain

For the 3 x 0.131" metal nails, 16 shear tests were conducted in side grain connections and the Results are in Table 2 below. The average ultimate lateral capacity was about 401 pounds per nail. These test were to provide a datum to compare the results and validity of the wooden nail test.

Table 2: Ultimate Shear Capacity of 3 x 0.131" Metal Nails in Side Grain Connections.

Nail Type	Specific Gravity	Number of Nails	Ultimate Connection Load [lb]	Ultimate Divided by # of Nails [lb/nail]
3 x 0.131"	0.5	1	365	365
3 x 0.131"	0.5	1	425	425
3 x 0.131"	0.5	1	377	377
3 x 0.131"	0.5	2	852	426
3 x 0.131"	0.5	2	802	401
3 x 0.131"	0.5	2	887	443
3 x 0.131"	0.5	4	1516	379
3 x 0.131"	0.5	4	1562	390
3 x 0.131"	0.5	4	1568	392
3 x 0.131"	0.5	4	1592	398
3 x 0.131"	0.5	4	1486	371
3 x 0.131"	0.5	6	2485	414
3 x 0.131"	0.5	6	2405	401
3 x 0.131"	0.5	6	2414	402
3 x 0.131"	0.5	6	2516	419
3 x 0.131"	0.5	6	2479	413
			Average	**401**

Metal Nails End Grain

Fourteen shear tests were conducted on end grain connections and the results are displayed in Table 3 below. For these connections, the grain of the main member and the fastener were perpendicular to the load. The average ultimate lateral capacity was about 312 pounds per nail.

Table 3: Ultimate Shear Capacity of 3 x 0.131" Metal Nails in End Grain Connections.

Nail Type	Specific Gravity	Number of Nails	Ultimate Connection Load [lb]	Ultimate Divided by # of Nails [lb/nail]
3 x 0.131"	0.5	6	1611	268
3 x 0.131"	0.5	6	1766	294
3 x 0.131"	0.5	6	1726	288
3 x 0.131"	0.5	6	2200	367
3 x 0.131"	0.5	6	2126	354
3 x 0.131"	0.5	6	1754	292
3 x 0.131"	0.5	6	2136	356
3 x 0.131"	0.5	6	2112	252
3 x 0.131"	0.5	12	3268	272
3 x 0.131"	0.5	12	4088	341
3 x 0.131"	0.5	12	4455	371
3 x 0.131"	0.5	12	3178	265
3 x 0.131"	0.5	12	3075	256
3 x 0.131"	0.5	12	3523	294
			Average	**312**

The end grain adjustment factor for shear connections is Ceg=0.67. From this adjustment factor, an estimation could be made that the measured shear capacity of the 3 x 0.131" nails in end grain connections would be around 67 percent of the measured capacity of the side grain connections. The results did not reflect this 67 percent value and were closer to 78 percent. This could mean a couple of things; the side grain shear capacity tests results are low due to the 4 x 4 post and moisture content, or the end grain reduction factor is very conservative. All members measured under 19 percent moisture at the time of testing but wood dries from the outside in and the moisture meter used only penetrates the outer most surface. If the average side grain shear capacity, 401, is divided by the wet service factor CM=0.7 then the average capacity would increase to about 573. The end grain capacity would then be closer to 54 percent of side grain. More tests would be necessary to determine the cause of this discrepancy.

Wooden Nails Side Grain

According to the National Technical Approval, the shear capacity of wooden nails can be determined with the following equations in Figures 5.3 and 5.4. For values such as the bearing strength of components one or two, the NDS was used for those values. These equations also include a partial safety factor for material properties when determining the components bearing strength which is being assumed to have already been applied to the bearing strength in the NDS.

The shear capacity of a side grain connection with wooden nails is estimated around 160 pounds per nail.

For the 2.25 x 0.185" wooden nails, 16 shear tests were conducted in side grain connections and the results are displayed in Table 4 below. In these connections, all member's grain was in line with the load and the nail was perpendicular to the load. The average ultimate lateral capacity was about 197 pounds per nail. This implies that some sort of strength reduction or safety factors are being applied in the National Technical Approval and/or the EuroCode.

Table 4: Ultimate Shear Capacity of 2.25 x 0.185" Wooden Nails in Side Grain Connections.

Nail Type	Specific Gravity	Number of Nails	Ultimate Connection Load [lb]	Ultimate Divided by # of Nails [lb/nail]
2.25 x 0.185"	0.5	1	204	204
2.25 x 0.185"	0.5	1	256	256
2.25 x 0.185"	0.5	1	209	209
2.25 x 0.185"	0.5	2	440	220
2.25 x 0.185"	0.5	2	370	185
2.25 x 0.185"	0.5	2	387	193
2.25 x 0.185"	0.5	4	736	184
2.25 x 0.185"	0.5	4	751	188
2.25 x 0.185"	0.5	4	755	189
2.25 x 0.185"	0.5	4	819	205
2.25 x 0.185"	0.5	4	844	211
2.25 x 0.185"	0.5	6	1073	179
2.25 x 0.185"	0.5	6	1142	190
2.25 x 0.185"	0.5	6	1059	177
2.25 x 0.185"	0.5	6	1083	180
2.25 x 0.185"	0.5	6	1602	177
			Average	**197**

Wooden Nails End Grain

Since there is no approval for end grain connections, the National Technical Approval does not list an end grain adjustment factor. Sixteen additional tests of end gain connections were tested to determine if there was any reduction in end grain application from side grain application and those results are displayed in Table 5 below. For these connections, the grain of the main member and the fastener were perpendicular to the load. The average ultimate lateral capacity was about 202 pounds per nail. There is no statistically significant difference to the capacity of the wooden nail in side grain connections.

Table 5: Ultimate Shear Capacity of 2.25 x 0.185" Wooden Nails in End Grain Connections.

Nail Type	Specific Gravity	Number of Nails	Ultimate Connection Load [lb]	Ultimate Divided by # of Nails [lb/nail]
2.25 x 0.185"	0.5	6	1166	194
2.25 x 0.185"	0.5	6	1100	183
2.25 x 0.185"	0.5	6	1255	209
2.25 x 0.185"	0.5	6	1180	197
2.25 x 0.185"	0.5	6	1272	212
2.25 x 0.185"	0.5	6	1190	198
2.25 x 0.185"	0.5	6	1183	197
2.25 x 0.185"	0.5	6	1314	219
2.25 x 0.185"	0.5	12	2733	228
2.25 x 0.185"	0.5	12	2718	227
2.25 x 0.185"	0.5	12	2288	191
2.25 x 0.185"	0.5	12	2352	196
2.25 x 0.185"	0.5	12	2394	199
2.25 x 0.185"	0.5	12	2391	199
2.25 x 0.185"	0.5	12	2397	200
2.25 x 0.185"	0.5	12	2255	188
			Average	**202**

These tests results demonstrate that 2.25 x 0.185" wooden nails do not behave differently in side grain connections or end grain connections. This is most likely due to the lignin welding and failure mode. The lignin weld taps into the tensile strength of the fibers of the wood members and relies less on the internal pressure of the wood members to resist withdrawal which leads to the brittle fracture in shear. Therefore, Ceg could be considered 1.0.

CONCLUSION

The results of these experiments and statistical analysis support the use of 2.25 x 0.185" wooden nails in light-framed construction. The wooden nails are two to four times as strong in withdrawal as metal nails and therefore any connection that has withdrawal and shear load demand will be controlled by shear. The 2.25 x 0.185" wooden nails only have 50 to 60 percent capacity of 3 x 0.131" metal nails in shear. The prescribed replacement ratio of 3 x 0.131" metal nails by 2.25 x 0.185" wooden nails could be one-to-two for Table R602.3(1) of the IRC.

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Residential Construction Solutions Using MassBu Panel Systems

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ABSTRACT

In an attempt to make better use of bamboo in construction, the authors have invented a construction material called MassBu, which is based on the use of lightly-modified bamboo (LMB) elements, which include flattening the top and bottom of the culm faces to provide gluing surfaces. Through various research efforts, the authors have investigated the material uses of MassBu panels and beams. Production of MassBu panels has also been optimized to rely on appropriate technology specifically designed for developing economies where bamboo is prevalent. The purpose of this paper is to present a set of structural system plans for one- to three-story residential buildings using MassBu elements for floors, roofs and walls. This work represents a significant step from material properties to building systems thinking related to bamboo. Special attention is given to story details and connections for lateral design. This work discusses the process of transforming a novel material into a building system ready for costing and implementation.

The Versatility of SIP Systems in Emergency Housing

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ABSTRACT

The versatility stems from the rowing demand originating from a sustainable and economic ideology that's advocates maximizing the use of a material or architectural design based on its diverse applications or functionalities. In this context, rethinking the role of the architect and others in the construction field has become a subject of interest, particularly within the scope of emergency architecture, a field that faces bureaucratic, financial, and logistical challenges that often delay the response to disasters. The immediate priority of any government, non-governmental organization, or civil society is to provide safe and temporary shelters until the permanent homes of affected citizens are fully reconstructed. This study addresses all these issues by comparing them with what is available on the market to facilitate the creation of an emergency and/or urgent housing module, aiming to solve the primary need of victims of natural disasters or potential social problems. It is from this perspective that wood emerges as a promising alternative to respond to the previously mentioned characteristics. Progressively, new techniques are emerging that allow for better efficiency of this renewable resource, as exemplified by SIP panels, a self-supporting material that already includes thermal insulations in its composition. The goal is for the module's design to include a heterogeneity of solutions for the number of occupants, durations of occupations, locations of implementation, ease of assembly, and transport, which essentially provides the necessary comfort for the recovery of its inhabitants and avoids material waste in its construction.

Keywords: Emergency Architecture; Modular Architecture; Vulnerable Communities; Shelters; Versatility.

INTRODUCTION

Modular architecture represents a construction methodology designed to enhance efficiency by utilizing prefabricated and standardized modules. In contrast to conventional on-site construction, these modules are manufactured in a factory setting and delivered to the

construction site ready for assembly, facilitating the swift erection of structures. This production process, conducted within a controlled environment, ensures superior product quality and minimizes material waste. Furthermore, the compact design of the modules enhances their versatility in terms of transportation and functionality, enabling easy assembly, disassembly, and relocation. The incorporation of Structural Insulated Panels (SIP) within these modules offers a solution to the demand for thermal comfort in residential spaces. Their composition, which provides effective insulation, allows for more economical construction with reduced material usage (Mullens and Arif, 2006). The proposal and innovation presented in this article focus on the reconfiguration and adaptation on this composite panel for housing modules designed for post-catastrophe contexts or emergency scenarios. The objective is to address the urgent deficiency in accommodation, predicated on the principle that dignified housing constitutes a fundamental right for every individual. This approach emphasizes construction simplicity, supplanting the complexity of traditional methods, which is particularly vital in emergency situations where design options and material availability are limited.

BACKGROUND AND MOTIVATION

The evolution of global challenges, including armed conflicts, humanitarian crises, natural disasters, and the proliferation of major epidemics, underscores the vulnerability of numerous communities. The severity of these consequences has escalated, and national responses frequently prove inadequate. There is a recurrent lack of capacity to provide essential means of survival and delays in the reconstruction of permanent housing (Félix et al., 2013). Furthermore, the reliance on donations and civilian volunteering for initial aid, along with the failure to implement mitigation measures, underscores the necessity for more effective and immediate solutions. The housing crisis is a global issue affecting multiple countries, not solely Portugal. The shortage of social housing is evidenced by long waiting lists and the vulnerability of populations that endure years of waiting for relocation to social housing. Despite the existence of various humanitarian projects and studies, many fail to reach a significant number of individuals in need. These failures are often attributed to logistical challenges, cost, lack of prior planning, and cultural and social inadequacies.

The impetus for the selection and development of the current project is rooted in this reality. On a global scale, individuals affected by disasters and humanitarian crises possess the right to receive assistance and protection. It is imperative for nations to acknowledge the threats present within their borders and to learn from the consequences of each disaster to adequately prepare and ensure the protection to which their population are entitled. Nonetheless, it is reasonable to assert that casualties are unavoidable, necessitating the implementation of measures that safeguard the population post-event, ensuring access to essential needs such as food, clean water, shelter, and emergency health care (Proteção Civil, 2020).

In the context of temporary shelters, the initial response may be improvised with the utilization of public buildings, such as gyms, schools, and parish halls, to provide a secure and warm environment during the initial hours or days following an emergency. Subsequently, feasible options include lodging with family or friends and rehousing through official programs. In

Portugal, the BNAUT (National Emergency and Temporary Housing Exchange) program endeavours to address the shortage of emergency shelters, while other nations employ alternatives such as FEMA or resCEU. Nevertheless, these systems are frequently criticized for their bureaucratic nature and slow response times, as their capacity is inadequate to meet the daily volume of appeals, despite efforts to assist those in need.

In response to these vulnerabilities, a versatile housing module is proposed, designed from commonly available market materials. This module is not confined to emergency scenario; it can also serve as urban support infrastructure. Its permanent presence in the area, such as its role in providing shelter for victims, represents a strategic solution that could be implemented to address a substantial portion of aid requests and alleviate pressure on existing support systems. The design aims to efficiently meet multiple requirements, achieving a balance between the needs of the victims and operational constraints.

PROJECT DESCRIPTION

This emergency housing module is proposed as a solution to address the survival needs of disaster victims or individuals experiencing social challenges. Given the operational constraints that can delay response efforts, this module is designed to function as an element of urban support or to be stored in containers for immediate transportation and development when required. Its adaptable design allows for utilization in various contexts and timeframes: in the short term, it can be easily assembled and disassembled, serving as temporary shelter or, when not in use, as a public service; in the long term, it can be repurposed for functions such as social housing or use in refugee camps. Although adapting to all cultural contexts presents challenges, the module features a simple base design that leverages the metric of SIP panels to form the space. The selected cladding material, intended to preserve the module's structure, functions as a "sacrificial material" to extend its life cycle. However, the choice of cladding can be tailored to the specific location and the needs of its occupants. In an emergency, the implementation process is phased, beginning with the provision and assembly of the initial module. The subsequent phase involves adding modules to the composition to accommodate the spatial requirements of each household or individual, with necessary equipment already in place, ensuring strategic and compact use of space. Thereafter, water and sanitation modules are incorporated, replacing community kitchens and public bathrooms. In the final phase, the temporary shelter transitions into a permanent structure, thereby enabling residents to modify it according to their specific needs. The responsibility for these adaptions' rests entirely with the residents.

Currently, various housing modules are deployed to assist populations affected by social vulnerabilities or natural disasters. Although each project possesses intrinsic characteristics and distinct construction systems that dictate their design based on specific priorities, they all share the common purpose of supporting communities in situations of extreme deprivation. The successful implementation of these projects globally demonstrates the viability of establishing an effective support network to address these social exigencies.

The Better Shelter (2025) constitutes an example of a modular, prefabricated and easily assembled shelter, specifically engineered to accommodate displaced families in crisis contexts. The system relies on a galvanized steel frame with lightweight anchors of the same material, exhibiting remarkable logistical efficiency, it can be transported in just two crates and assembled by a four-person team within one hour. The distinguishing feature of this project lies in the integration of lightweight polyolefin panels, which offer superior meteorological protection compared to traditional canvas solutions. These components are UV- resistant and ensure an estimated lifespan of three years, representing a significant advancement for prolonged displacement scenarios (Better Shelter, 2025).

In turn, Pallet Shelter was designed to manage homelessness crises and respond to natural disasters through the creation of structured communities. The system is based on composite aluminium cabins that can be assembled in under thirty minutes, integrating restroom modules and social support offices. This model differentiates itself by focusing on transitional housing, offering security and privacy through units equipped with HVAC systems and thermal insulation, ensuring dignified habitability across varied climates. Furthermore, the company promotes a circular economy by employing individuals with lived experience of homelessness in the production of the modules (Pallet, 2024).

Diverging from conventional methodologies, Shigeru Ban's Paper Log Houses assume a leading role in the field of emergency housing units. The system is predicated on the use of recycled cardboard cylinders as structural studs, utilizing low-cost byproducts with remarkable mechanical properties. These structures exemplify the efficient use of ephemeral materials, the cardboard tubes are treated to ensure moisture and fire resistance, while insulation is reinforced with low-cost materials such as shredded newspaper. The system demonstrates that structural integrity depends on rigorously geometry and intelligent management of local resources (ArchDaily, 2025 December 15).

As previously mentioned, all these projects present specific vectors of relevance. It is precisely within this ideological framework that the current proposal emerges: the design of a habitable space that utilizes the Structural Insulated Panel (SIP) as an innovative element. The focus lies on developing interlocking systems that allow for disassembly without structural damage, ensuring that the modules can be successively redeployed where their need is most urgent.

THE CONSTRUCTION SYSTEM

The structural Insulated Panels (SIP) system comprises a rigid insulating core, designed to mitigate caloric dissipation and optimize thermal homeostasis, encapsulated between two structural skins (Figure 1). This construction methodology enables the creation of a hermetic envelope, ensuring high-efficiency thermal and acoustic performance. Although the composite panel concept dates back to the 20th century, its technical evolution was catalyzed by the escalating demand for sustainable and economically viable structural solutions.

The first modern experiments occurred in the 1930s in the United States through research conducted by the Fores Products Laboratory (FPL) where the initial prototype was developed. Frank Lloyd Wright utilized this system in several of his designs, such as the Usonian houses, establishing the foundational principles for the material's development. Subsequently Alden B. Dow, a former student of Wright and an advocate for rigid foam, refined the panel's performance and is credited with the production of the first contemporary SIPs (Smart SIPs, 2025, March 10). Since then, numerous projects have explored diverse material compositions, such as the La Dacha Refuge (ArchDaily, 2025 March 10) and the SIP m3 House (ArchDaily, 2026 January 05), alongside the emergence of specialized firms like SIP-Panel (2025, March 10), or Fractus (2024).

The system employs standardizes 2.50m x 1.25m SIP panel module, utilizing subtractive volumetric voids for apertures to effectively mitigate material dissipation. Each panel, consisting of a 120 mm XPS core between 12 mm OSB sheets, serves as a self-supporting, gravimetrically optimized unit that ensures high thermal performance (Figure 1). This lightweight configuration is structurally reinforced by lateral wooden rafters, balancing cost-efficiency with mechanical robustness (Amran et al., 2020).

Figure 1. Design and imagery of the SIP panel and its application.

The module is engineered for multifaceted implementation across diverse terrains, utilizing a foundation of wooden rafters (60mm x 120mm) fixed to the substrate via stakes (Figure 2). This elevated configuration optimizes the integration of plumbing and electrical infrastructure while providing a safeguard for inundation-vulnerable zones. The assembly follows a logical progression, from the platform and floor panels to walls with heigh extensions, culminating in the roof's installation as the primary structural integument. To ensure a circular lifecycle, the

design prioritizes mutual engagement interfaces and specialized corner connectors. This approach, supplemented by barrel nuts for permanent fastening, avoids the structural degradation typical of traditional nails, allowing for repeated assembly without compromising the material's integrity.

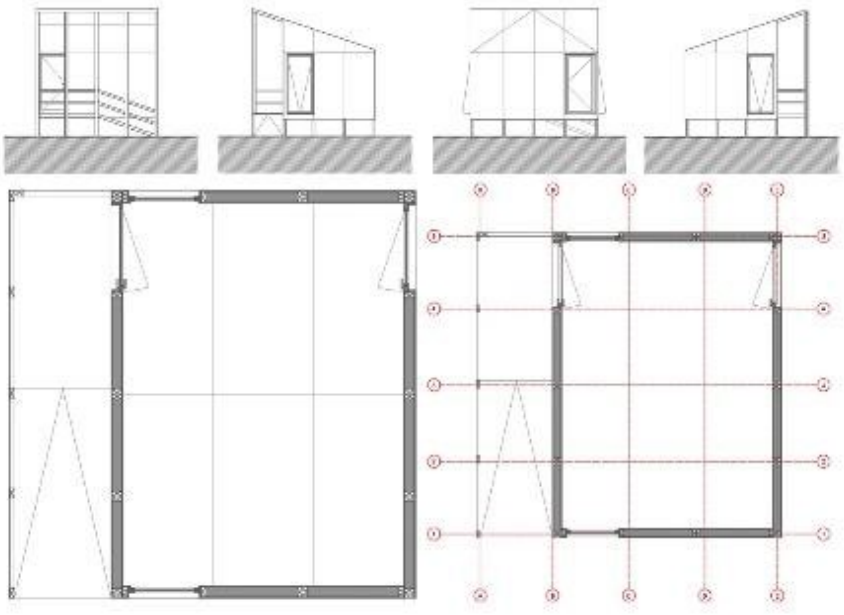

Figure 2. Elevations, floor plan with construction details of the module, and structural grid of the wooden beam platform.

The project design optimizes passive atmospheric circulation through strategic aperture placement, which simultaneously enables versatile modular expansion. It balances individual privacy via an internal refuge with communal cohesion through semi-private external zones, fostering interpersonal support frameworks essential for crisis-affected populations. The cantilevered, sloped roof ensures efficient hydrological drainage while maintaining panel dimensional integrity. Adhering to circular economy principles, the system employs interchangeable componentry, allowing standardized segments, such as roof sections and wall extensions, to be repurposed across various units. While the module (Figure 3) is available in its structural form, it can be augmented with optional cladding to enhance its morphological attributes and environmental protection. For walls and ceilings, Viroc boards, a sustainable wood-cement composite, were selected to optimize cost-efficiency while repurposing industrial wood waste (Albadrani, 2023). The flooring utilizes high-resilience vinyl, chosen for its tolerance for intensive pedestrian loading and superior ergonomic comfort, particularly in disaster scenarios where traditional bedding may be absent. Finally, the roofing system employs cost-effective profiled metal sheets to ensure robust waterproofing. To maximize efficiency, all components are transported with these finishing layers pre-installed.

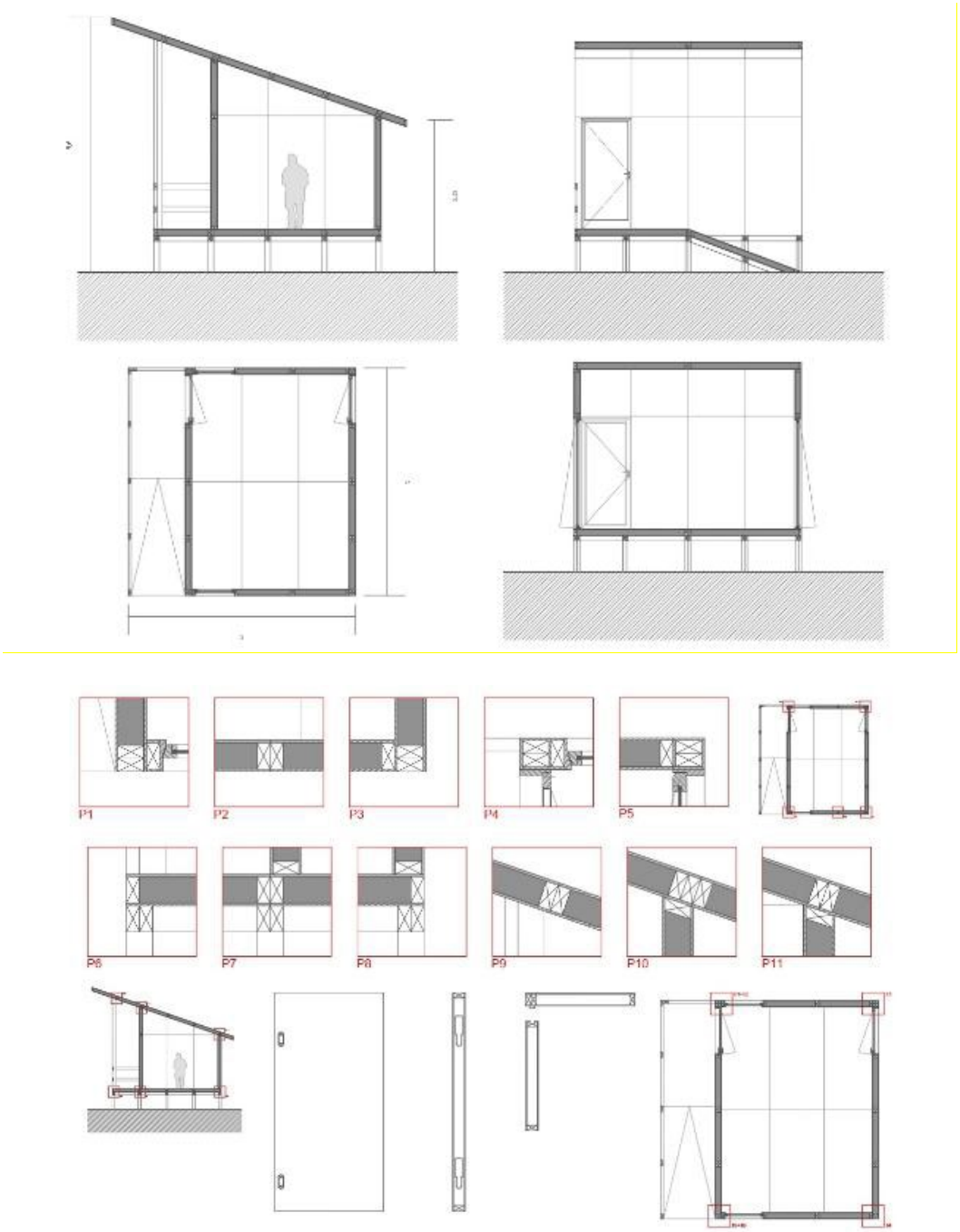

Figure 3. Sections and dimensions of the module, construction details in plan, in section, and corner joints of the wall panels and their location.

This construction system is designed to streamline the assembly and transportation processes by enabling the prefabrication of walls, roofs, and floors, complete with necessary openings.

However, due to their substantial dimensions, these components are divided into sections of manageable weight, allowing assembly to be performed by approximately two individuals (see Figure 4).

TRANSPORTATION AND ASSEMBLY LOGISTICS

The transportation strategy emphasizes not only the use of common and cost-effective modes of transport, thereby extending its reach to a boarder demographic and geographic area, but also the optimization of loading capacity to maximize the number of modules transported within a single compartment.

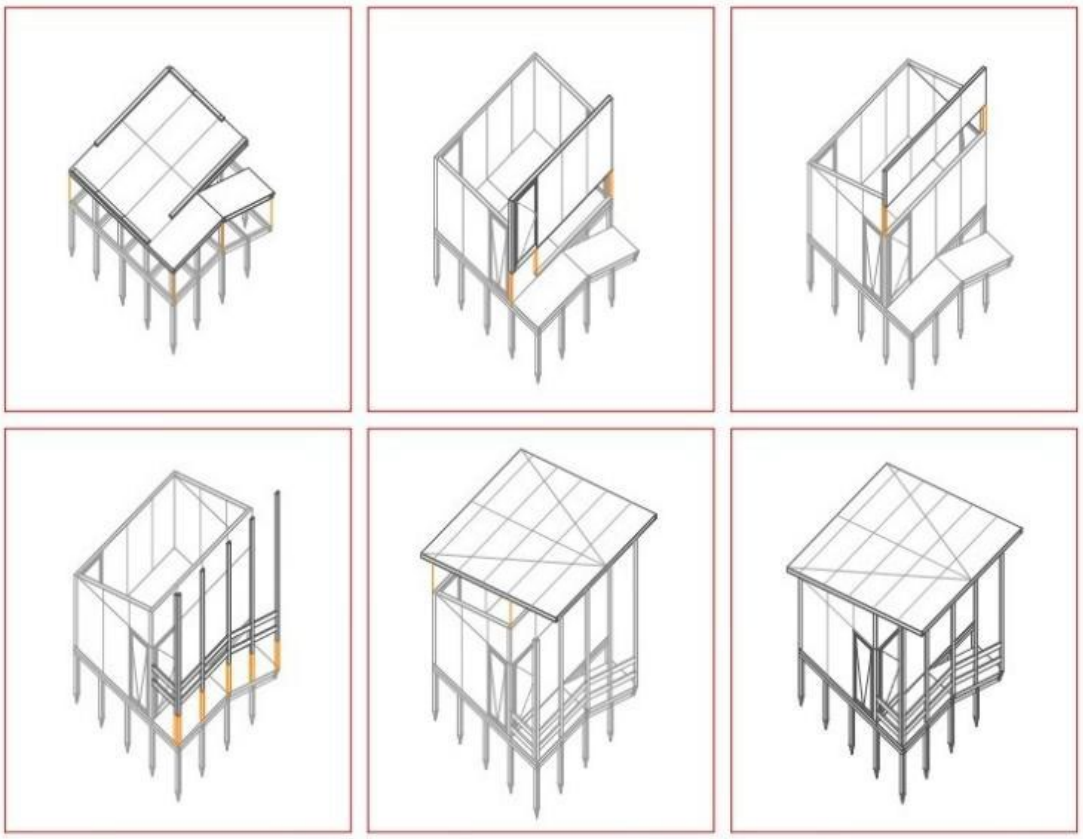

Figure 4. Axonometry of the assembly and the breakdown of the module's elements for transport.

The selection of transport containers is attributed to their versatility and widespread availability. Their capacity to be transported via sea, rail, and road, coupled with the option for temporary or permanent storage at port or intermodal terminals, renders them an efficient logistical solution. The diversity of types and dimensions of these containers enables them to accommodate the varied requirements of products being transported. Taking into account the cost-benefit ratio and

available dimensions, the 20' container was selected. This container, measuring 6.06 m in length, 2.44 m in width, and 2.59 m in height, was deemed adequate for the transportation of all the module components. The breakdown of component sizing was designed based on these measurements, with the additional aim of simplifying assembly to the greatest extent possible, given the labor constraints, which consist of volunteers and residents (see Figure 4).

CONCLUSIONS

Upon examining the objectives delineated in this document, it becomes apparent that solutions for urgent needs are frequently constrained, in contrast to the plethora of solutions available in other fields. Despite the evident global advancements across various domains, the slow progression in critical areas is underscored by the suffering and dissatisfaction of the populations this project seeks to assist.

The aim is to develop universal housing kits that cater to all individuals confronting a large-scale social issue, rather than a specific demographic. These modules, presented in their basic form (excluding finishes or furniture), are intended to demonstrate their adaptability to diverse cultures. Their flexibility permits the interior to be filled with each inhabitant's belongings and history, serving as a refuge for their past and a foundation for their future.

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Mechanical, Electrical, and Plumbing

Pipes and Ducts in the Urban Jungle: Where on Earth Is That Smell Coming from?

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ABSTRACT

Multifamily residential buildings contain an intricate (and delicate) network of pipes and ductwork acting as the building's circulatory system, constantly handling air and water. Residential buildings can be significantly more complex than their commercial counterparts due to the need to provide multiple duct and pipe runs to dozens or hundreds of individual units, as opposed to just a few localized bathrooms and utility rooms. Just like the complex network inside our own bodies, it can be only a small issue that causes a big problem.

In the authors' experience, these systems are very sensitive to quality of workmanship and adherence to best practices. Failure to properly design (or implement) mechanical and plumbing systems in multifamily buildings can lead to years of chasing problems. From the rooftop fans, air handlers, and waste stack vents–leading all the way down to the cellar–poor mechanical and plumbing system performance can cause air and water leaks, among other issues, leading to upset residents and property damage. Noise and odor transmission between units is a common symptom when something behind the walls and ceilings has gone awry. This can result in expensive lawsuits between the building representatives, the original developers, contractors, and the residents.

This paper discusses the basics of how mechanical and plumbing systems are distributed in multifamily buildings, highlighting key components and where things can go wrong. The authors present examples from recent projects to highlight these issues. Lastly, we discuss the costs and challenges associated with addressing these issues, further demonstrating the importance of quality design, construction, and oversight before these systems are concealed, and in some cases, inaccessible.

INTRODUCTION

In American football, analysts liken different aspects of the team to systems and components of the human body (for example, "…that quarterback is the team's backbone"). The individuals comprising the football team must adhere to the rules and regulations governing the sport: for fairness, safety, and results. Analogously, the rules that govern residential buildings are equally

rigid and essential, ensuring occupant safety and comfort. Most regulations defining the game lines, goal posts, and penalties pertaining to building design and construction are sourced from Standards Development Organizations (SDOs). The International Codes Council (ICC) develops and maintains model building codes that cover all aspects of buildings and influence local code requirements in all 50 states. A more focused example is the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), who develop industry-recognized technical details and standards of practice for heating, ventilation, and air conditioning (HVAC) systems. ASHRAE standards and guides are often incorporated or referenced in subsections of specific building codes adopted from ICC codes.

Governing construction codes vary by jurisdiction and often within individual states. For example, New York State currently uses modified versions of the 2018 ICC Codes (including Building, Energy, Mechanical, and Plumbing). However, in recognition of the unique building types, population density, and complex infrastructure within the city, the State legislature allowed the City to maintain its own building code provided it was at least as stringent, but in no cases less stringent than the state codes. This is often the case for large urban areas, including Philadelphia, Dallas, Seattle, and Chicago.

Navigating the intricacies of governing regulations pertaining to the design and construction of mechanical and plumbing systems in multifamily buildings is a collaborative effort between all the involved parties in residential construction. This paper will explore the interaction between code requirements, design, and construction of these complex systems to reveal the criticality of proper planning, workmanship, and quality control. Once these ducts and pipes are concealed behind walls and ceilings at the end of construction, potential issues are out of sight and out of mind – until it becomes a chronic and costly issue to address.

Multifamily Building Mechanical and Plumbing Systems

Behind the inlets and outlets of mechanical and plumbing systems in multifamily buildings lies a complex, interconnected network vital to the comfort, health, and safety of the building occupants. Unlike single-family homes or commercial spaces where systems are largely self-contained and serve limited subspaces within the building, the sheer number of individual rooms and fixtures in a large multifamily building requires a significant network of ducts and pipes to support. A large commercial office building could have only one or two central bathrooms per floor, requiring relatively small and consistently located (floor-to-floor) plumbing and exhaust chases. The rest of the building systems are likely contained within the floor plate, with only internal ductwork and possibly connections to a central water loop or independent refrigerant piping. For a multifamily building, there could be a dozen or more individual bathrooms and kitchens per floor, requiring both vertical and horizontal pipe runs, drain and vent lines, and bathroom and kitchen exhaust ductwork. The use of centralized mechanical ventilation (fresh air) systems introduces further complexity, since as opposed to an office building where fresh air ductwork only needs to connect to one or two air handlers that service a space, in a multifamily building fresh air needs to be individually ducted into each unit. A further complication arises from the need for ducts to penetrate fire-rated partitions between adjacent units, units and hallways, and floors. In some cases, this necessitates fire-rated enclosures/shafts, which must be

carefully sealed to avoid becoming conduits between spaces, while in others fire/smoke dampers can be installed in the ducts at the point of penetration.

A single value-engineering decision may drastically impact any of the considerations mentioned above, underlining the importance of collaboration between owners, contractors, installers, architects, engineers, and consultants to better understand the risks and implications associated with these decisions.

Mechanical System Composition

The mechanical system of a multifamily building is comprised of multiple HVAC networks. These ducts are critical to maintaining the building's internal environment, providing supply air (heating and cooling), fresh air (ventilation), and exhausting "stale" air from bathrooms, trash rooms, and similar locations. Openings at the outlet or inlet end of ducted systems typically have a decorative vent cover (Figure 1) or are otherwise just an opening through interior finishes (Figure 2) with a plenum box behind/above.

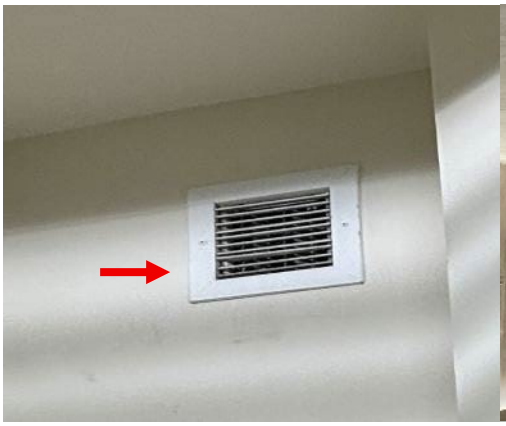

Figure 1: Decorative Vent Cover.

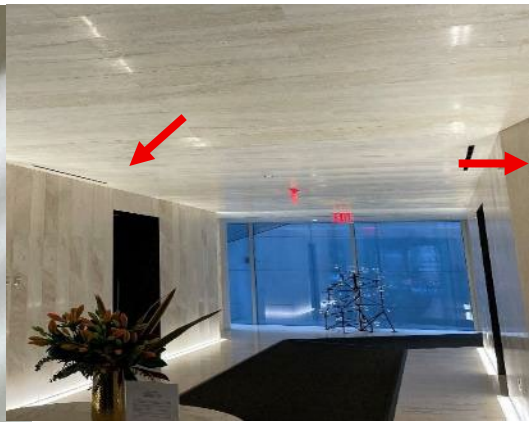

Figure 2: Exposed Vent Openings.

Regardless of aesthetics, some are designed as nothing more than a static opening at the end of a line of ductwork, subjected to airflow provided by mechanical units which may be localized or elsewhere (i.e., on the roof or in a remote mechanical room). The airflow provided at these vents depends on the geometry of the ductwork connected to that opening and the performance and capacity of whatever mechanical unit is serving that duct run. Similar to an electric circuit, where electrical resistance reduces current, fittings (such as elbows and tees), inline dampers, and the ductwork itself produce resistance to airflow that must be accounted for in the design of the equipment itself. Failure to design the operating pressure of a mechanical unit to the back pressure of the ductwork to which it is connected can result in reduced airflow, uneven airflow distribution, or both.

Some mechanical openings are designed with components which allow for manual or automatic control of airflow. Airflow at vents can be adjusted manually by mechanical dampers (Figure 3). Similar to adjusting the flow of your car's air conditioning, you manipulate the orientation of the damper's fins to manipulate airflow at that endpoint. However, this will impact the air flow at all other interconnected junctures (i.e., minimizing the air flow in one location will increase the flow at other connected locations). This makes "balancing" of airflow networks a critical step in achieving the desired system performance – an iterative process of adjustments and measurements to achieve design flow rates at all outlets (or within 10%, which is a typical target in the industry).

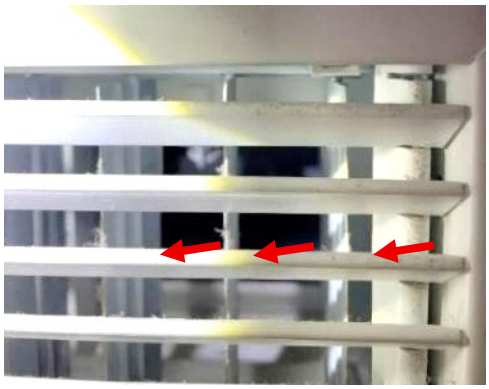

Figure 3: Manual damper blades behind decorative vent cover.

Alternatively, in-line constant air flow regulators (CARs) passively balance air flow by responding to pressure changes in the duct and opening or closing a damper to regulate air flow to a predetermined level (Figures 4, 5 and 6).

Figure 4: CAR being installed.

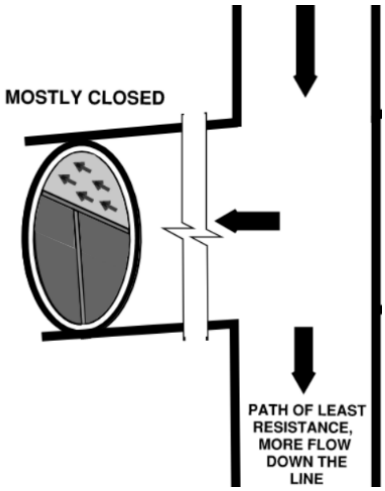

Figure 5: CAR mostly closed.

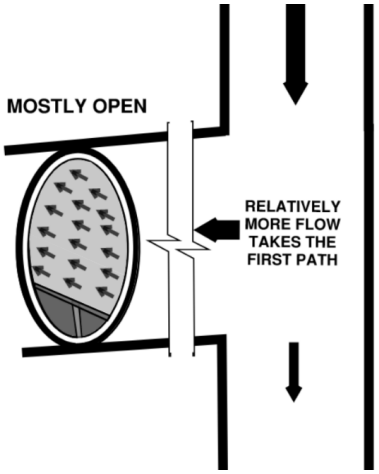

Figure 6: CAR mostly open.

Although it is theoretically possible to design a duct system to be perfectly matched to a piece of equipment and provide balanced airflow to all outlets, the realities of construction and building operation make this impractical since even small deviations from the design could result in significant imbalances. Even in a well-designed system, without these components to allow for balancing, vents closer to the fan will experience the highest airflows and the ones furthest away will have reduced flow, or in extreme cases, airflow in the opposite direction. These uneven flows can cause noise at outlets or inlets and pressure imbalances that lead to odor transfer between units.

Natural and "Corridor" Ventilation

For as long as the authors have been practicing in this field, there has always been confusion over building code requirements for ventilation in multifamily, high-rise construction. The 2024 International Mechanical Code notes that dwelling units meeting IECC / ASHRAE airtightness requirements (i.e., a whole-building leakage rate of 0.35 cfm/sf at a pressure differential of 75 Pa) must be ventilated by mechanical means. This requirement reflects the common understanding that the previously accepted method of relying on "incidental air leakage" through building enclosures is inappropriate for modern, airtight buildings with extremely low air leakage rates. However, that same code states that for Group R-2 occupancy, mechanical ventilation can be provided by an exhaust system, supply system, or combination thereof. This provision implies that exhausting air from a space, and assuming the ventilation air will come from other sources (air leakage, corridors, etc.) is acceptable.

Relying on operable windows to provide ventilation air has been a "tried and true" practice in buildings for centuries, but this approach is completely unsuitable for modern, tall, airtight buildings. This is due to the lack of "incidental" air leakage when windows are closed, internal pressure differences which can reduce airflow through window openings, and the simple fact that

occupants in New York are as unlikely to keep their windows open in February as those in Miami are to keep windows open during the humid summer months. In practice, relying on operable windows results in high interior RH levels, comfort issues, condensation, and potentially reduced exhaust flows. These problems are difficult to fix given the impracticality of installing extensive duct runs in finished spaces, and can generate costly disputes since in many jurisdictions the approach is fully code compliant.

Some have attempted to improve on this system, while still saving money on dedicated central ventilation to each unit, by employing the "corridor ventilation" approach. In this scheme, the ventilation air to corridors is designed to meet both the corridor requirement (based on floor area served) and all individual units on that floor (typically based on occupants or number of bedrooms). Doors to the units are undercut to allow airflow from the corridors, the intent being exhaust from the bathrooms creates negative pressure that draws ventilation air in from the corridor to meet unit requirements. While in theory this can work successfully, factors such as the effectiveness of bathroom exhausts, seasonal stack effects which affect floor-to-floor pressures, and occupant behavior (e.g., "I hear noise from the hallway so I installed a gasket to cover the bottom of the door") can quickly render it ineffective. From a code compliance standpoint, the authors have investigated several buildings where local code officials rejected the approach (in one case, at the final inspection for the building) citing fire safety and the risk of smoke/fire transfer from the pressurized corridors into the lower-pressure units. In that case, sealing doors with fire-rated gaskets resulted in severe pressure imbalances in the building due to an additional design issue with bathroom exhaust stacks. The building's upper floors, closer to the bathroom exhaust fan, experienced negative pressures so high that balcony doors experienced approximately 50 lbf of inward pressure, making them dangerous to operate.

Some municipal energy codes have compensated for issues specific to high-rise construction with additional mechanical ventilation requirements. For example, the 2022 New York City Mechanical Code (Chapter 4) requires full mechanical ventilation of units in R-2 occupancies when the sum of exhaust flows for those units exceeds 75 cubic feet per minute (CFM). But unfortunately, for much of the country the code requirements for ventilation remain unclear, and the eventual selection of a ventilation scheme is primarily based on cost and schedule rather than real-world performance.

Energy Recovery Ventilators

Another critical component of a building's mechanical system is the Energy Recovery Ventilator (ERV). An ERV is a type of air-to-air heat exchanger that manages both temperature and humidity between the incoming fresh air and the outgoing stale air. Unlike a traditional system that simply exhausts conditioned air and replaces it with unconditioned outdoor air (a highly inefficient process), an ERV captures a significant portion of the energy used to heat or cool the indoor air and transfers it to the fresh air intake stream. In a common configuration, bathroom exhausts feed into one or more ERVs which then supply fresh air ventilation for the individual units via distributed ductwork.

For instance, in the winter, the warm, moist air exhausted from the building passes through the ERV, transferring its heat and moisture to the cold, dry air being pulled in from outside. In the summer, the process is reversed: the cool, conditioned air being exhausted transfers its coolness to the warm, humid air entering the building. This process significantly reduces the energy required to cool and dehumidify the incoming air, lowering the building's operational costs. This can be a key factor in achieving green building certifications and complying with increasingly stringent energy codes.

A single ERV can be ducted to serve multiple units, or each unit can have a dedicated one. The proper installation and sealing of the ductwork are paramount to the ERV's performance. Air leaks in the system can bypass the heat exchange core, rendering the unit inefficient and negating its intended energy-saving benefits. For this reason, these units and their ducting must be meticulously installed and tested before being concealed.

CASE STUDY 1

Odor and Noise Transmission Between Units

The authors were tasked by an existing client to investigate odor and noise transmission between units in a high rise residential building. In this building, residential units are served by a rooftop toilet exhaust fan (TEF) and in some cases an energy recovery ventilator for fresh air delivery (ERV). Either way, the bathrooms receive continuous exhaust (as opposed to flipping a switch to turn on intermittent exhaust).

The local governing code requires a minimum of 20 CFM air flow for continuous ventilation in bathrooms and 25 CFM for kitchens. Despite a test report from over five years ago showing adequate exhaust rates (and suspiciously–the exact design flow rate for almost every unit), multiple residents reported inadequate exhaust and fresh air flows to their units.

This building was designed to rely on CARs to distribute airflow from the rooftop units throughout the building. Behind every bathroom, kitchen, or fresh air vent was intended to be a CAR. Our investigation revealed mechanical dampers integral with the finished grilles were installed in lieu of CARs as a "value engineering" decision, and most were in the fully open position. Pressure therefore was not being properly distributed, and our field measurements showed that not a single vent was operating at the design airflow, and many had no flow at all – or were moving air in the opposite direction. The fresh air ductwork, intended to have branches and CARs, consisted of a single, constant-section duct running vertically through a fire rated shaft. The vents were installed directly through the sidewall of the duct, creating an unobstructed path for noise transmission between units.

Odor and noise transmission are directly linked to the ventilation system's ability to maintain designed pressure relationships as well as the configuration of the ductwork. In a properly functioning mechanical ventilation system, CARs are crucial for ensuring that each branch of the ductwork receives its intended airflow, regardless of the static pressure fluctuations in the main

lines. By maintaining a constant flow rate, CARs prevent excessive positive or negative pressure within the ductwork.

The substitution of CARs with mechanical dampers, particularly those that are fully open, created a significant systemic imbalance. Without the flow-regulating function of the CARs, the system's air flow is governed entirely by the principle of least resistance. This means that units closest to the exhaust fans are likely "over-ventilated," while those at the end of the duct runs or on lower floors are "under-ventilated" or may even experience reverse airflow–all cases that we found with direct airflow measurements.

Odor Transmission

In a properly balanced system, each bathroom is kept under negative pressure relative to the hallway or the rest of the unit. This ensures that odors are exhausted from the space and do not migrate into adjacent areas or other apartments. When the system is unbalanced, the pressure relationship is compromised. A unit that is under-ventilated can develop a positive pressure, causing bathroom odors to migrate out of the unit and into the common hallway, or worse, into a neighboring unit that is also under-ventilated.

Noise Transmission

The fully open mechanical dampers and lack of branch ductwork from the main allowed for relatively unrestricted sound transmission between units. We could clearly hear dogs barking and light conversation one and two units away in several cases through the fresh air vents. Had this system been built as designed, with CARs, smaller branch ducts, and several turns in the duct run – that same sound would have dampened to the point where it was not a problem.

A complicating factor in this building's performance was the lack of sufficient airflow at the end point of the bathroom exhaust. We measured, via duct traverses, almost 40% lower airflow than the design, meaning even if perfectly balanced the bathrooms would still not provide enough flow. We are currently working with the owner and a mechanical contractor to modify the systems, diagnose the low flow at the bathroom exhaust fan, and install CARs and alternate duct runs, but it is a long process given the sheer number (hundreds) of air outlets and inlets in the building.

Plumbing System Composition

Similar to duct systems, the sheer length (which for a tall building could be measured in miles) of plumbing systems makes them inherently susceptible to problems. A single domestic hot water riser may have hundreds of individual fittings, each of which is a potential point of failure. For cold water piping, missing insulation or damaged vapor barriers can lead do concealed condensation within walls and ceilings and long-term damage to building systems.

While water leaks from plumbing systems are the primary concern of most installers, less obvious issues with drain and vent piping can lead to difficult-to-diagnose odor issues within units and common spaces. Building drainage systems can be combined with vent systems, or require a secondary vent line depending on the jurisdiction. The concept is simple–the drainage

system needs to be open to the exterior at the "top" to avoid creating suction when fixtures are actively draining and to allow sewer gas from the municipal sewage system – the end point of the drain line–to vent out and not build up (hence the common reference to rooftop plumbing vents as "stink pipes"). These plumbing vents are concealed behind walls and above ceilings, but since they do not carry water, leaks may go unnoticed until conditions arise that create an odor problem. The following section described such an issue that the authors investigated and diagnosed.

CASE STUDY 2

11th Floor Sewer Smell

Even the most luxurious residential condominiums can be affected by smells with unknown origins. The authors were called by an existing client to investigate the source of a reported "sewage-like" smell being reported by two unit owners.

Combining experience from whole-building airtightness testing (ASTM E779) and air leakage investigations using theatrical smoke (ASTM E1186), we created a custom test rig to inject smoke into the plumbing vent stack on the roof (Figure 7). In the bathroom with the strongest reported smell, we concurrently used a blower door to negatively pressurize that space (Figure 8).

Figure 7: Rooftop waste stack setup.

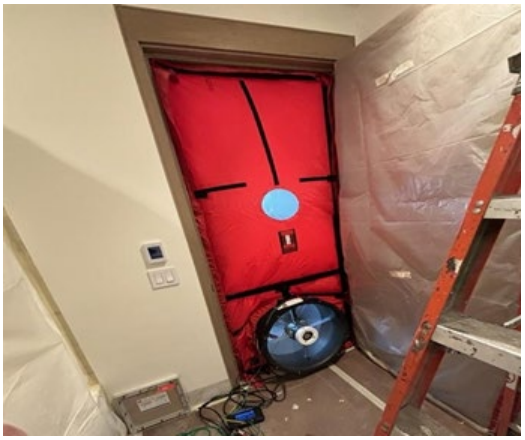

Figure 8: Blower door.

By balancing negative pressure in the bathroom with the introduction of smoke into the stack from the roof, we were able to locate a discontinuity in the waste stack behind the bathroom wall (Figure 9). The client engaged a contractor to fix the issue, and following the repair, the resident reported the sewer smell was gone (Figure 10). This is a fairly simplified version of the process, which did require multiple rounds of testing and probe openings on the interior. The relative difficulty of locating the pipe breach, which appears to have resulted from an installer simply not

making a proper connection, highlights the importance of construction oversight for the "guts" of a building.

Figure 9: Pipe leak discovered.

Figure 10: Pipe leak fixed.

CONCLUSIONS

Effective quality control is the lifeblood of urban infrastructure, where systems get buried behind multiple layers of finishes very soon after installation. While proactive measures like designing for maintenance are crucial for ensuring long-term accessibility, the reality is that not all systems can be designed to be readily accessible for future work. This is where meticulous oversight during construction becomes paramount. As this paper has demonstrated through its case studies, a small leak in a waste stack or the seemingly minor substitution of a CAR with a mechanical damper can lead to chronic and costly problems like sewer smells and noise transmission.

Just as a well-trained quarterback studies every play and a coach prepares for every scenario, successful projects depend on a rigorous process of detailed design, careful shop drawing review, and preinstallation conferences. These practices serve as a critical defense against future failure, ensuring that potential issues are identified and resolved long before they are concealed behind finishes.

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Residential Heat Pumps: An Update

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ABSTRACT

Heat pump technology has been used for several decades in residential applications. Recently this technology has gained popularity and heat pumps sales have exceeded gas furnace sales for residential central heating in the United States. Advantages of heat pumps include high efficiency and no direct use of fossil fuels lowering the carbon footprint. Traditionally heat pumps have been air-to-air heat units, but new applications include air to liquid units and hybrid systems that combine traditional gas furnace with heat pumps. This study reviews the current products available and reviews their applications.

INTRODUCTION

Although there are several types of heat pumps, this article focuses on residential heat pumps that use outside air as the source of heat or cooling. Heat pumps use compressors which circulate refrigerant through coils. The coils are exposed to air circulated by a fan. They only use electricity, so they do not directly use any fossil fuels. Heat pumps that extract ambient heat from the ground or air for circulation in radiant heat systems are among the principal solutions for the decarbonization of residential heating (Theodoros Arvanitopoulos, 2025).

Heat pumps can be very cost effective for residential heating in warmer climates. However, performance decreases with outdoor temperatures as shown in Figure 1. All heat pumps have minimum low temperature of operation. The formation of frost on the outdoor coil occurs when moisture in the incoming air meets the surface of the cooler coil, leading to the deposition of water vapor, visible as frost. In the short term, frost formation will result in a reduction in the effectiveness of the equipment. Long term buildup of frost will result in physical damage to the equipment (Mohammad Rafati Nasr, 2014). This phenomenon occurs when heat pumps are operated in heating mode with a relative humidity higher than 65% and an ambient temperature ranging from 19°F to 41°F. (Mei, Domitrovic, Chen, and Kilpatrick, 2022).

This study reviews cost analysis and optimization of the types of heat pumps, stages of heat

pump operation, and hybrid heat pump systems. This study informs educators, homeowners, and contractors about the diverse types of heat pump equipment and the economics associated with them.

TYPES OF HEAT PUMPS

There are three types of air source systems for residential applications, air-to-air heat pumps, air-to-water heat pumps, and mini split systems. All three systems have an outdoor compressor/condenser and have a fan and coil indoors. Geothermal, also known as ground source systems, also uses heat pump technology and has residential applications but is outside the scope of this study.

Central air-to-air heat pump equipment is like traditional residential air conditioning equipment. An evaporative coil is in the furnace plenum, and a cube shaped condensing unit is located outside the structure. In heating mode, heat pumps use the refrigeration cycle to extract heat from a colder air source to heat indoor space. These systems can be inverted to extract heat from buildings like traditional air conditioning systems.

Traditional air-to-air heat pumps are the most common residential heat pump application. Air-to-water heat pumps use the refrigeration cycle to produce hot or cold water. In the heating mode, hot water circulates through fluid heat emitters such as in-floor heating systems, radiators, or fin tube baseboard radiators. In the cooling mode, cool water circulated through coils in an air handler. Unlike traditional air-to-air systems, both the evaporator and coil are outside the structure.

The best application for air-to-water heat pumps is for homes that have boiler systems and that have fluid heat emitters. They are capable of air conditioning with the addition of an air handler and ductwork. Mini split systems, also known as ductless systems, transfer refrigerant to a wall unit which has a coil and a fan. These systems circulate refrigerant to a wall unit without duct work. These are air-to-air systems that perform similarly to central air-to air systems that use a central coil, fan, and ductwork. Each wall unit has a remote control for operation.

HEAT PUMP STAGES

Heat pump stages refer to the number of heating output levels a heat pump can produce. Heat pumps can be single-stage, two-stage, or multi-stage, commonly referred to as variable speed. A single-stage heat pump is either fully on or off while a two-stage heat pump can operate like a single-stage heat pump at full capacity or at about 65% capacity. By having two stages, the heat pump meets demand by running longer during cycles. Variable speed heat pumps operate anywhere between 30% and 100% capacity.

The advantages of the two-stage and variable speed heat pump are that the cycles are longer; startups occur less often which increase efficiency. Another advantage is that the equipment produces less noise than single-stage, control humidity better in the cooling cycle, and has less

indoor temperature swings (Energy Star, 2022).

In a case study in Knoxville, Tennessee, researchers compared single-stage to variable speed heat pumps. The study showed that when comparing data for outdoor temperatures, the variable speed heat pump used 17-38% less power during heating and 34-38% less power during cooling conditions than the single-stage heat pump (Electric Power Research Institute, 2014).

COLD CLIMATE HEAT PUMPS

According to Energy Star V6.1, cold climate heat pumps are required to have a Coefficient of Performance (COP) of 1.75 at 5°F and a heating capacity at 5°F greater than 70% of that at 47°F. (Energy, 2021) To improve the low temperature COP values, economizer vapor injection and internal heat exchangers can be added to the air source heat pumps.

A study conducted by Yin et al. (2016) comparing the performance of air-source heat pumps using economizer vapor injection and internal heat exchangers in cold regions. According to the study, the conventional air source heat pump had a COP of 1.63 at -13°F. With the economizer vapor injection, the COP was 1.89 at -13°F and with an internal heat exchanger the COP was 1.96 at - 13°F (Jin, Yin, Pan, Yang, and Cao, 2016).

EFFICIENCY

Heat pumps can extract heat or cold without consumption of fossil fuels. This allows for heat pumps to produce more heat than the electricity they use. They can also reduce the carbon footprint if the electricity comes from a renewable source. The COP is the amount of heat units that are produced in comparison to electricity used. For example, if a heat pump produces three units of heat using one unit of electricity, the COP is three. In the heating mode, heat pump COP decreases with outdoor temperature. Each heat pump performance is slightly different, but heat pumps commonly operate with a COP from 3.0 to 5.0 but the COP will drop to about 2.0 when temperatures are near 0°F to 10°F making them inefficient and no longer economical or in some cases able to operate.

HYBRID SYSTEMS

The need for supplemental heat in colder climates has increased the demand for hybrid systems. Hybrid heat pump systems use heat pumps to produce heat when temperatures are ideal and alternative fuels when it means economic sense. The most common alternate heat sources are fossil fueled furnaces and electric resistive heaters.

Each fuel type has its associated cost per British Thermal Unit (BTU) and equipment cost. Based on current energy prices, electricity is by far the most expensive in terms of cost per BTU, making operational costs high as shown in Table 1. However, electric resistive heat has the lowest equipment cost. For residential construction that has an existing furnace, the furnace can be used as a backup heat source.

Break-even analyses for hybrid systems should be calculated regularly to determine the temperature at which the alternative fuel should be used, especially when significant fluctuations in fuel prices occur.

COMPARING ENERGY COSTS

Operating costs of residential heating systems including heat pump systems can are calculated by determining cost per British Thermal Units (BTUs). BTUs/hour are the units used in determining heating and cooling loads and sizing equipment. For instance, a northern climate house may have a heat loss of sixty thousand BTUs/hour in northern climates when temperatures are near 5°F. It is common to use the unit of one million BTUs (MBTU) for comparison purposes.

Using an electric rate of $0.12/Kw, the cost of one million BTUs Is $37.34.

1,000,000 BTU/ (3214 BTU/KW) = 311.13 kw

311.13 Kw x $0.12/KW = $37.34/MBTU

The break-even COP is the cost of one million BTU from electricity divided by the cost of one million BTU from an alternate heat source.

MBTU electricity/MTBU alternate fuel = Break-even COP

Using the COP graph, the changeover temperature is the temperature where the break-even COP occurs. These calculations show the cost of MBTU of a fuel oil system and the break-even COP. Assumptions include fuel cost of $2.897/gallon fuel oil and 90% efficient furnace.

1,000,000 BTU/138690 BTU/gallon/0.9 = 8.011gallons
8.011gallons x 2.897/gallon = $23.20/MBTU
37.34/23.20 = 1.61 is the break-even COP

These calculations show the cost of MBTU for a $1.851/gallon propane system and 95% efficient furnace.

1,000,000 BTU/92,000 BTU/gallon/0.95 = 11.44 gallons
11.44 gallons x $1.851 = $21.17/MBTU
37.34/21.17 = 1.76 is the breakeven COP

For natural gas at 11.37/MCF and 95% efficient furnace,

1 MCF = 1,036,000 BTU
1,000,000 BTU/1,036,000 BTU = .96525
0.96525 x 11.37 = $10.97/BTU
37.34/10.97 = 3.40 is the break-even COP

Table 1. COP Breakeven Analysis.

Fuel	**Electricity**	**Fuel Oil**	**Propane**	**Natural Gas**
Units	Kw	Gallons	Gallons	MCF
Cost/Unit	0.12	2.879	1.851	11.37
Cost/MBTU	37.34	23.2	21.17	10.97
Efficiency of Furnace	1	0.9	0.95	0.95
Break Even COP	1	1.61	1.76	3.4
Break Even Temp. F Single-Stag	N/A	3	5	46
Cold Climate	N/A	*See Note*	*See Note*	40

Note: The break-even temperature for the cold climate heat pump was below the lowest operating temperature of - 13°F.

Table 1 shows that at current energy prices, homes with a single-stage heat pump and fuel oil as an alternative fuel source. Fuel oil should be used at temperatures below 3°F. For propane, this temperature is 5°F. If a cold climate heat pump is used with fuel oil or propane as the alternative fuel, the heat pump should be until it no longer works Since the BTU cost of natural gas is low, the breakeven temperature is much higher at 46°F. Therefore, with natural gas as the alternate heat source it is more economical to turn off the heat pump and use the natural gas furnace at temperatures below 46°F. It is important to note that energy prices will vary based on time of year and location.

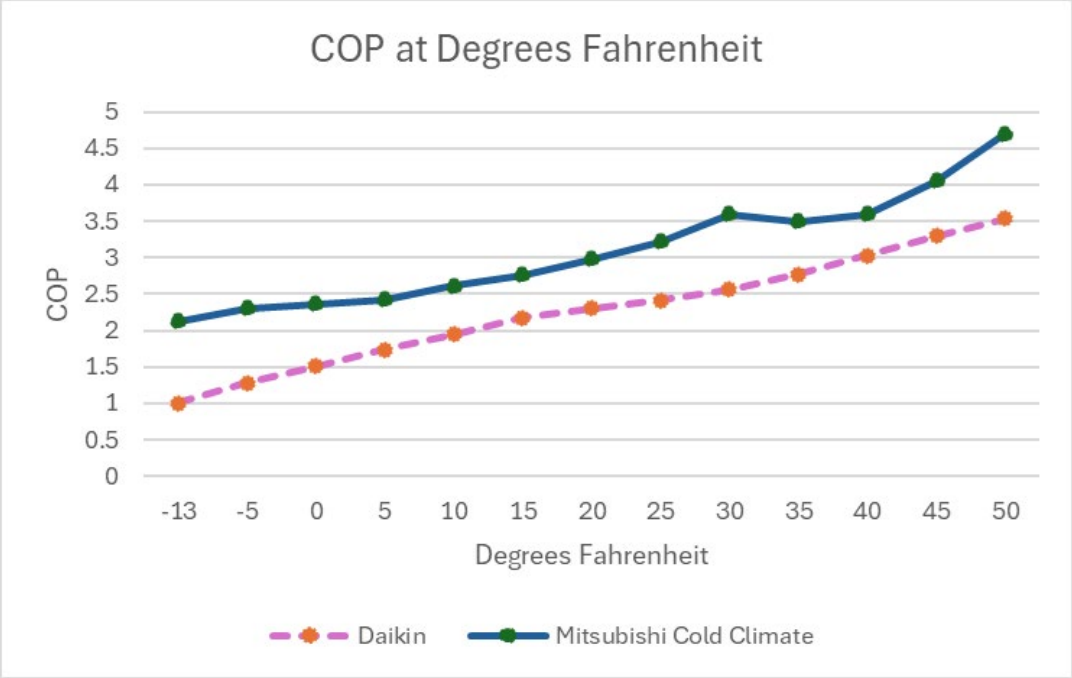

Figure 1. COP at Degrees Fahrenheit from -13°F to 50°F.

ENERGY COST COMPARISONS

Calculations were completed to compare energy usage and costs. Several assumptions were made to conduct the calculations. Heat loss calculations were completed for an 1,800 sf house in Eau Claire, Wisconsin using a design temperature of -10°F to find BTU/hr/ft^2. The temperature was assumed to be constant throughout the month and the COP used was for the average temperature.

In Table 2, the heat loss in BTU/hr/ft^2 was multiplied by 1800 square feet and by the number of hours in a month to find MBTU/month which was multiplied by $/MBTU for find monthly fuel cost. For the heats pumps, the COP was found for the monthly average temperature and used to determine $/MBTU and monthly fuel cost.

Table 2 shows the results of the calculations. With the Daikin model DH6TED90, the estimated heating season energy cost is $1809.92. Compared to the savings for fuel oil and propane and $1004.24 and $758.00 respectively over the coldest six months of the year. With the Mitsubishi Hyper heat Model MXZ-3C30NAHZ Cold Climate Heat Pump the energy saving for fuel oil and propane were $1419.16 and $1170.89 respectively.

When comparing natural gas seasonal cost to the Daikin heat pump it would cost $479.26 more than having one the heat pump. This supports the use of a hybrid system the allow the operation of a natural gas in colder temperatures. Use of the Mitshbishi heat pump would cost $87.54 in

comparision to natural cost. This value is lower than the Daikin model because the COP are higher for the lower temperatures.

Table 2. Daikin Air-To-Air Heat Pump Model DH6TED90.

	BTU/ Hr/ Square ft	MBTU / Month	Average Temp	Daikin COP	Heat Pump $MBTU	Heat Pump Cost/Month	Electricity Cost/Month	Fuel Oil Cost/Month	Propane Cost/Month	Natural Gas Cost/ Month
Oct.	7.46	10	48	3.45	$10.82	$108.23	$373.40	$232.00	$211.70	$109.70
Nov.	12.21	15.8	34	2.72	$13.73	$216.90	$373.40	$366.56	$334.49	$173.33
Dec.	16.8	22.5	20	2.3	$16.23	$365.28	$840.15	$522.00	$476.33	$246.83
Jan.	18.66	25	15	2.17	$17.21	$430.18	$933.50	$580.00	$529.25	$274.25
Feb.	16.7	20.2	20	2.3	$16.23	$327.94	$754.27	$468.64	$427.63	$221.59
March	12.89	17.3	32	2.64	$14.14	$244.69	$645.98	$401.36	$366.24	$189.78
April	8.14	10.5	46	3.36	$11.11	$116.69	$392.07	$243.60	$222.29	$115.19
Total						$1,809.92	$4,312.77	$2,814.16	$2,567.92	$1,330.66

Table 3. Mitsubishi Hyper Heat Cold Climate Heat Pump Model MXZ-33C30NAHZ.

	BTU/ Hr/ Square Ft.	MBTU/ Month	Average Temp	COP	Heat Pump $MBTU	Heat Pump Cost/Month	Electricity Cost/Month	Fuel Oil Cost/Month	Propane Cost/Month	Natural Gas Cost/ Month
Oct.	7.46	10	48	4.44	$8.41	$84.10	$373.40	$232.00	$211.70	$109.70
Nov.	12.21	15.8	34	3.52	$10.61	$167.61	$589.97	$366.56	$334.49	$173.33
Dec.	16.8	22.5	20	2.98	$12.53	$281.93	$840.15	$522.00	$476.33	$246.83
Jan.	18.66	25	15	2.76	$13.53	$338.22	$933.50	$580.00	$529.25	$274.25
Feb.	16.7	20.2	20	2.98	$12.53	$253.11	$754.27	$468.64	$427.63	$221.59
March	12.89	17.3	32	3.54	$10.55	$182.48	$645.98	$401.36	$366.24	$189.78
April	8.14	10.5	46	4.21	$10.55	$110.75	$392.07	$243.60	$222.29	$115.19
Total						$1,418.20	$4,529.34	$2,814.16	$2,567.92	$1,330.66

CURRENT FUEL USE FOR HEATING SOURCES IN THE UNITED STATES

As shown in Figure 1, the southeastern part of the United States primarily uses electricity for residential heating indicating extensive use of heat pumps. One reason for this is because heat pumps can meet heat demand on the coldest days without supplemental heat and provide adequate air conditioning as well. In the northeastern part of the United States, fuel oil is the primary residential fuel source while much of the Midwest uses propane. In these regions, annual

heating fuel costs are higher than in regions that use electricity to operate heat pumps or natural gas as a fuel source. These regions would benefit the most from the newer heat pump technology.

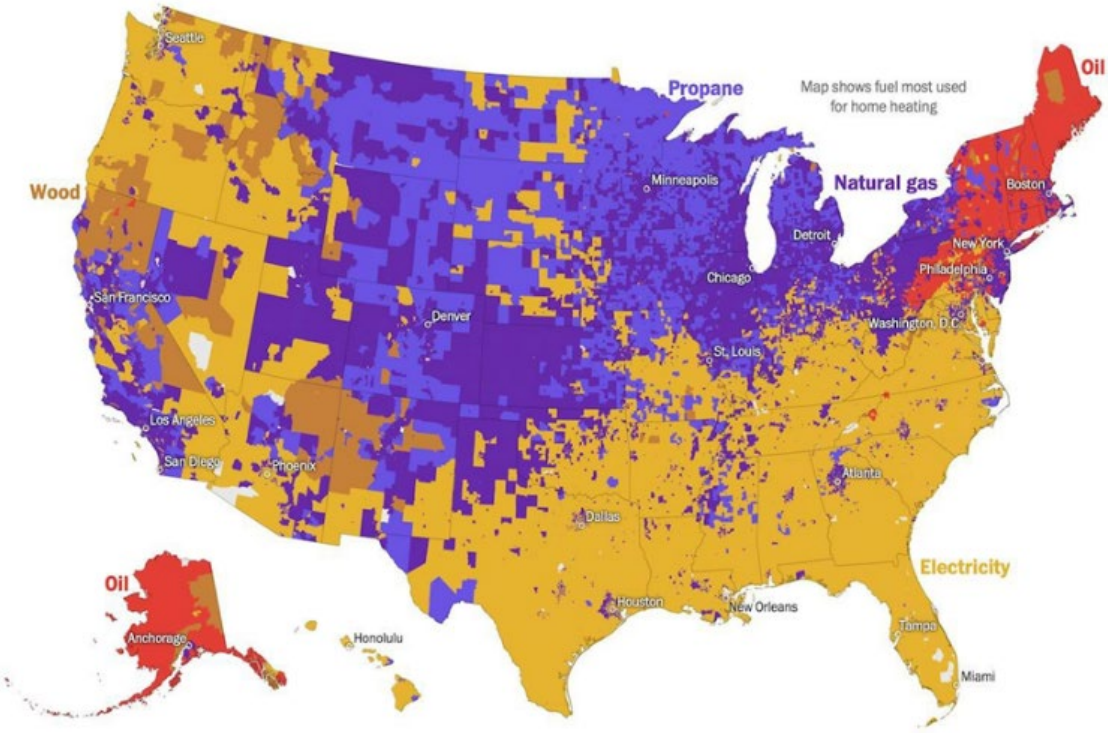

Figure 2. Predominate fuel sources by region.

CONCLUSIONS

Based on the information obtained during this study, the following conclusions have been made.

- In moderate to hot climates in the southeastern United States, traditional air-to-air heat pumps will continue to gain market share as they are the most cost-effective residential heating and cooling system in comparison to other fuels.

- In cold climates where supplemental heat may be needed, hybrid systems will gain market share especially where propane and fuel oil are used.

- Fuel prices will have an impact on the heat pump residential market. A market surge would occur if natural gas prices increased sharply. Demand would decrease if electricity rates increased sharply.

- Air-to-water heat pumps are ideal for homes with fluid heat emitters.

• Calculations can be made to determine break-even temperatures for hybrid systems to optimize efficiency.

• Some cold climate heat pump systems are effective to –13F and can be used in much of the United States without supplemental heat.

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A Review of Residential HVAC Quality Installation and Commissioning in Efficiency Programs

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ABSTRACT

Utility programs that include incentives for residential heating, ventilation, and air conditioning (HVAC) to reduce costs and improve energy efficiency are ubiquitous across the United States. Quality installation and maintenance is required to capture the energy savings potential of these HVAC improvements. A 2018 literature review revealed that 70-90% of residential HVAC systems in the U.S. have at least one fault that impacts performance (EERE, 2018). Further, a study by the National Renewable Energy Laboratory (NREL) estimates that up to 20.7 terawatt hours of energy is wasted annually in central residential HVAC systems over a no-fault baseline, due to two common faults: airflow and refrigerant charge (Winkler et al., 2020). This paper discusses the importance of quality installation and commissioning practices in the residential HVAC industry, provides an overview of quality installation related measures in technical reference manuals, and highlights efficiency programs that are paving the way for improved quality installation and commissioning practices among their contractors.

INTRODUCTION: COMMISSIONING FOR RESIDENTIAL HVAC

High efficiency HVAC systems in American homes improve thermal comfort and energy efficiency. However, recent literature suggests that up to 70-90% of residential HVAC systems have at least one performance-related fault that comes from improper installation or maintenance (EERE, 2018). Another study estimates improper airflow and refrigerant charge faults waste up to 20.7 terawatt hours of energy in the U.S annually (Winkler et al., 2020).

To address this issue, HVAC professionals are leveraging industry-developed quality installation protocols and system commissioning. Quality installation refers to the comprehensive implementation of industry-recognized best practices when setting up residential HVAC systems. This includes proper equipment sizing, ductwork design, and placement, as well as

verification of refrigerant charge, airflow, and system controls. Commissioning expands upon these steps by incorporating active performance testing and adjustments to ensure the system operates as designed and achieves optimal efficiency. While some commissioning tasks are embedded within quality installation protocols, commissioning provides a deeper level of system validation and refinement. The practice of commissioning is more prevalent in the commercial buildings sector; however, it is rarely performed in the single-family residential sector–leading to wasted energy, higher energy bills, and reduced equipment reliability. In residential contexts, commissioning is typically conducted by the HVAC contractor, contrasting with the specialized third-party approach more common in commercial buildings.

Efficiency programs that incentivize high-efficiency HVAC equipment can improve outcomes by broadening quality installation and commissioning practices among contractors. Because these programs often establish contractor networks and set incentive requirements, they are uniquely positioned to influence and improve industry installation practices regionally. Historically, these programs have prescriptively incentivized higher efficiency HVAC equipment. However, poor installation of this equipment can lead to unrealized energy efficiency. By encouraging contractors to conduct proper system testing and verification for every installed system, programs can ensure their participants are receiving the thermal comfort and efficiencies they expect.

This paper discusses how broader adoption of quality installation and commissioning can provide more assurance of efficiency programs' ability to provide energy security and savings; provides a review of quality installation measures in technical reference manuals; and finally, highlights residential efficiency programs with quality installation embedded into their incentive structures.

HVAC SAVINGS IN ENERGY EFFICIENCY PROGRAMS

Energy efficiency programs provide savings benefits to both utilities and residential customers. By providing rebate or financing incentives for customers to overcome barriers to entry, they help to increase market adoption of higher efficiency systems that aid in balancing the grid, leading to greater energy security and lower utility costs. These same programs, though, face challenges in potentially falling short of providing the systems' expected thermal comfort and energy efficiencies.

In a paper on the uncertainties of energy savings from HVAC maintenance measures, Heinemeier et al. (2012) discuss the variables that can impact the success of HVAC maintenance programs achieving savings for residential and small commercial buildings. These elements can also apply to the uncertainties surrounding HVAC installation programs for residential buildings. In particular, the authors highlight several reasons that maintenance measures can provide energy savings but that end up not providing the intended savings to utilities and customers. These include program verification and incentive design; adherence to process; types of testing instruments used, the accuracy and calibration of instruments, instrument placement, and the ease of using instruments; the system's condition and age, and the environmental conditions

during system testing; and finally, the contractor's business model, their technicians' training and skill level, integrity, motivations, and attention to detail, (Heinemeier et al., 2012). Many of these factors can be addressed by adding requirements for quality installation and verification in energy efficiency programs.

Industry leaders have developed protocols and guidance for residential HVAC quality installation that include elements commissioning to ensure systems are being installed and commissioned correctly. These include Air Conditioning Contractors of America (ACCA) HVAC Quality Installation, ACCA Quality Installation Verification Protocols, RESNET/ACCA 310, and ASHRAE 221 (Valoria et al., 2024). Adoption of these quality installation and testing protocols among HVAC professionals are still not industry wide. Broader incorporation and use of these protocols and guidelines in energy efficiency programs' requirements could help to deliver the anticipated efficiencies of newly installed and maintained HVAC systems.

REVIEW OF TECHNICAL REFERENCE MANUALS

Technical Reference Manuals (TRMs) outline procedures, methods for calculating energy savings, and measurement and verification steps used by efficiency programs. We reviewed TRMs from various states and regions across the U.S., focusing on quality installation (QI), quality installation verification (QIV), and tune-up measures for vapor-compression based residential HVAC systems. Duct sealing and insulation measures were also noted but not studied in detail. Some TRMs contain measures with titles specifically referring to QI or QIV, however several TRMs have language regarding QI and QIV embedded within their residential HVAC measures. Best judgement was used to appropriately categorize these as QI or QIV measures. For this analysis:

- QI refers to the requirement for contractors to follow and document compliance with industry-accepted installation protocols,

- QIV refers to verification of quality installation, typically through digitally recorded in-field performance testing, and

- tune-up refers to optimization of existing equipment, often including coil cleaning, filter change, refrigerant charge adjustment, and airflow adjustment.

QI offers an improvement over prescriptive residential HVAC measures by incentivizing both higher efficiency equipment and proper installation of equipment. Often, QI is implemented in programs through requiring a form with key equipment information and measurements (e.g., AHRI number, refrigerant superheat/subcooling, airflow, external static pressure). Since these forms are manually filled by the installing contractor, this introduces an opportunity for human error, or in some instances 'gaming' the program by entering values that the contractor knows will pass without taking measurements. In addition, QI measures require review from program implementation staff that may not have the experience or time necessary to thoroughly interpret the QI reports. QIV offers a solution to these problems by requiring in-field testing and

measurements on every installation, often using digital diagnostic tools and software. The requirement of measurements directly recorded from digital tools reduces the risk of contractors gaming the rebate program and software-based verification reduces burden on the program implementation staff.

Table 1 provides an overview of residential HVAC QI, QIV, tune-up, and duct sealing and insulation measures across the 27 TRMs reviewed. Among these TRMs, QI measures are included in 8 (approximately 30%), QIV measures are included in 3 (approximately 11%), tune-up measures are included in 18 (approximately 67%), and duct-related measures are included in 21 (approximately 78%).

Savings factors used for energy and peak demand savings calculations for QI, QIV, and tune-ups, are also included in Tables 2 and 3. For cooling-only equipment, such as central air conditioners, energy savings is calculated using average equivalent full load cooling hours, equipment capacity and cooling efficiency, and savings factor. For equipment that also provides heating, a similar equation is used with average equivalent full load heating hours, equipment capacity, heating efficiency and savings factor. For most QI, QIV, and tune-up measures, a single savings factor is provided, but in several separate savings factors are provided for cooling energy, heating energy, and peak demand savings calculations. Across all TRMs reviewed, tune-up savings factors ranged from 1-12.1% and QI/QIV savings factors ranged from 5 to 22% for cooling, 5 to 11.8% for heating, and 5 to 20% for peak demand. For tune-ups, five TRMs (Arkansas, Hawai'i, Missouri, New Mexico, and Louisiana) provide a method for calculating energy savings based on pre- and post- energy efficiency measurements.

Incremental cost for QI, QIV, or tune-up measures are included in Tables 2 and 3. Typically, these costs were estimated through surveying local contractors. For tune-up measures, incremental costs range from $122 to $225; however, four TRMs (Iowa, Illinois, Indiana, and Minnesota) mention that the actual cost of the tune-up should be used instead. Incremental costs for QI and QIV range from $100 to $330.

Table 1. Summary of QI, QIV, Duct, and Tune-up Measure Coverage in TRMs.

State	Arkansas	Arizona	California	Colorado	Connecticut	Hawaii	Iowa	Illinois	Indiana	Massachusetts	Maine	Mid-Atlantic[4]	Minnesota	Missouri	New Hampshire	New Jersey	New Mexico	New York	Ohio	Pennsylvania	Pacific Northwest[5,6]	Rhode Island	Tennessee	Texas	Vermont	Wisconsin	Louisiana
QI		✓	✓[1]	✓[2]			✓[7]	✓[7]	✓[7]				✓							✓[3]							
QIV					✓					✓												✓					
Ducts	✓		✓		✓		✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Tune-up	✓					✓	✓	✓	✓	✓			✓	✓		✓	✓	✓	✓	✓		✓	✓	✓		✓	✓
(Reference)	(APCS, 2024)	(ACC, 2024)	(CTF 2025)	(COPUC, 2024)	(DPUC, 2025	(HE, 2024)	(IUC, 2025)	(ICC, 2025)	(IURC, 2017)	(Mass Save, 2022)	(EMT, 2024)	(MATRM, 2022)	(MN DOC, 2024)	(MOPSC, 2017)	(NHPUC, 2021)	(NJCEP, 2024)	(NMPRC, 2025)	(NYDPS, 2025)	(PUCO, 2020)	(PA PUC, 2024)	(NPCC, 2020)	(RI EERMC, 2022)	(TVA, 2023)	(PUCT, 2023)	(VDPS, 2023)	(PSCW, 2025)	(ENO, 2023)

Notes

1. No reference to quality installation in residential HVAC measures; however, measures require Title 24 compliance which includes quality installation and commissioning related tests.
2. HVAC measures reference required program specific quality installation guidelines.
3. Includes 'Proper Sizing Factor' in HVAC energy saving algorithms which accounts for proper sizing and installation practices. This is not available on midstream delivery options.
4. The Mid-Atlantic TRM covers Maryland, Delaware, and District of Columbia.
5. The Regional Technical Forum covers Washington, Oregon, Idaho, and Montana.
6. Previously implemented the Performance Tested Comfort Systems (PTCS) program as part of the Residential Heating and Cooling Controls, Commissioning and Sizing measure; however these measures were sunset in 2020.
7. Cooling and/or heating efficiency is derated if QI is not completed.

Table 2. Savings Factors and Incremental Costs for TRM Tune-up Measures.

State	Savings Factor	Cost per unit
AR (APSC, 2024)	Varies 1,2	-
HI (HE, 2024)	8%, (92% adj. factor for post tune-up run time)	-
IA (IUC, 2025)	7.5% cooling, 2.3% heating	actual cost
IL (ICC, 2025)	5%	$225 or actual cost
IN (IURC, 2017)	5%	$225 or actual cost
MA (Mass Save, 2022)	5%	-
MN (MN DOC, 2024)	5% (coil cleaning and filter), 12.1% (charge and airflow)	$175 or actual cost
MO (MOPSC, 2017)	Varies2	$175
NJ (NJCEP, 2024)	5%	-
NM (NMPRC, 2025)	Varies2	-
NY (NYDPS, 2025)	Varies1	-
OH (PUCO, 2020)	5% (2% demand)	$175
PA (PA PUC, 2024)	5%	-
RI (RI EERMC, 2022)	5%	$175
TN (TVA, 2023)	1%	-
TX (PUCT, 2023)	5%	-
WI (PSCW, 2025)	7.40%	$122
LA (ENO, 2023)	Varies2	$175
Notes: TRM provides a table for calculated efficiency improvements based on precent over- or under-charge for fixed orifice and TXV metering devices. Uses direct site measurements of pre- and post-tune up EER		

Three methods for including QI/QIV were identified in the eleven TRMs that contained QI/QIV (Table 3), including: 1) requiring QI/QIV within the common residential HVAC measures, 2) derating equipment efficiency in the common residential HVAC measure unless QI/QIV is completed, and 3) providing additional savings through an independent QI/QIV measure. Five of the eleven TRMs included an independent measure:

- Arizona – Equipment Replacement with Quality Installation
- Connecticut – Quality Installation Verification
- Massachusetts – Central AC Quality Installation Verification, Heat Pump Quality Installation Verification, Ductless Mini-Split Heat Pump Quality Installation Verification
- Minnesota – Central AC/ASHP Quality Install Additional Savings
- Rhode Island – Mini Split Heat Pump QIV, CoolSmart AC QIV ES, CoolSmart HP QIV ES

Table 3. Savings Factors and Incremental Costs for TRM QI and QIV Measures.

State	QI	QIV	Savings Factor	Cost per unit
AZ (ACC, 2024)	✓		10% (20% for peak demand)	$330
CA (CTF, 2025)	✓1		-	-
CO (COPUC, 2024)	✓2		-	-
CT (DPUC, 2025)		✓	11% (heating), 22% (cooling)	-
IA (IUC, 2025)	✓		11.8% (heating), 10.5% (cooling)	$150
IL (ICC, 2025)	✓		10% (heating), 10% (cooling)	-
IN (IURC, 2017)	✓		10% (heating), 10% (cooling)	-
MA (Mass Save, 2022)		✓	5%	-
MN (MN DOC, 2024)	✓		10% (8% for peak demand)	$250
PA (PA PUC, 2024)	✓3		-	-
RI (RI EERMC, 2022)		✓	5%	$175 (CAC), $100 (MSHP)

Notes:

1. No reference to quality installation in residential HVAC measures; however, measures require Title 24 compliance which includes quality installation and commissioning related tests.

2. HVAC measures reference required program specific quality installation guidelines.

3. Includes 'Proper Sizing Factor' in HVAC energy saving algorithms which accounts for proper sizing and installation practices. This is not available on midstream delivery options.

Additional insights were noted during review of the TRMs. Connecticut's QIV measure has the highest energy savings factor, but unlike other measures it requires duct sealing to be performed. California's measure does not mention quality installation explicitly, but it does require compliance with Title 24 which contains aspects of quality installation, such as proper sizing, refrigerant charge, and airflow verification. Other than how the QIV measures were titled, there does not appear to be any characteristics that greatly differentiate them from the QI measures; however, it may be common knowledge among program implementers that QIV programs typically require diagnostic software.

This review only summarizes related measures in TRMs, however further research is necessary to understand their effectiveness in programs. In addition, better understanding of the advantages and disadvantages of the three methods for incorporating QI/QIV into TRMs would help inform future TRM workpaper submissions. Although TRMs help provide valuable information for utility-designed incentives, programs are where energy savings happen. The next section highlights program designs that incorporate a range of quality installation, commissioning, and tune-up practices.

REVIEW OF EFFICIENCY INCENTIVE PROGRAMS

TRMs provide guidance to utilities in the design of their HVAC incentive programs and savings calculations. However, utilities ultimately have autonomy in their program and incentive offerings. QI and QIV measures are not common among many utilities' programs. According to the Consortium for Energy Efficiency (CEE) 2024 Residential HVAC Program summary, only 3% of CEE members offer Quality Installation measures (CEE 2024).

Some residential HVAC incentive programs inspect a small percentage of installations; however, these are often only visual inspections and do not include performance testing. Some programs require HVAC systems to be installed by contractors from the program's verified contractor network for the customer to be eligible for an incentive. These contractor networks list contractors who have been vetted by the program by having the required business licenses and certifications, or who have gone through program-specific training. While some of these certifications or training cover the importance of quality installation and commissioning, it does not guarantee that contractors will follow best practices on every job, nor does it guarantee that the individual installing the equipment has gone through the required training. Other programs that are more cognizant of the importance of quality installation and commissioning include specific system measurements be checked off or manually filled in on rebate forms, but these also run the risk of human error or gamification on the contractors' end to speed up the process, ensure the system qualifies for the rebate, or both.

We reviewed utility incentive programs across the U.S. and communicated with five program implementers about their experiences incorporating QIV and commissioning, and quality tune-ups. Similar to how we have defined QIV and tune ups in TRMs, we define QIV and quality tune-ups as efficiency programs by the following:

• QIV refers to verification of quality installation, typically through digitally recorded in-field performance testing, with digitally connected, geotagged, and recorded system measurements, or photo documentation of system installation and measurements, and

• Quality tune-up refers to optimization of existing equipment, often including coil cleaning, filter change, refrigerant charge adjustment, and airflow adjustment, which is digitally recorded or documented via photos or digitally connected system measurements.

Nine utility programs showcase unique and innovative quality installation and commissioning requirements for contractors to participate in residential HVAC incentives, and two programs upskill participating contractors through access to discounted tools and training.

Cedar Falls Utilities Residential HVAC Quality Installation Program, Iowa
In Iowa, where there are QI and tune up measure requirements in the Iowa TRM, Cedar Falls Utilities (CFU) introduced its Residential HVAC Quality Installation Program in 2025 as a strategy to transform the local residential HVAC workforce. Previous iterations of their residential HVAC incentive programs required a simple online submission form with system information, efficiency ratings, and measurements, which led to occasional issues and complaints from customers about improperly installed system performance after project completion. In response, CFU moved towards QIV reporting with a digital diagnostic and commissioning platform. CFU provided training on the process and platform in December of 2024, where participating contractors were also given free sets of digital diagnostic tools to make the process of utilizing the platform as easy as possible. Participating contractors are required to use digital diagnostic tools in conjunction with the platform for all new and existing HVAC projects as a quality assurance strategy, ensuring all testing procedures are vetted. All installed equipment requires diagnostic and commissioning reports. The program also lists only participating contractors on its contractor network on the utility website, offering greater visibility to customers seeking HVAC rebates (Matthew Hein and Jacob Boeschen, personal communication, July 23, 2025).

Frontier Energy's Quality Residential HVAC Services Program, California
While California's TRM does not specifically reference QI for HVAC, the TRM requires Title 24 compliance which includes tests relating to quality installation and commissioning. Frontier Energy launched the Quality Residential HVAC Services Program in 2025, with the intent to transform the residential HVAC workforce by encouraging industry practices aligned with quality installation, quality maintenance, and energy efficient technologies. The program helps contractors in their businesses to differentiate between services to justify premium fees and incentivizes improving HVAC service quality within the residential sector. The program provides different tiers of participation, with training and resources to achieve external industry-recognized certifications (Parker Wall, personal communication, July 21, 2025).

The tiers determine the participating contractors' eligibility for certain incentives related to system inspections, tests, design, adjustments, and service completion: Tier 1 being the baseline of required measures serviced to the customer, and Tier 2 being the most comprehensive set of

measures provided. The program offers categories of Quality Bid, Quality Install, Quality Maintenance Call, and Quality Maintenance Set Up. Quality Bid means the contractor does their due diligence during the bid phase, going beyond responding to a customer's needs but also providing a professional assessment of what would be beneficial. Quality Install includes the proper design and installation for HVAC at an existing building, conducting all proper calculations, testing procedures, and adjustments to ensure it is a working system upon installation. Quality Maintenance Call encompasses routine annual or bi-annual assessment of the system's operation and condition, with maintenance activities to make minor adjustments or fixes. Quality Maintenance Set Up is a more thorough maintenance assessment that includes commissioning services of setting baseline performance, conducting tests, and making system adjustments.

For contractors to receive rebates for any of these categories and tiers, they must complete comprehensive checklists and calculations for each service line item and are required to upload photo documentation of specific design, adjustments, and service completion tasks for verification. All participating contractors are listed in a directory, which customers can access when choosing an HVAC company for installation or maintenance. Programmatically, this helps homeowners and customers identify third party verified contractors that are following quality installation and quality maintenance practices, providing greater confidence in their new or serviced HVAC systems. The program's quality installations also benefit California utilities by reducing loads to the grid.

PSEG Long Island Smart Tool Reimbursement Program, New York

Although the Public Service Enterprise Group (PSEG) Long Island's Home Comfort Program does not require its contractors to perform QI and commissioning measures for its rebates, it offers a few other incentives that upskill its contractor network with quality installation procedures. One of the main incentives provided by PSEG is its Tool Reimbursement Program, which provides qualifying contractors with reimbursements for 75% of the cost of digital smart tools for heat pumps. Tools include smart vacuums, smart probes, digital pressure gauges, charging systems with digital scales, digital manometers, and cordless power flaring tools. Contractors must complete a minimum of 10 residential incentive projects with PSEG to qualify (Joshua Ebner, email message to the author, July 1, 2025). This program runs similarly to a tool reimbursement program that was run by MassSave in 2018, which offered up to $150 reimbursement for qualifying tools, and $100-$200 reimbursement for training.

In addition to participating contractors being eligible for tool reimbursements, PSEG offers access to free training on ACCA Quality Installation procedures. HVAC Training for ACCA's Quality Installation typically costs between $99-$139 depending on ACCA membership status. Providing this as another resource for Home Comfort contractors, PSEG addresses the need for quality installations from a different approach –by removing some of the initial cost barriers contractors and technicians face to conduct quality installation and commissioning.

TECH Clean California Single Family Heat Pump Rebates, California

TECH Clean California is a state funded initiative that offers incentives for residential high

efficiency HVAC systems. TECH Clean California's HVAC rebate projects require photo documentation with the Pacific Northwest National Laboratory Quality Install Tool (QI Tool). The QI Tool is an open-source web application that expedites the installation documentation process. The tool guides the user using photo prompts to document the installation or upgrade process of a wide range of HVAC, plumbing, safety, envelope, and electrical workflows that require testing procedures. Contractors must use the QI Tool for HVAC projects where HERS testing is not required, for HVAC replacement projects to assess the existing equipment, and for HVAC projects that leave a combustion appliance remaining in the space and require Combustion Appliance Safety testing. Use of the tool provides another avenue for verification in efficiency programs that want to ensure uniform data collection while minimizing the risk of manipulated testing numbers to meet required thresholds. The QI Tool also provides the option of uploading photos directly to allow for geotagged locations of the photos. Similar to Frontier Energy's program, TECH Clean California, these rebates align with California's TRM which references Title 24 requirements.

Tucson Electric Power's Efficient Home Program HVAC Incentive, Arizona

In 2023, Tucson Electric Power (TEP) integrated a diagnostic and commissioning platform's digital reporting as a requirement for its residential contractors as part of the utility's Efficient Home Program HVAC incentives. The software is compatible with several brands of smart digital tools, providing timestamped and geotagged measurements from connected tools in its reporting system (Ian Adrian, personal communication, July 26, 2025). This reporting ensures that all testing measurements are tied to the system at the exact time and location of testing, increasing the confidence in the validity of contractor-submitted testing measurements. While other programs typically require basic information on energy efficiency ratios of installed systems, or manual checklists of certain design or testing parameters, TEP's use of this reporting goes a step beyond typical rebates by including this verification step in its process.

Tune-up Programs, Maryland

Under ICF's program design and implementation, SMECO, BGE, PEPCO, and Delmarva Power in Maryland provide free residential HVAC tune-ups for ducted central air conditioners and air source heat pumps in working condition. Contractors run the customer's system through various procedures including system performance testing, coil inspection, indoor and outdoor coil cleaning (if accessible), electrical inspection, refrigerant level inspection, and condensate draining cleaning (if accessible). Systems are eligible for tune-ups every three years. The differentiating factor between these quality tune-up programs and others is that contractors are required to use digital diagnostic tools and a diagnostic platform to perform the tune-ups (Carlos Gallardo, personal communication, March 14, 2025). Like TEP's Efficient Home Program, the contractors can receive their incentives for tune-ups only upon submitting proper digital diagnostic reports on the systems they service. These reports, while primarily utilized by ICF as the program implementer to track and collect data on the tune-ups performed, also help to ensure contractors are not just checking off measures on a rebate form without verified proof. A simplified customer-facing report is then provided to the customer to understand how their system was retroactively commissioned through the tune-up. The Mid-Atlantic TRM does not have any measures for QI, QIV, or tune-ups, so ICF's tune-up programs are on the cutting edge

by offering these incentives, which require ICF to calculate the deemed savings without guidance from a TRM.

DISCUSSION AND FUTURE WORK

Optimizing HVAC equipment through quality installation, commissioning, and tune-ups can solve the widespread problem of energy waste due to improper installation and maintenance. TRMs provide valuable information for planning, implementing and evaluating efficiency programs, so incorporating residential QI, QIV, tune-up, and duct measures should be prioritized. Of the 27 TRMs reviewed, 16 did not have a QI or QIV related measure, 4 did not have a duct sealing or insulation measure, and 7 did not have a tune-up measure, so a practical next step would be to develop workpapers for the TRMs for these missing measures. For the 8 TRMs with a QI but not QIV measure, a next step would be to consider upgrading to a QIV measure.

Connected commissioning systems are an emerging residential HVAC technology that use onboard sensors to detect installation faults and can guide the technician through a commissioning workflow (Valoria et al., 2024). As this technology evolves, it could be the next generation QI measure. This work summarizes the landscape of QI, QIV, tune-up, and duct sealing and insulation TRM measures, but further research is required to understand advantages and disadvantages of how these measures were incorporated into TRMs.

Feedback from some of the programs mentioned in this paper highlights the value of QIV and quality tune-up measures for successful program implementation. The use of tools like diagnostic and commissioning platforms has allowed programs to hold contractors accountable to a common set of metrics. In other programs, the use of QIV is also being used as a strategy to ensure quality assurance for customers by eliminating the risk of human error or “gamifying” values – an issue that had been observed by programs in the past. However, while most programs we were able to speak with found reception of QIV and quality tune-up requirements among participating contractors relatively seamless, initial transitions from other data collection platforms may require a learning curve among contractors and a substantial investment in time for successful transfer to a QIV process. One program faced difficulties in gaining traction and participation among contractors. Ongoing research will be needed to further understand the motivations and barriers for contractors’ adoption of quality installation and commissioning as common practice in the residential sector. Future work may also include a deeper dive into incentive amounts and the threshold to participation.

Delivering the expected benefits of high efficiency residential HVAC will require the effective transformation of residential HVAC industry practices. A multi-faceted approach of upskilling the workforce while also requiring more technologically advanced instruments, software, and equipment in TRM and efficiency program design will help to better ensure contractors understand the importance of quality installation and commissioning in their services.

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Panelized, Modular, and Offsite Construction

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Documenting Constructability and Quantifying Sustainability for a Concept Home That Integrates Consumer-Driven Design and Modular Construction as a Scalable Solution to "Missing Middle Housing" in Urban Settings

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ABSTRACT

Approximately 1.55 million new dwellings are needed annually through 2030 to keep pace with population growth, household formation, and the replacement of aging inventory. Demand for attainable and sustainable housing is escalating, and homebuilders must align their projects with evolving consumer needs to bridge this gap. The Picket Fence is a concept home that integrates consumer-driven design and modular construction as a replicable industry blueprint to address the urgent need for livable, constructable, and sustainable "missing middle housing" solutions in urban settings.

This scalable concept home built in Pittsburgh, Pennsylvania leverages findings from the America at Home Study, the only longitudinal consumer study tracking lasting changes in consumer behavior and home preferences since the pandemic, to account for consumer motivators in the final design. The team embraced the factory-built modular construction method to incorporate advanced building systems, enhance quality control, reduce construction waste, and minimize the home's carbon footprint. The project team documented the design and modular construction process through Rummler-Brache diagrams to aid in replicability and scalability and identified efficiencies through systems-built construction solutions. The sustainability of the concept home was quantified through an environmental life cycle assessment (LCA) of the home to estimate the embodied carbon and energy. The team conducted a comparison between different LCA software, such as the Embodied Carbon Construction Calculator (EC3), Athena, and Tally, along with process-based and bottom-up LCA using ecoinvent data through OpenLCA to provide the U.S. Department of Housing and Urban Development with a recommendation on the best approach. The team's vision is to provide a platform for scalability

across the U.S. to enable developers and builders of all sizes to capture the benefits of systems-built construction towards delivering more gratifying homes at a lower cost.

A Novel Timber Modular System for Mid-Rise Buildings

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ABSTRACT

This study introduces a novel construction system that challenges current construction models by utilizing prefabricated two-dimensional (2D) timber-frame panels and three-dimensional (3D) units as primary components of a modular system designed to address the current housing crisis. Focusing on adaptability and architectural versatility, the panels have been developed to support an industrialized production process based on standardized dimensions, CNC-controlled cutting and drilling, and automated fastening and assembly. This approach enables repeatable solutions for walls, floors, and roofs with varying structural and performance specifications. Furthermore, these panels incorporate functional layers and accommodate MEP (mechanical, electrical, and plumbing) systems, ensuring efficient and streamlined installation. Fully pre-assembled 3D modules are then produced by assembling the previously developed 2D panels in controlled factory conditions, addressing both the design requirements for the 3D elements and the specific programmatic needs. Notably, wet modules have been developed for bathroom and kitchen facilities. This system is engineered to satisfy both structural and functional requirements for residential, leisure, and health buildings while also addressing logistical constraints. Its development is facilitated through a Building Information Modeling (BIM) environment, which promotes interdisciplinary coordination, optimizes material use based on panel dimensions, and enables the automated integration of MEP systems. To ensure quality and compliance with industry standards, prefabricated panels undergo comprehensive experimental evaluation in accordance with European standardization testing protocols, assessing both mechanical and functional performance. The ultimate objective is to develop a European Technical Assessment (ETA) for each of the proposed prefabricated components.

KEYWORDS: Architecture; Modular; Prefabrication; Timber; 2D Panels.

INTRODUCTION

The use of timber in multi-story buildings has attracted significant attention over the past decade from researchers, construction professionals, and governments worldwide. Its sustainable profile, combined with structural properties such as a favourable strength-to-weight ratio, has made it an ideal material for modern structures. This growing interest has led to a rise in timber multi-story buildings, with increasing confidence in this typology (Tenório et al., 2024). Countries with a strong tradition of timber construction have quickly adopted new high-rise technologies, benefiting from their experience, trust in the material, and well-established market structures. In contrast, countries like Portugal have made slower progress.

Characterized by its robustness, lightness, ease of handling, and compatibility with industrialized manufacturing processes, timber presents itself as a strategic choice for the modular and prefabricated construction developed in this study. Moreover, the construction of prefabricated timber modules stands out as one of the driving sectors of architectural flexibility, due to its speed of execution, ease of transportation and assembly, and lower costs compared to the traditional construction system (Kouvara et al. 2023, Domingos, 2013), having been adopted and adapted to the desired solutions.

In the contemporary context, characterized by challenges such as climate change, the housing crisis, and the shortage of skilled labor, the adoption of prefabricated solutions emerges as an efficient and innovative response.

Prefabrication in construction offers key advantages. Conducted in a factory, it ensures strict quality control, enhancing predictability and precision. This efficiency shortens project timelines and cuts costs by improving schedules and productivity. Prefabrication also minimizes on-site activities, preserving component integrity and durability, and reduces labor, traffic, noise, and community disturbances. It enhances safety, reduces reliance on traditional equipment, and eliminates issues with wet processes, waste, and improper material handling, creating a more controlled indoor environment (Gallo et al., 2021). Modular construction embodies the principles of prefabrication, using a kit-of-parts approach to achieve design goals with minimal variation in building components, regardless of target programs (Howe et al., 1999). This strategy supports the growing trend of modular construction and prefabrication, highlighting the benefits of standardized, repeatable elements in the built environment (Li et al., 2023).

This study presents an innovative construction system within the “R2U Technologies” framework, balancing repetition and adaptability. The goal is to efficiently combine and reconfigure components to meet diverse architectural and functional needs, providing a fast, efficient, and sustainable solution to Portugal’s housing crisis and urban development.

SCOPE, DESIGN CONSTRAINTS AND ASSUMPTIONS

Market Target

The timber modular construction system developed in this study is designed as a strategic solution for sustainable urban development in Portugal, enabling the rapid construction of dignified, energy-efficient, and affordable spaces. Given the geographical proximity and strong commercial ties between Portugal, France, and Spain, these last two countries have also been identified as key target markets for the implementation of the system. To ensure its feasibility and scalability, the system has been developed with careful consideration of several critical factors, including the availability and market acceptance of materials, the logistical requirements for manufacturing, transportation, and on-site assembly, as well as the specific regulatory requirements and constraints in each country.

Building Scale and Applications

The system is engineered to accommodate buildings of up to four stories (ground floor plus three additional levels), making it a versatile solution for various applications. Given the project's scope, the design adopts a panelized timber-frame approach as the primary structural strategy; selected elements are assembled in the factory into volumetric wet-pods where required—hence, the system is best described as a hybrid panel-to-module solution. The intended uses of buildings constructed with this system encompass a diverse range of programs, including:

- Multi-family housing, addressing the growing demand for affordable and high-quality residential units in urban and suburban areas;
- Senior living facilities, offering safe and comfortable accommodations tailored to the needs of aging populations;
- Student residences, providing efficient and well-designed housing solutions for university and college students;
- Hotels, facilitating the development of modular, cost-effective, and rapidly deployable hospitality infrastructure;
- Hospitals, supporting the construction of adaptable and scalable healthcare facilities, particularly in response to urgent or evolving medical needs.

By integrating standardization with adaptability, this modular construction approach seeks to optimize efficiency while ensuring flexibility to meet the diverse requirements of different building types and regulatory frameworks.

Transportation

Transportation constraints arise from both the type of vehicles used and the legal regulations governing safe circulation. Given the target market, road transport is prioritized, as it sets dimensional limits not only for accommodating prefabricated elements within trucks but also for

ensuring compliance with road regulations in the designated regions. Throughout Europe, unescorted vehicles up to 2.55 meters in width are generally permitted. However, to avoid excessive restrictions on unit dimensions, the use of specialized transport for oversized loads is also considered. This requires meticulous logistics planning, including the selection of appropriate vehicles, lifting equipment, and, most importantly, the expertise necessary to ensure safe and efficient transportation throughout the entire route.

According to EU legislation 2015/719/EU, the maximum allowable dimensions and weights for national and international road transport within the EU are:

- 16.5 meters (m) in length (18.75 m for road trains);
- 2.6 m in width;
- 4 m in height; and
- 40 tonnes (t) in weight (44 t for combined transport, e.g., rail and water).

Oversized loads can also be transported, though specific requirements vary depending on the load's dimensions. Throughout Europe, Directive 96/53/EC establishes a standardized framework for the movement of abnormal loads across the 28 European states, ensuring that such transport operations are conducted safely and efficiently.

For the proposed modular system, both standard and special-dimension transport are considered to avoid excessive constraints on unit size and architectural flexibility. This dual approach enhances design adaptability while maintaining logistical feasibility.

Beyond road transport, maritime shipping has also been accounted for, with dimensions compatible with standard 20' and 40' containers. This expands the system's scalability, facilitating future market expansion through international trade.

Technology and Equipment Available

The production phase of the panels is subject to constraints imposed by the available technological and material resources, which directly impact both manufacturing efficiency and the allowable panel dimensions. To optimize production speed and ensure precision, the system will be manufactured using an advanced automated production line, specifically designed to handle, cut, and assemble its components with minimal manual intervention. This automated production line integrates multiple processing stages, including material handling, CNC cutting, robotic assembly, and quality control mechanisms. The machinery is programmed to execute precise cuts, ensuring uniformity and reducing material waste. Additionally, automated fastening and bonding processes enhance structural integrity while increasing production efficiency. Layout options (linear vs. cellular) are chosen based on forecasted volume and product mix. The entire workflow is optimized for speed and accuracy, significantly reducing lead times and minimizing human error.

As a result, the dimensions of the system's components must be compatible with the operational capacity of the machinery, which is limited to a maximum width of 3.5 meters and a length of 9 meters. These limitations define the modular configuration of the system, influencing both design decisions and logistical considerations for transport and assembly.

Material Properties and Dimensions

Beyond the constraints imposed by mechanized processing, the panels also incorporate engineered wood boards—specifically, OSB (Oriented Strand Board)—which are commercially available in standardized dimensions. These predefined sizes played a key role in material selection, panel detailing, and the modular design strategy, ensuring that dimensions align with industry standards. By optimizing panel sizing to match standard board dimensions, the system minimizes the need for additional cutting, reducing material waste, lowering production costs, and streamlining the manufacturing process.

Working with standardized materials also enhances supply chain efficiency, ensuring greater availability and shorter lead times. Additionally, optimizing panel sizes to minimize off-cuts not only reduces waste but also decreases energy consumption during production and assembly, reinforcing a more sustainable construction approach. The use of widely available materials further increases the system's adaptability across different markets, simplifying sourcing and improving integration with regional supply chains.

For the structural linear elements, standard cross-sections were carefully selected to guarantee not only material availability and cost-effectiveness but also structural reliability and ease of assembly. Opting for readily available dimensions prevents the need for excessive wood processing, which could otherwise increase production complexity and costs. The chosen dimensions—45×95 mm, 45×145 mm, 45×170 mm, 45×195 mm, and 70×220 (solid wood); and 12×280 mm (glued laminated timber)—were selected to strike an optimal balance between structural integrity, efficient manufacturing, and logistical feasibility. These standardized sections contribute to a more sustainable and scalable production process while maintaining the adaptability required for diverse architectural applications.

In terms of strength, timber from the C24 strength class is utilized (EN 338), while the thicknesses of the OSB panels vary depending on the type of panel in which they are applied (e.g., wall, floor, etc.). Moreover, specialized components, such as CLT (cross-laminated timber)-based components and linear elements, can be applied for superior performance and reinforcement in targeted applications.

METRICS

The definition of a specific architectural metric arises as a comprehensive response to the array of functional and technical requirements inherent in the various pro-grams constituting the project. The implementation of a standardized metric system facilitates the optimization of products, thereby reducing labor demands, enhancing the automation of production processes, and minimizing material waste resulting from unnecessary cuts and handling.

The metric established for this system is predicated on a regular orthogonal grid of 1.25 x 1.25 meters (Figure 1). This configuration facilitates the industrialization of the system through the standardization of components, while simultaneously pre-serving the flexibility of architectural design.

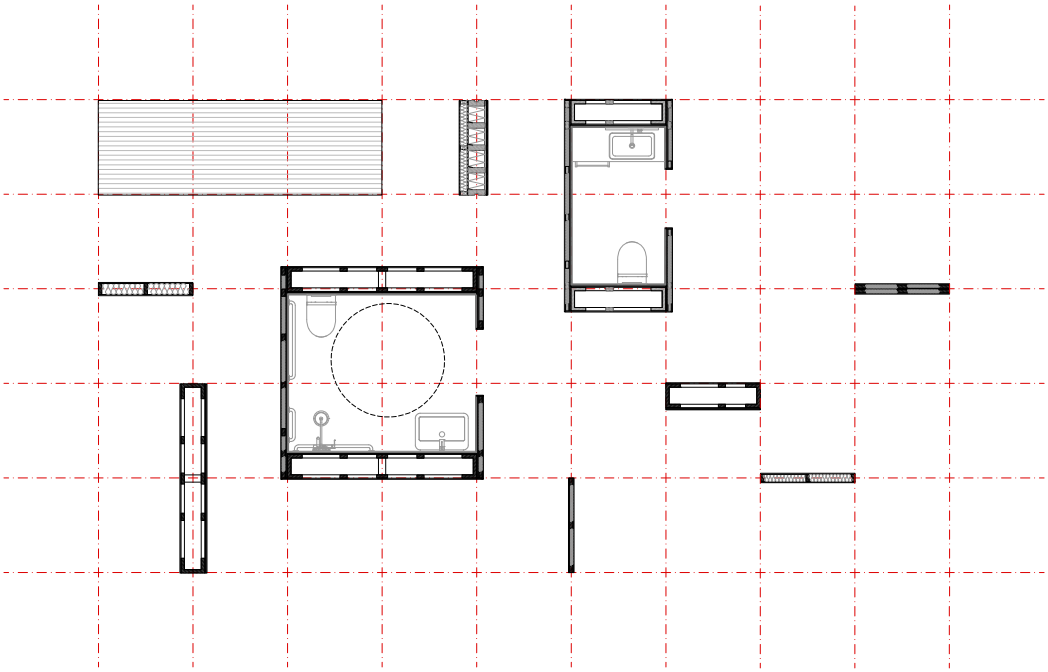

Figure 1. Rule for designing 2D and 3D components of the prefabricated system.

The wet units are designed through the aggregation of two-dimensional panels that follow this modular logic. However, some components may have different dimensions from the established standard, as consequence of structural demand imposed by transportation and installation.

The definition of a sizing rule increases the prefabrication degree, and thereby, contributing for industrialization (Staiy et al., 2008). This generic response promotes production and assembly, but also the spatial and functional organization of the project, ensuring that various regulatory requirements of each space and program, are met. This approach allows greater control over the processes, reduces construction complexity and with that ensuring compatibility between panels (2D) and units (3D) and facilitates any future adaptations.

The Construction System

The construction system is centered around the development and innovation of prefabricated components, with timber as the primary material, including floor and wall panels, designed for

both structural and non-structural applications, suitable for internal and external configurations (Figure 2).

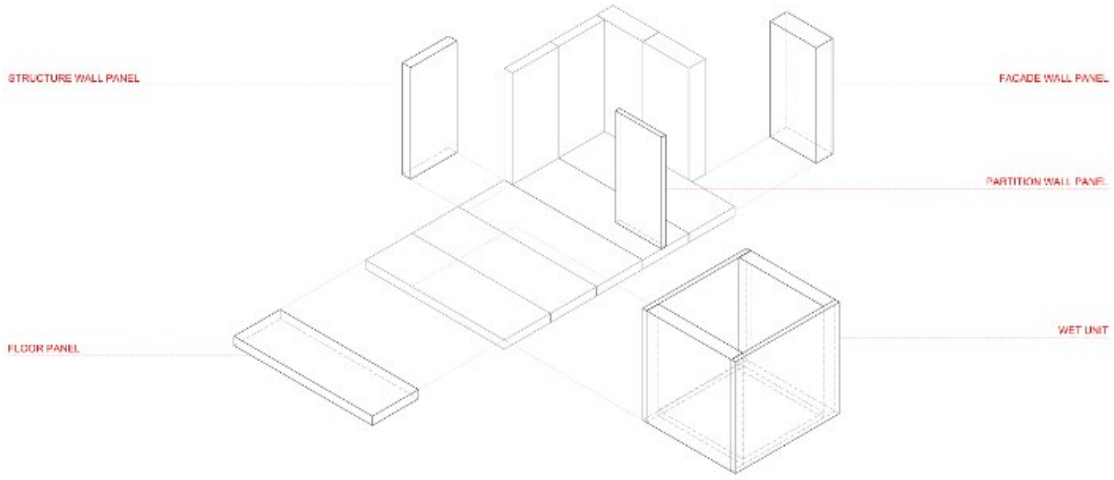

Figure 2. Axonometric view of the overall constituents of the system.

The system's component dimensions and maximal module sizes were established to match typical road transport limits and factory handling capacities; these constraints directly inform panel dimensions, connection detailing, and cranage requirements during on-site assembly. These panels integrate functional layers and accommodate MEP (mechanical, electrical, and plumbing) systems, ensuring efficient and streamlined installation.

For walls, the components include facade wall panels, structural and non-structural wall panels, and shafts. For flooring, three distinct options were created: a standard panel for dry areas, a specialized panel for wet areas, and a support panel designed specifically for wet areas. Each panel type is designed with a base composition that includes specific layering, material options, and dimensions tailored to its intended function.

Panels can be further enhanced with additional layers, allowing the system to adapt to various scenarios (e.g., climate, usage, protection requirements, maximization of prefabrication, quality control, and comfort). These reinforcements improve thermal, acoustic, fire protection, and aesthetic performance, while also enabling the integration of infrastructure.

Fully pre-assembled 3D modules are created by integrating the previously developed 2D panels, addressing both the design requirements for the 3D elements and the specific programmatic needs. For example, bathrooms and kitchens are factory-assembled as wet-pods to improve control over waterproofing and finishing quality. Factory waterproofing uses multi-layer membranes, pre-formed sloped decks with integrated drains and sealed penetrations. The design

also avoids horizontal pipe runs within pods by concentrating plumbing within core units, which minimizes leak risks and simplifies maintenance.

The system also permits individual components to be used independently, making it suitable for rehabilitation projects as well. This 2D-fundamental unit principle extends to the integration of linear structural reinforcement elements, which are also configured as flat components that align with the system's established metrics.

This system is engineered to meet both structural and functional requirements, while also addressing logistical constraints. Its development is facilitated through a Building Information Modeling (BIM) environment, which promotes interdisciplinary coordination, optimizes material use based on panel dimensions, and enables the automated integration of MEP systems. To ensure quality and compliance with industry standards, prefabricated panels undergo comprehensive experimental evaluation in line with European standardization testing protocols, assessing both mechanical and functional performance. The final goal is to develop a ETA (European Technical Assessment) for each of the proposed prefabricated component. Additionally, an Environmental Product Declaration (EPD) is generated for the final components, providing an in-depth analysis of their environmental impact and sustainability metrics.

CONCLUSIONS

The aim of this construction solution is to contribute to the development of modular timber construction by introducing a kit-of-parts system using timber-frame wall and floor panels for four-storey buildings. It demonstrates the effective integration of 2D and 3D components, highlighting the efficiency of prefabricated timber systems.

Material selection and transportation strategies were pivotal to the project's outcomes. The research addressed logistical constraints by evaluating both road and maritime transport modalities, with maritime transport restricted to 2D modular components due to dimensional limitations. The engineered wood products (EWPs) selected for the system are OSB and glulam in standardized dimensions, while, when possible, solid wood elements are also utilized. Furthermore, the automated production line was designed to accommodate components up to 3.50 × 9 m2. The spatial matrix was created through a thorough analysis of the needs for various building types, including hospitals, senior residences, student dormitories, hotels, and collective housing. By incorporating standard material dimensions and transportation constraints, a modular matrix of 7.5 × 7.5 m2 was defined.

Key findings include the successful use of pre-assembled bathroom modules for reliable waterproofing and quality control, as well as the benefits of a modular matrix system for optimizing space utilization and resource management. The deployment of EWP and modular design principles has led to significant gains in construction efficiency, materials optimization and use of renewable resources.

Future efforts should focus on performance validation through further testing, exploring design optimizations, material innovations, and advanced technologies to further enhance the sustainability, adaptability, and overall efficiency of modular construction. Currently, acoustic tests (airborne and impact sound) and mechanical tests (bending and rocking shear) on wall and floor panels are already being conducted.

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Presenting the Background for a Methodological Framework Evaluating Alternative Housing Technologies in Post-Disaster Recovery Contexts within Texas

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ABSTRACT

The increasing frequency and severity of natural disasters, in states like Texas, accentuates the need for resilient, sustainable, and affordable housing alternatives. With Texas sustaining an estimated $440 billion in disaster-related impacts from 1980 to 2024, the demand for housing that can quickly deploy and transition to permanence is growing. Existing systems, such as those deployed by FEMA post-Hurricane Harvey, reveal gaps in efficiency, cost-effectiveness, and long-term habitability in disaster housing programs.

This study aims to discuss the tailoring of multiple methodological frameworks for evaluating alternative housing technologies for disaster recovery, focusing on market-ready, scalable solutions that balance durability, affordability, and rapid deployability.

The objective is to provide background for the basis of the frameworks presented herein around the feasibility of various housing models to determine their viability for both short-term disaster response and long-term post-disaster recovery. These housing models include modular, prefabricated, kit-built, and 3D-printed structures. The methodology employs structured feasibility evaluations of each housing model. Three key impact criteria: constructability, timeliness, and cost-effectiveness are used to synthesize data extracted from companies. Data was collected through surveys from housing vendors, industry reports, and stakeholder consultations. Results of the frameworks employed will allow for a comparative analysis of the strengths and limitations of each technology as supported by constructability, timeliness, and cost scoring matrices to facilitate evidence-based decision-making. The findings highlight the potential for this research to serve as a viable option to assess alternative housing units (AHUs) to reduce recovery timelines and minimize financial waste in post-disaster scenarios.

***Keywords*:** Disaster Planning; Resilient Housing; Disaster Recovery; Affordable Housing; Sustainable Construction; Modular Housing.

INTRODUCTION

The increasing frequency and severity of natural disasters in Texas have resulted in staggering economic impacts, exceeding $440 billion between 1980 and 2024 (NCEI, 2025). Each major event leaves behind a critical and urgent need for housing, a challenge traditionally addressed by federal programs such as The Federal Emergency Management Agency (FEMA) deploying solutions like trailers and manufactured housing units (MHUs) (Roberson, 2005). However, these legacy systems have consistently demonstrated significant shortcomings. Analyses reveal the extreme costs associated with FEMA trailers, and significant health and safety oversights, such as the unsafe levels of formaldehyde present in units following Hurricane Katrina (Verderber, 2008).

Additionally, FEMA response effectiveness is often curtailed by the current temporary housing limitations of their existing response programs such as Temporary Sheltering Assistance (TSA) and the Individual Housing Program (IHP) (Roberson, 2005). The long-term structure of direct assistance through these programs reveals a model that is both expensive and ill-suited for helping communities transition to in place permanent recovery. These failures underscore that the existing approach to post-disaster housing is often inefficient, expensive, and ill-suited for transitioning communities from temporary shelter to permanent (i.e. temporary-to-permanent) recovery without displacing families and communities (Askar et al., 2019).

In response to Hurricane Harvey, the Texas General Land Office (GLO) led the short-term housing mission, partnering with FEMA to help Texans return to their homes and communities. This was the first time a state agency partnered with FEMA on such a large-scale short-term housing effort following a natural disaster. Subsequently, the GLO conceptualized the Alternative Housing Study to analyze and evaluate alternative housing options to determine if there are innovative solutions for accommodating disaster survivors, including those with low to moderate incomes, that are cost-effective, safe, secure, and allow for faster construction. The efforts supported through this program are directed toward how Texas can mitigate future disaster impacts through local and statewide development of disaster resilience (GLO, 2020). Although resilience was identified as a root metric for greater performative housing, this aspect is not a direct focus of this paper.

Diversifying the vendor ecosystem is essential to implementing safe and attainable temporary-to-permanent housing. However, a significant methodological gap exists. Disaster response agencies lack a holistic and standardized framework to evaluate the operational feasibility of these diverse technologies. Current assessment methods often focus on isolated metrics like cost or architectural design, failing to capture the complex interplay of factors that determine successful deployment in a post-disaster environment (Roberson, 2005).

The primary objective of this study is to provide a grounded background for the basis of the frameworks presented herein around the feasibility of various housing models to determine their viability for both short-term disaster response and long-term post-disaster recovery. Criteria to be

integrated into this framework include constructability, timeliness, and cost-effectiveness indicators.

LITERATURE REVIEW

The Federal Post-Disaster Housing Model and Its Limitations

Case studies of FEMA's housing programs reveal a complex and often lengthy timeline for delivering assistance. The TSA program, which provides immediate hotel stays, and the IHP, which can provide direct housing like MHUs, operate on different and sometimes overlapping schedules (Verderber, 2008). A holistic assessment of a housing solution's timeliness must therefore consider the entire deployment process. Key factors that heavily influence the timeline include factory production capacity, shipping and transportation times, and potential bottlenecks from required permitting and inspections (Roberson, 2005).

Calls for innovation in this sector are not new. Government bodies, including the Government Accountability Office (GAO), and agencies like the Department of Housing and Urban Development (HUD) have repeatedly highlighted the inefficiencies of the status quo and the need for more resilient and cost-effective housing solutions (Windle et al., 2019). Academic literature further supports this, arguing that diversifying procurement pipelines is essential for creating a more adaptable and sustainable response. A broader vendor ecosystem can introduce a variety of technologies and production methods, reducing bottlenecks and enhancing the capacity to meet the diverse needs of a disaster-affected population (U.S. Government Accountability Office, 2007).

Regulatory Barriers as a Primary Obstacle to Innovation

There is substantial state-by-state variation in permitting requirements, modular building approvals, and contractor licensing (Windle et al., 2019). For example, Texas lacks a uniform state-wide building code for modular construction, leaving approval to the Texas Department of Licensing and Regulation (TDLR) and local jurisdictions, which can create uncertainty. Furthermore, a fundamental conflict often arises between the federal HUD code, which governs MHUs, and the International Residential Code (IRC), which is typically adopted at the state or local level for permanent, modular, and site-built homes (Windle et al., 2019).

For this reason, regulatory approval timelines are a relatively unexplored key variable. A vendor may have a technologically advanced and rapidly assembled product, but if it cannot achieve local code approval in a timely manner, its utility in a disaster scenario is severely diminished (Malagoda et al., 2014).

Grounding the Evaluation Criteria: A Review of Core Concepts

Standing literature cites the need for structured frameworks to capture decisive phases, including manufacturing capacity, transportation logistics, and on-site work duration (Apurva et al., 2020). Remaining persistent to this point, Patel, S., and Hastak, M. (2013) iterate that there always remains trade-offs when assessing which core response categories must be identified and utilized in a post-disaster environment. For example, Patel, S., and Hastak, M. (2013) states that "time,

cost, and resources like labor and equipment… are related to each other where increase or decrease in one would impact others." It is critical to acknowledge, however, that there remains a significant gap in the literature and in practice regarding how to reduce the regulatory and permitting burden in disaster scenarios.

The federal response to disaster housing has long been characterized by an over-reliance on a limited inventory of solutions, primarily MHUs and travel trailers. As of 2006, over 98,000 FEMA trailers and MHU had been deployed nationwide. This approach, while established, has created significant gaps in scalability and sustainability. It is important to note that FEMA already contracts with private sector manufacturers to produce these traditional units (Verderber, 2008). Therefore, the concept of engaging a broader ecosystem of vendors to provide alternative housing is not a departure from the existing procurement model but rather an evolution of it (U.S. Government Accountability Office, 2007).

The concept of "constructability" is well-established in construction management literature, often defined by entities like the Construction Industry Institute (CII) as "the optimal use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII, 1998). However, its definitions within a disaster recovery context have placed a greater emphasis on speed and minimal resource dependency (Patel and Hastak, 2013).

For this framework, constructability is measured by the inputs required for assembly. The evaluation of constructability includes factors of habitability. Considering the unit's livability, privacy, and its capacity for upgrades or expansion, this final point accentuates the goal of the "temporary-to-permanent" conversion (Askar et al., 2019). Literature on disaster recovery suggests that the ability to adapt or expand a unit is critical for long-term success, though this can be at odds with policies that strictly define aid as "temporary" such as the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act) (Askar et al., 2019) and (FEMA, 2023).

A comprehensive financial evaluation of a disaster housing solution must go beyond the base unit price. The total deployment cost, comprising the base cost, transportation, and installation, is a more accurate reflection of the initial financial outlay (GLO, 2020). Furthermore, affordability must be assessed against established benchmarks and program constraints, such as those defined by HUD's FMR data and the regulations of disaster grant programs under the Stafford Act (FEMA, 2023).

Methodological Gaps in the Literature

There is a notable lack of multi-criteria scoring frameworks designed to evaluate alternative housing solutions from a logistical and operational perspective. Most studies tend to focus on a single aspect, such as architectural innovation or a narrow cost analysis (Verderber, 2008). Few, if any, have focused on the intersection of constructability, timeliness, cost, and regulatory fit, particularly within the specific context of Texas. This study contributes to the field by proposing a needed replicable scoring matrix model rooted in the principles of operational feasibility,

addressing a consistent and well-documented challenge in disaster recovery planning (Hosseini et al., 2020).

METHODOLOGY

Typology and Scoping

The selection process began by building a list of commercial and nonprofit housing providers that possessed both "responsive" and "responsible" bidding capabilities (Texas Code of Regulations, 2013). This initial pool was identified by a market search for companies demonstrating potential for post-disaster housing solutions. Potential vendors were recognized by their demonstrated production capacity, availability of a prototype or deployed unit (TRL 6 or higher), geographic relevance and willingness to operate in Texas, and interest in disaster recovery markets.

Through the lens of these criteria and the data collected from surveys, the vendor pool was systematically reduced to a final selection of companies demonstrating feasibility to deploy units in a disaster response scenario. The screening process prioritized entities with prior FEMA/HUD experience, scalable factory-based production, or relevant industry certifications. The final selected Alternative Housing Units (AHUs) represented a cross-section of five distinct construction typologies: 3D-Printed, Kit-Built, Modular Foldable, Modular Panelized, and Modular Prefabricated. This selection provided a basis for evaluating varied materials, installation models, and scalability.

Survey Design and Distribution

To capture accurate and relevant data, the survey instruments utilized built on existing research aimed at assessing the feasibility of housing vendors in post-disaster scenarios known as the Housing Assessment Tool (HAT) (GLO,2020). Expanding on this approach, this study intentionally sequenced three surveys. Each round of surveys is described in Table 1.

Table 1: Survey Categories for Matrices Distribution.

Assessment Category	Highlights / Purpose
	Survey I
Organizational & Contact Information	-Collects basic administrative data (name, location, contacts).
Authorization & Business Structure	-Confirms respondent authority and clarifies vendor/manufacturer relationship and verifies U.S. business licensure.
Unit Classification & Description	-Classifies product into predefined categories (e.g., modular, kit-built, 3D printed) to inform the study's typology.
Technology Readiness Level (TRL) & Deployment Status	-Assesses solution maturity using the TRL scale. -Gathers evidence of real-world viability and production forecasts.

Assessment Category	Highlights / Purpose
	Survey II
General Information & Classification	-Defines the unit's development stage, intended lifespan, and past disaster deployment history.
Codes, Standards, & Accessibility	-Tracks compliance with building standards (IRC, HUD), hazard codes (ASCE, FEMA), and accessibility standards (ADA, UFAS).
Resilience	-Assesses unit performance against specific hazards like flooding and fire, focusing on damage-resistant materials.
Unit Size & Amenities	-Evaluates livability by capturing detailed measurements, room counts, and a full inventory of included amenities.
Customization & Adaptability	-Assesses flexibility to meet aesthetic needs and the unit's capability for expansion or "temporary-to-permanent" conversion.
Structural Systems (Framing, Roofing, Foundation)	-Gathers in-depth technical data on the core structure, including materials, connectors, and foundation type.
Building Envelope & Utilities	-Evaluates envelope materials (insulation, siding, windows) and all major utility systems (HVAC, electrical, plumbing).
Construction, Site, & Production	-Assesses practical deployment needs, including transportation, on-site footprint, labor, and required equipment.
Production Capability & Cost	-Quantifies the vendor's ability to scale production and gathers comprehensive cost data (purchase, turnkey, bulk discounts).
	Survey III
Physical Description of Model	-Collects foundational specifications like square footage and occupancy to serve as a baseline for analysis.
Code Compliance	-Investigates adherence to IRC and hazard resilience tests to determine suitability for long-term housing in Texas.
Evaluating Cost	-Captures the total deployment cost, including transportation, installation, regional turnkey pricing, and demobilization fees.
Construction Process	-Provides a detailed breakdown of all manufacturing and on-site assembly steps, supply chains, and regulatory timelines.
Demobilization & Re-deployment	-Assesses the reusability of temporary units, including associated costs and turnaround time for relocation.

Scoring Matrix Architecture

The core of the feasibility analysis is a set of scoring matrices designed to evaluate each AHU. These matrices are structured to provide a broad and rooted quantitative assessment of constructability, timeliness, and cost. Key assumptions underlying the matrices include the parallel timelines for permitting and production, and the availability of both standard and skilled regional labor. Further illustration of these matrices is outlined in Table 2.

Table 2: Scoring Matrices Rationale and Key Variables Assessed.

Matrix Rationale	Key Assessed Variables	Answer Type
Constructability Matrix		
To evaluate the practical ease and feasibility of assembling a unit benchmarked against a traditional site-built home, post-disaster environment. This moves beyond cost to assess true operational viability on-site. Yes/No answers are translated to "1" or "0" and aggregated into the construction steps extracted from the benchmark. The output is a timeline correlated to the size and necessary construction steps for vendors.	-Defines Labor type necessary on site (skilled vs. unskilled) -Defines Tools and equipment needed (Telehandler vs. hand tools) -Foundation and site prep complexity -Necessary on-site construction steps (Install vs. hook-up only) -Identification of inspection processes -Reductions in complexity on-site attributed to off-site manufacturing	-Yes/No -63 questions
Timeliness Matrix		
To measure the entire deployment-to-occupancy lifecycle, providing a realistic estimate of how quickly a unit can be made available to a survivor.	-Factory production capacity/relative location and supply chain logistics -Shipping logistics and transport class -On-site installation duration -Regulatory and permitting timelines - Need for trained crew and equipment	-Yes/No -Scaled timelines -30 questions
Cost-Effectiveness Matrix		
To provide a financial assessment that captures the total cost of deployment, not just the unit purchase price, allowing for more accurate budget planning and understanding of price determiners.	-Cost-per-square-foot ($/sq. ft.) -$/occupant (occupancy-adjusted) -Transportation and installation costs - Turnkey delivery capacity -$/sq. ft. for expansions	-Yes/No -Scaled Costs -26 questions

Variables identified as critical activities (e.g., foundation set time, permitting, transportation logistics, etc.) were assigned a multiplier within the matrix to reflect their disproportionate impact on total deployment time compared to non-critical tasks (e.g., cosmetic finishes). The framework produces a normalized "Feasibility Index" for each vendor. This allows for direct comparison where a higher score in "Timeliness" indicates faster deployment, and a higher score in "Cost" indicates higher affordability.

DISCUSSION

The essence of construction project management is the effective control of scope, schedule, and budget. In the environment of disaster recovery, these principles translate to the critical metrics of constructability, timeliness, and cost-effectiveness.

Constructability

In post-disaster scenarios, the physical and logistical challenges of building are immense. Therefore, constructability must be evaluated as a distinct metric, independent from cost. A simple cost-per-square-foot ($/sqft) analysis fails to capture the true construction capabilities and potential bottlenecks of a housing solution. For instance, a low-cost unit that requires highly specialized labor, heavy machinery, or complex site preparation may be entirely infeasible in a disaster zone where such resources are scarce or non-existent. For example, Hosseini et al., (2020) provided understandings drawn from an Indonesian post-disaster recovery effort that sited "complexity of organizing the tasks involved in the recovery program, some organizations were not specialized in housing reconstruction, poor unit performance, site location problems, insufficient consideration given to infrastructure provision, insufficient coordination between agencies, and shortfall in materials."

The constructability matrix was designed to address this by assessing factors like workforce requirements, necessary tools and equipment, and foundation needs. Data gathered for this study highlighted that some solutions are designed for assembly by unskilled labor with minimal tools, a significant advantage in a post-disaster context. Others emphasize factory completion to minimize on-site construction activities. By measuring these attributes, the framework allows for a nuanced assessment of how a unit's design translates to robust conversations regarding feasibility regarding real-world deployment.

The data collected on physical specifications, including accessibility features, utility connections, and the potential for future expansion, is used to evaluate a unit's suitability for providing safe, dignified, and functional housing. These criteria serve as a practical test of a unit's real-world usability and its readiness to meet building codes and the diverse needs of survivors. This is particularly important for fulfilling the goal of "temporary-to-permanent" housing.

Timeliness

For disaster survivors, time is the most critical resource. The timeliness matrix is structured to measure the entire deployment timeline, from permitting and factory production to resident occupancy. This view is essential because focusing only on manufacturing speed or shipping time alone can be misleading. The true measure of timeliness must account for all potential delays, including factory capacity, transportation logistics, on-site construction, and, crucially, the regulatory approval process.

While this framework cannot solve systemic issues relating to permitting, it incorporates regulatory timelines into its scoring to provide a more realistic estimate of time-to-occupancy. The weighting of the matrix further reflects operational priorities; factors with the greatest

potential impact on the timeline, such as a vendor's maximum factory output and the complexity of on-site preparation, are given greater significance. This ensures that the final timeliness score is a robust indicator of a vendor's ability to deliver housing quickly when it is needed most.

Cost-Effectiveness

While affordability is a primary concern, the framework's cost matrix is designed to look beyond the initial purchase price. The total cost of deploying a housing unit in a disaster context includes a wide range of expenses, from transportation and installation to the operational costs required to make a unit habitable. The matrix captures this full spectrum of expenditures to provide a comprehensive "turnkey" cost estimate.

To ensure a fair and meaningful comparison between different types of units, the costs are normalized and adjusted for key variables. The analysis includes a standard $/Sqft metric, but more importantly, it calculates a $/occupant. This adjustment is critical because a smaller, less expensive unit may be less cost-effective on a per-person basis than a larger unit designed for a family. Conversely, a smaller modularized unit may be more efficiently poised for expansion. Evaluating cost through these multiple lenses can spur greater discernment of potential vendors for deployment.

Methodological Strengths

By using weighted matrices informed by operational priorities, it provides a consistent and evidence-based approach to vendor evaluation to be adapted to different disaster types and geographic locations. This supports the diversification of the post-disaster housing supply chain, allowing agencies to select the most appropriate technology for a given scenario. By streamlining the evaluation of multiple vendors, the framework can help coordinate responses, ultimately supporting the ability of survivors to remain in and rehabilitate their communities (Patel and Hastak, 2013).

A more holistic evaluation is achieved through the demonstrated intersection of the three core assessment matrices. It has been observed in preliminary data collection that constructability, timeliness, and cost-effectiveness are deeply interconnected. For instance, high on-site constructability needs were shown to negatively impact both timeliness and overall cost. Different housing typologies yield distinct performance profiles, with strengths in one metric often balanced by trade-offs in another. The capabilities of a given housing solution can be aligned with the unique constraints of an individual disaster scenario. A portfolio of vetted solutions is suggested to build a more resilient and adaptable response capability.

CONCLUSIONS

Texas's post-disaster housing response is hampered by legacy systems that are costly, slow, and impose a prolonged financial and logistical burden on survivors (Verderber, 2008). While innovative AHUs offer a promising path forward, their adoption is hindered by the lack of a comprehensive framework to evaluate their operational feasibility. This ongoing research studies that gap by introducing the background for a multi-criteria methodological framework for the

systematic, evidence-based assessment of new housing technologies. The modular scoring matrices allow for easy insertion and evaluation of emerging vendors, ensuring the framework remains adaptable over time.

Future work will embody a comprehensive assessment that is necessary to effectively gauge disaster response preparedness. As mentioned, legacy systems for the procurement of safe, durable, and resilient housing following natural disasters have presented a pervasive challenge, often resulting in prolonged recovery timelines and financial waste as evident through FEMA's response to Hurricane Katrina in 2005. Focusing on the ability of state entities to rapidly and efficiently respond in these scenarios, the ongoing study exists to validate, through full-scale construction, monitoring, and structural testing, a previously developed evidence-based decision-making framework outlined in this study. This verified framework will aspire to streamline the procurement of resilient post-disaster housing in Texas as investigated in earlier phases of this study.

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Resilience and Affordability: A Data-Driven Evaluation of Industrialized Construction's Economic Viability

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ABSTRACT

Offsite construction, utilizing modular and panelized technologies, presents a viable solution for the urgent need for affordable and disaster-resilient housing. This study quantifies the time and cost savings achievable through offsite methods compared to traditional site-built construction, focusing on affordable housing projects, while also evaluating the cost implications of integrating disaster resilience measures. Through data collection from past projects and real-time subcontractor cost analysis, an "apples-to-apples" cost comparison was developed. Preliminary findings indicate substantial potential for cost reduction and expedited construction timelines, alongside a clearer understanding of the economic feasibility of incorporating resilience. This research aims to provide concrete evidence that supports the adoption of offsite construction as a crucial strategy for increasing access to affordable, safe, and durable homes. By quantifying the benefits and costs, this study empowers stakeholders to make informed decisions, facilitating the efficient delivery of much-needed housing solutions.

INTRODUCTION

The U.S. housing sector is grappling with two intersecting challenges: a widening affordable housing deficit and increasing exposure to climate-related risks such as flooding, wildfires, and hurricanes. Traditional site-built techniques face delays, escalating cost, and limited capacity for integrating resilience features at scale. Industrialized construction (IC)—the application of manufacturing-style systems, lean workflows, and standardized assemblies—presents a viable alternative. Authorized definitions include those from Lean Construction Institute and P2SL (UC Berkeley), framing IC as the translation of high-volume mfg. principles into building delivery.

Beyond qualitative benefits, IC is now a substantial and rapidly growing industry:

- The global modular construction market is projected at USD 100-110 billion in 2024, with a CAGR of ~8% through 2030 (Grand View Research).
- In the U.S., permanent modular construction captures roughly 5% of total construction activity, with valuations in the USD 20–25 billion range and steady annual growth (Modular Building Institute).

- U.S. HUD/NIBS roadmap highlights factory-built methods as key to reduce costs and improving quality, suggesting large potential to scale in affordable housing contexts (NIBS).

By framing IC not only as a technological paradigm but also as a growing economic force—with measurable cost and schedule benefits—this paper seeks to quantify its value proposition in the context of affordable, disaster-resilient housing. This is our first (and preliminary) study that will continue to grow in scope and scale year-on year. The research objectives remain:

- What are the differences in total costs between IC and site-built construction?
- To what extent can industrialized methods reduce overall construction timelines?
- What is the marginal cost associated with integrating resilience measures within IC?

LITERATURE REVIEW / PRIOR WORK

Types of Industrialized Construction Technologies

Industrialized construction (IC) encompasses several prefabricated or factory-integrated building system types. These typologies vary by prefabrication level, fabrication-to-installation workflow, and structural format. Below are a few categories used in contemporary IC practice.

- Volumetric Modular Construction: Factory-fabricated three-dimensional units—pre-assembled with structural framing, finishes, and mechanical/electrical/plumbing (MEP) systems—that are transported and installed onsite through craning (NIBS).
- Panelized Construction Systems: Two-dimensional panels—such as walls, floors, and roof cassettes—prefabricated under controlled conditions (often including structural panels, insulation, MEP rough-ins) and assembled onsite (NIBS; Offsite Construction Network).
- Cross-Laminated Timber (CLT): Large-format, engineered wood panels created from orthogonally layered timber boards, producing structural panels for walls, floors, and roofs.
- Open-Panel Timber Frame: Frame panels composed of timber studs and sheathing on one face, delivered to sites in an “open” configuration (1 face unboarded) (Designing Buildings Wiki; ASBA Architects).
- 3D-Printed Additive Construction: Robotic extrusion technologies build structural elements (e.g., walls,) layer-by-layer using concrete, polymers, or composites (Ahmed).

● Shipping-Container Based Construction: Repurposed shipping containers converted to habitable modules. Typically require significant retrofitting for code compliance.

Note: This list is not exhaustive; new technologies continue to enter the market each year.

Industry Size and Market Growth

This section provides a detailed overview of the scale and recent trends in Industrialized Construction (IC) in the U.S, focusing on both volumetric modular and panelized systems. Volumetric Modular Construction (U.S.): The U.S. permanent modular construction segment was valued at approximately USD 20.3 billion in 2024, representing about 5.1% of total construction spending, according to the Modular Building Institute (MBI). The market is projected to grow at a compound annual growth rate (CAGR) of 4.5%, reaching approximately USD 25.4 billion by 2029. Sub-segment trends indicate:

● Hospitality modular segments are projected to grow at 9.2% CAGR over the same period.

● Multifamily housing is expected to grow at a 4.7% CAGR over the same period.

Panelized Construction in Single-Family Homes: According to the U.S. Department of Housing and Urban Development (HUD) and the National Association of Home Builders (NAHB) panels and other non-site-built systems accounted for only 3-4% of new single-family homes built as of 2016. Parallelly, more recent data from Eye on Housing (based on U.S. Census completions) reports that in 2023, combined modular and panelized single-family homes represented ~3% of total completions—about 27,000 homes out of ~999,000, up modestly from 2% in 2022.

Trends and Comparisons: IC has maintained a relatively small share of overall U.S. housing production, despite industry optimism and renewed interest. Public-sector endorsements (e.g., HUD, NIBS) continue to highlight the promise of IC, but market penetration remains modest.

Cost and Time Savings from Empirical Studies

This section synthesizes empirical findings on the cost and schedule performance of industrialized construction (IC)—with a focus on modular and panelized systems—relative to traditional site-built methods, as documented in government reports and academic literature.

Quantitative Evidence from U.S. and Academic Sources

The National Renewable Energy Laboratory (NREL) reports that modular construction projects typically result in 20-50% schedule compression and up to 20% total hard cost savings. Industry surveys cited by NREL show:

- 91% of general contractors observed cost reductions using IC,
- 8% reported schedule improvements, and

- Over 50% saw cost reductions exceeding 10%.

A systematic literature review published in Applied Sciences (MDPI) found high variability in outcomes across project types, but still reported:

- Average cost reductions of 7-50%
- Time savings ranging from 9% to 50%, depending on delivery method, project scale, and labor context.

The Terner Center for Housing Innovation at UC Berkeley conducted case studies of offsite delivery in mid-rise, wood-framed multifamily housing, concluding that:

- Construction costs may be reduced by up to 20%, and
- Construction timelines shortened by 40-50%, depending on design repetition and trade integration.

A detailed case study by NREL on a 200-unit modular multifamily development observed a six-month shorter build schedule (15 months vs. 21 months). However, it also noted that equity requirements were higher (~30%) due to early-stage deposits and factory production milestones, indicating the need for non-traditional financing options. These findings collectively affirm that IC methods can significantly reduce both time and cost, especially when factory workflows are fully optimized and project designs are standardized.

Prior Research on Resilience Integration

As climate risks intensify, housing resilience—particularly for low-income populations and communities in hazard-prone regions—has emerged as a defining measure of building performance. Recent studies have examined how industrialized construction (IC) methods, including prefabricated modular and panelized systems, perform under these demands.
The Resilience and Performance of Prefabricated Modular Buildings Against Natural Disasters study (2023)17 finds that modular systems, when engineered with hazard-specific reinforcements, can maintain structural integrity and expedite post-disaster recovery. Research on prefabricated frame rocking wall (PFRW) systems (2022)18 demonstrates that advanced connection designs enable prefabricated assemblies to achieve seismic performance comparable to or exceeding conventional construction under lateral loading. A comparative analysis by Zhou et al. (2024)19 shows that modular can reduce on-site exposure to hazards, improve quality consistency, and limit schedule disruptions—critical elements in resilience.

Resilience also depends on the ability of supply chains to withstand and recover from disruptions. Xinnan Liu's 202420 study on supply chain resilience in prefabricated construction identifies strategies such as diversified supplier bases, regionalized production hubs, and dynamic capability building as key enablers of continuity. Related research on resilient supply

networks highlights the importance of redundancy, real-time monitoring, and adaptive logistics planning to maintain material and component flows during adverse events.

Collectively, this body of work indicates that IC offers tangible opportunities to integrate resilience at both the building and system levels—combining enhanced structural performance with robust, adaptable supply chains capable of maintaining production and delivery under challenging conditions.

Gaps in Current Literature

Limited Multi-Dimensional Comparative Studies: While multiple systematic reviews, including PRISMA-based analyses of up to 90 peer-reviewed articles, highlight relative benefits of IC in terms of cost, schedule, energy, and emissions, the findings exhibit substantial variance. For example: Documented cost outcomes range from -7% to +72%, Schedule savings vary from minimal to 50%+ depending on geography, building type, and labor context. Most of these studies lack a standardized, unified framework for cross-typology comparison (Lund University).

Scarcity of Energy Performance Analyses: Peer-reviewed, empirical comparisons of operational energy consumption or embodied carbon between IC and site-built construction remain rare. While many design-stage studies and lifecycle modeling exercises suggest that factory-built systems can reduce operational energy demand by up to 90%, these are often based on idealized simulations or assumed performance inputs, rarely validated with post-occupancy monitoring, and seldom disaggregated by delivery method (modular vs. panelized vs. site-built).

Underdeveloped Quality and Customer Satisfaction Evaluations: Most construction quality and customer experience literature centers on site-built delivery. Studies that do examine IC often highlight; Information asymmetry, where buyers, occupants, developers may lack familiarity with industrialized systems and Perceptions of IC as lower-end or lower-quality, despite evidence to the contrary in many factory QA processes. There is a need for structured post-occupancy evaluations, covering buyer satisfaction, Service quality and maintenance outcomes (Junnonen and Kankainen).

Insufficient Marketing-Quality Documentation: Public and private stakeholders—including municipalities, housing authorities, and developers—often lack clear, visually compelling documentation that presents IC as a performance-equal or performance-superior option. This absence contributes to continued skepticism and under-adoption, particularly in public procurement environments. Available materials often:

- Focus narrowly on cost savings,
- Underemphasize durability, design quality, or resilience advantages, and
- Fail to show how IC fares vs traditional methods in structural and energy performance.

Lack of Affordable Housing Contextualization
There is limited insight into how modular and panelized systems perform in the affordable housing context, where: Cost ceilings are tighter, public subsidy rules constrain delivery timelines, and stakeholders (e.g., nonprofits, housing finance agencies) have unique risk profiles. This gap is particularly relevant as IC is increasingly proposed as a scalable strategy for addressing affordable housing shortfalls.

METHODOLOGY

This study employs an approach that combines active project data from panelized construction (specifically, Structural Insulated Panels–SIPs) used in the Duke Street Cottages development with forward-looking pricing models for volumetric modular construction. These are rigorously compared against regionally validated subcontractor pricing for conventional site-built construction to develop an empirical, apples-to-apples comparison of industrialized construction (IC) versus traditional methods. The methodology aims to quantify differences in hard construction costs, project duration, and cost of resilience features, specifically within the context of affordable, energy-efficient housing.

Case Study Context
The Duke Street Cottages project—a pocket neighborhood of DOE Zero Energy Ready Homes in Granite Falls, North Carolina—is used as the empirical foundation for this analysis. The builder utilized panelized SIP assemblies for the building envelope to expedite construction and enhance thermal performance. Future phases of the project are planned to include volumetric modular units, enabling direct comparison across IC systems (Offsite Builder Magazine; Pacific Northwest National Laboratory).

Data Collection Strategy
The analysis draws on three primary data streams to construct a structured comparison across delivery types; Panelized construction data from an active project, forward-looking pricing for modular construction and, regionally adjusted subcontractor quotes for site-built construction. Each stream supports a consistent, normalized comparison of cost and schedule.

Panelized Construction Dataset-Duke Street Cottages: The panelized baseline is anchored in the built performance of the Duke Street Cottages development. Panelized SIP assemblies were used for wall and roof enclosures across 9 detached units ranging from approximately 800 to 1,400 ft². Primary data was obtained through: Incurred construction costs + Verified builder experience + energy modeling and timeline analysis

Key parameters collected:

- Envelope and assembly type (SIP thickness, air barrier strategy)
- Foundation type, framing system, and on-site labor coordination

- Schedule milestones: start-to-close timelines across units

This dataset provides the basis for benchmarking enclosure costs, envelope performance, and sequencing efficiencies of panelized construction workflows.

Modular Construction Pricing (Forward-Looking):
To establish a modular baseline, forward-looking pricing was developed for a 1,100 ft² volumetric modular unit, designed to match the building materials, finishes, and energy performance of the panelized Duke Street homes. This modular unit is currently under construction and scheduled for completion in Fall 2025. Input sources include:

- Subcontractor and modular manufacturer quotes normalised for current square footage,
- Factory production scope sheet (including envelope, MEP rough-ins, finishes), and
- Site scope assumptions: crane set, foundation coordination, MEP tie-ins, punch-list work.

The modular unit is configured as a double-module assembly that replicates the layout of the Duke Street homes. Identical material finishes, window specs, and HERS 44 energy targets were applied. As this estimate is forward-looking, assumptions were validated with IC practitioners to ensure that they reflect realistic workflows and onsite processes for modular construction.
Site-Built Subcontractor Pricing: The site-built baseline was developed using regionally adjusted subcontractor pricing for conventional stick-built construction in western North Carolina. The model assumes a 1,200 ft² detached single-family home with the same layout, finishes, and energy performance as the Duke Street case study. Input sources include:

- Quotes from framing, MEP, drywall, insulation, and finish contractors,
- Design specs held constant across typologies (e.g., window types, cladding, roof slope), and
- Site conditions typical of the Hickory–Granite Falls micropolitan area.

Contractor assumptions included: standard subcontractor markups, mobilization logistics, and sequential installation workflows. This dataset serves as a credible, localized benchmark for traditional construction and enables a comparison of cost and timeline against IC models.

LIMITATIONS

While this study offers a replicable comparison framework, there are several limitations:

- Forward-Looking Modular Pricing: This work is not yet done and relies on estimates.

- Single Geographic Market: All data reflects conditions specific to Western NC.
- Assumed identical finishes across typologies may obscure inherent tradeoffs.
- The panelized cost includes only enclosure assembly; MEP and interiors were site-built.
- Cost of resilience upgrades is based on subcontractor input, not verified installs.
- Financing and Closing Costs Excluded; assuming they would be the same across all.
- Sample Size and Case Rarity: The analysis draws from a single 11-unit project; projects using multiple delivery methods in parallel remain rare.

RESULTS

Bottom-Line Cost Comparison

This analysis compares total hard construction costs across three delivery methods for an 1200 ft² starter home. All designs, finishes, and energy performance targets were held constant to isolate the impact of the delivery method. Panelized construction was the most expensive, at $180,000, or 3.7% higher than site-built and 4% higher than modular. The premium reflects higher SIP material costs and hybrid labor needs.

- Modular construction was the least expensive at $173,050, slightly below site-built, driven by integrated factory production despite minor on-site stitching tasks.
- Site-built construction cost $173,500, with the highest field labor exposure.
- All three methods fell within a 4% cost range, confirming that IC methods can compete on cost when scope is standardized and workflows are optimized.

Schedule and Overhead Comparison

Project durations were modeled to reflect full timelines, including inspections, weather delays, and subcontractor sequencing: modular at 22 weeks, panelized at 35 weeks, and site-built at 39 weeks. Modular construction required the least on-site supervision, valued at $4,000 of time saved versus the site-built baseline of $15,350. Panelized supervision savings were estimated at $1,500 of time saved. Shorter durations in both methods also reduce temporary utility costs, construction-loan carrying costs, and general conditions. Site-built delivery required the most supervision, with sequential trade mobilization and full exposure to weather and labor delays.

Resilience Feature Cost Impact

Resilience upgrades were modeled as a $4,500 addition to each typology to meet IBHS FORTIFIED Home™ standards, adding upgrades including:

- FORTIFIED Roof; wider drip edge, fully adhered starter strip, sealed roof deck (ZIP System qualifies), ring-shank nails, impact-resistant shingles.

- FORTIFIED Silver; impact protection for windows/doors, reinforced soffits, gable-end brace.

- FORTIFIED Gold; pressure-rated windows/doors, stronger exterior sheathing, engineered roof-to-wall, story-to-story, and wall-to-foundation connections.

The upgrades increase total costs by approximately 2.5-2.7%, depending on the delivery method. The relative ease of implementation varies by delivery method. Modular delivery can integrate resilience features directly into factory workflows, improving quality assurance and reducing on-site labor. Site-built and panelized methods require more subcontractor coordination, with some details harder to inspect or enforce consistently in the field.

CONCLUSION

This study compared modular, panelized, and site-built construction methods for a 1200 ft² starter home using normalized scope, matched finishes, and consistent energy-performance targets. Total hard construction costs across all three delivery approaches fell within a narrow four percent range, confirming that industrialized construction (IC) methods can compete directly with conventional site-built housing when scope is standardized and optimized. Panelized construction was the most expensive option at $180,000—approximately 3.7% higher than site-built and 4% higher than modular—reflecting higher SIP material costs and hybrid labor requirements. Modular construction delivered the lowest total cost at $173,050, slightly below site-built at $173,500, driven by integrated factory production despite limited on-site stitching. Beyond direct costs, IC methods demonstrated advantages in schedule compression and efficiency. Project durations were 22 weeks for modular construction, compared to 35 weeks for panelized and 39 weeks for site-built construction. These timelines translated into reduced supervision and general-conditions costs. Modular construction required $4,000 in supervision, compared to $15,350 for site-built, while panelized delivery yielded an estimated $1,500 in supervision savings. Reduced durations lower exposure to weather delays, subcontractor sequencing risk, and construction-loan carrying costs.

The analysis confirms the economic viability of integrating resilience features across delivery methods. Upgrades aligned with IBHS FORTIFIED Home™ standards including enhanced roof systems, reinforced connections, and impact-rated openings added approximately $4,500 per unit, representing a 2.5-2.7% increase in total construction cost. While all delivery types can accommodate these measures, modular construction offers the most consistent implementation pathway by embedding resilience features within factory workflows, improving quality control and reducing reliance on field inspections and multi-trade coordination.

Key takeaways:

● Modular construction should be prioritized when speed, labor constraints, or resilience integration are critical, delivering the fastest schedule and lowest supervision burden.

● Panelized systems offer incremental benefits for builders transitioning from site-built methods but retain hybrid inefficiencies that limit full cost and schedule optimization.

● Site-built construction remains cost-competitive but carries the greatest exposure to labor variability, weather risk, and schedule uncertainty.

● Financing models must evolve to better support IC's front-loaded capital requirements and factory-deposit structures. We are now pursuing a broader pipeline—including a planned 44-unit disaster recovery project with a local nonprofit—to refine this model and inform scalable IC adoption.

Future Research Directions

● Longitudinal Project Data: Most studies rely on single-project estimates; multi-project, multi-region data is needed to assess cost, schedule, quality, and performance trends.

● Resilience Cost–Benefit Modeling: Future work should quantify the full value of resilience upgrades—comparing their upfront costs to avoid damage, reduced recovery time, and insurance savings. Lifecycle modeling would support hazard-prone strategies.

● Post-Occupancy Energy and Carbon Performance: Measured performance—including energy use, thermal comfort, and air quality should be tracked to confirm modeled gains.

● User Experience and Market Perception: Post-occupancy evaluations on satisfaction, maintenance, and perceived quality can help improve adoption in affordable housing.

● Policy and Code Readiness: Research should explore how policy tools—like modular overlays, expedited approvals, and financing guidelines—can reduce deployment friction.

● Supply Chain and Labor Readiness: Assess factory locations, logistics, and workforce availability to align IC expansion with regional economic development.

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What Is Right with You? Charting the Success of Attached Residential Offsite Construction in the South Atlantic Division of the United States

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ABSTRACT

Offsite construction methods, including modularization, panelization, and precutting, have the potential to revolutionize housing productivity, efficiency, and affordability throughout the world. While home builders in European and Asian countries have well-established offsite solutions with robust standardized tracking systems to match their housing needs, the offsite residential industry in the United States is still searching for answers. One of the most salient obstacles facing the United States is monitoring offsite home building activity. Presently, the United States has no standardized systems for tracking residential offsite activity requiring the construction industry and academic researchers to measure its progress. Using a new method to aggregate and analyze regional microdata of 661,671 homes included in the U.S. Census's Survey of Construction between 1999 and 2023, this research found that the South Atlantic division (Census Division 5) is a positive outlier in attached (e.g., townhomes and duplexes) residential offsite adoption, keeping pace proportionately with its onsite counterpart, and potentially serving as a model for the other eight census divisions where offsite output is lower. A likely contributor to the success of attached offsite residential construction in the South Atlantic division is the consistently high volume of home-building activity in the area. Future research should continue to explore the root causes of the success in this division and search for new ways to promote them for the advancement of domestic offsite residential construction more broadly.

Keywords: Offsite Construction, Residential Construction, Home Building, Modular, Prefabrication.

INTRODUCTION

Permanent offsite residential construction (PORC) is a general term for any construction method that completes some portion of the home-building process in a controlled environment, typically an enclosed factory, not including manufactured housing (i.e., not mobile homes or trailers with a steel chassis) (Smith, 2023). The purpose of using PORC methods is to reduce the duration and exposure of building materials to unpredictable onsite conditions by adding a preparatory stage of construction in a controlled setting in which efficiency and quality can be optimized. Common PORC methods include volumetric modular construction, non-volumetric modular construction, and precutting (Fannie Mae, 2020). Volumetric modular construction refers to the offsite construction of finished or nearly finished three-dimensional units of a home that can be shipped

to the home site for assembly. Non-volumetric modular construction, also called panelization, refers to the offsite construction of two-dimensional panels of wall, roof, and floor assemblies that can be stacked on the back of a truck and transported to the home site for assembly (Fannie Mae, 2020). Precutting refers to the preparation of a building package in which all construction materials have been counted and cut before shipment for final installation at the home site (U.S. Census Bureau, n.d.). Manufactured housing, often referred to as mobile homes or trailers, is categorically different than, and defined separately from, PORC homes because it is not a permanent real estate improvement, rather it is impermanent by design, constructed with a steel chassis and wheels instead of a concrete foundation securing it permanently to the land.

The market penetration of PORC (hereafter referred to as offsite or PORC) homes varies geographically. On the global scale, Sweden and Japan have the highest market share of offsite housing anywhere in the world (Smith, 2023). Just under half of all homes in Sweden, and approximately 15 percent of all homes in Japan, are built using offsite methods. In the United States, the best estimates for the market penetration of PORC are between three percent and six percent overall (Blanco, 2023). Unfortunately, due to the scale of the U.S. housing production and the lack of standardized tracking systems (Smith, 2023), accurate and reliable data about the status of offsite construction at the state and division level is unavailable, leaving open questions about which markets in the United States have the greatest success with offsite construction. The purpose of this paper is to help address this problem by providing better data and insights into the performance of PORC in the United States, identifying which areas have had the most success, and disseminating best practices that can lead to more widespread adoption.

LITERATURE REVIEW

The United States has no standardized system for measuring the market performance of permanent offsite residential construction (PORC) (Smith, 2023). What data are available comes from a relatively small number of offsite building associations, private industry reports, and academic research publications. The most reliable and accessible offsite data comes from building associations, most notably the Modular Building Institute (MBI) and Mod X in partnership with the National Institute of Building Science (NIBS). Broadly, their collective research shows that offsite has been increasing its market share over the past two decades in the United States since the housing collapse in the mid-2000s that reoriented homebuilding away from single-family housing developments to multifamily developments (Modular Building Institute, 2024; Smith, 2023). Unfortunately, most of the data from these reports are unable to be disaggregated by research category, for example, by companies producing the homes, geographic areas of building activity, construction methods used to build (i.e., 3-D volumetric modular construction, 2-D non-volumetric modular construction, and precutting), or details about the type, style, or size of the housing products (e.g., townhomes, entry-level single family homes, estate homes, high-rise multi-family). Private industry reporting from organizations such as McKinsey Global Institute, Dodge Data and Analytics, Inc. Market Research Future, Global Industry Analysts, Freedonia, and others have been helpful in examining certain key metrics of the offsite market and tends to confirm much of the data provided by offsite building associations—that offsite construction is growing and will continue to grow—however, in a

recent in-depth review of these reports, Mod X and NIBS expressed concern that many of the methods used to gather the data were sporadic, incomplete, and lacked precision in collection, analysis, definitions, and scope (Smith, 2023). Following their evaluation of the industry reporting, Mod X encouraged the stakeholders in the United States to continue moving toward modeling their offsite reporting after Japan and Sweden, countries with robust, standardized tracking and reporting systems that have been in place for decades.

Another source of offsite performance data comes from the academic literature, most of which used industry interviews and surveys in their research (Assaad et al., 2022; Razkenari et al., 2020; Smith and Tarr, 2018; Sutrisna et al., 2022). Nearly all of them forecast an increase in the adoption rate of offsite construction methods in the future. For example, Assaad et al. (2022) reported that nearly nine in ten industry professionals surveyed believed offsite construction will be more prevalent in the 2030s than it is in the 2020s. They found their respondents were able to specify the locations with the most offsite factories in Texas, Louisiana, California, Alabama, and Mississippi. The locations with the most offsite projects in Texas, Louisiana, California, Pennsylvania, Florida, and Alabama. These findings mostly confirm the seminal 333-page Mass Production report by Ivan Rupnik's master's research studio at the Northeastern University School of Architecture from a decade prior in which his team used data from Google Maps API, the National Association of Home Builders (NAHB), and modularhomeowners.com to locate and count the number of offsite companies operating in the United States (Rupnik, 2014). They found that Texas, California, Pennsylvania, New York, Virginia, and North Carolina had the highest density of offsite vendors. Secondary indicators are another way academic researchers have used to examine the market status of the offsite industry. Some of these include tracking commodities and materials (Bock 2017), product patents (Dou et al., 2020), and academic publications (Lim et al., 2022). Common limitations of the academic studies reviewed were impractically small sample sizes, the lack of a defined scope identifying which offsite housing products and services were under examination, specification of region-specific offsite data, or even precise terminology regarding construction method or type of construction. No industry or academic report could be found that provided robust, precise, and detailed offsite data that had been or could be disaggregated by product, method, and geographical region.

METHODS

Every year since 1999, the United States Census Bureau, in partnership with the Department of Housing and Urban Development (HUD), has published the Survey of Construction (SOC), a public report providing national and regional housing data for single and multi-family homes. Source data for the SOC comes from approximately 900 randomly sampled permitting offices and another sample of approximately 70 land areas without municipal permitting oversight (U.S. Census Bureau, Survey of Construction, n.d.). The contents of the SOC include more than 60 physical and financial characteristics of the surveyed homes, including size, foundation type, number of bathrooms and bedrooms, type of financing, sales price, type of heating, type of exterior cladding, inclusion of air conditioning, and attached or detached, among others. Also included in the SOC are the construction methods used to build each home, specifically site-built, modular, and panelized/precut. For this research study, the background microdata of

661,671 homes included in the SOC survey between 1999 to 2023 were collected and disaggregated by product type (detached vs attached single-family homes) and construction method (site-built, modular, and panelized/precut). This data was filtered by census division (New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, Pacific) to identify which had the highest level of adoption (i.e., total counts) of offsite construction over the past quarter century. For the SOC, "offsite" homes were defined as dwelling units built using either modular or panelized/precut methods (i.e., not onsite homes). Only attached single-family homes were included in the counts, those with a ground-to-roof shared wall (e.g., townhomes and duplexes), no units above or below them, and separate utility meters, heating/cooling systems. Manufactured (i.e., mobile) homes were not included. Descriptive statistics were used to summarize, characterize, and compare the data in the nine census divisions between 1999 and 2023. A single-factor analysis of variance (ANOVA) was used to identify statistical differences between the means of the nine census divisions in the time frame. A post-hoc, two-sample t-test assuming unequal variances was selectively applied to examine any differences between the two divisions with the highest home counts.

RESULTS/FINDINGS

The study found that the South Atlantic census division consistently had the highest adoption rate of attached permanent offsite residential construction (PORC) in the United States from 1999 to 2023 (Figure 1), producing a total of 2075 homes. The lowest number of PORC homes were produced in the West South Central division in that same period, with a total of 50 homes. For nine of the 25 years examined (2002, 2003, 2009, 2012, 2016, 2019, 2020, 2021, 2023), more offsite homes were produced in the South Atlantic division than all other divisions combined. Before the housing recession in 2008, the year with the lowest number of offsite homes recorded in the South Atlantic division (2008, n=82) was higher than the highest years of all other divisions. After the end of the recession in 2010, the year with the lowest number of offsite homes recorded in the South Atlantic division (2014, n=28) was higher than the highest years of all other divisions with the only exceptions in the East South Central division in 2017 (n=29) and the West North Central in 2022 (n=30), and tied in 2023 (n=28).

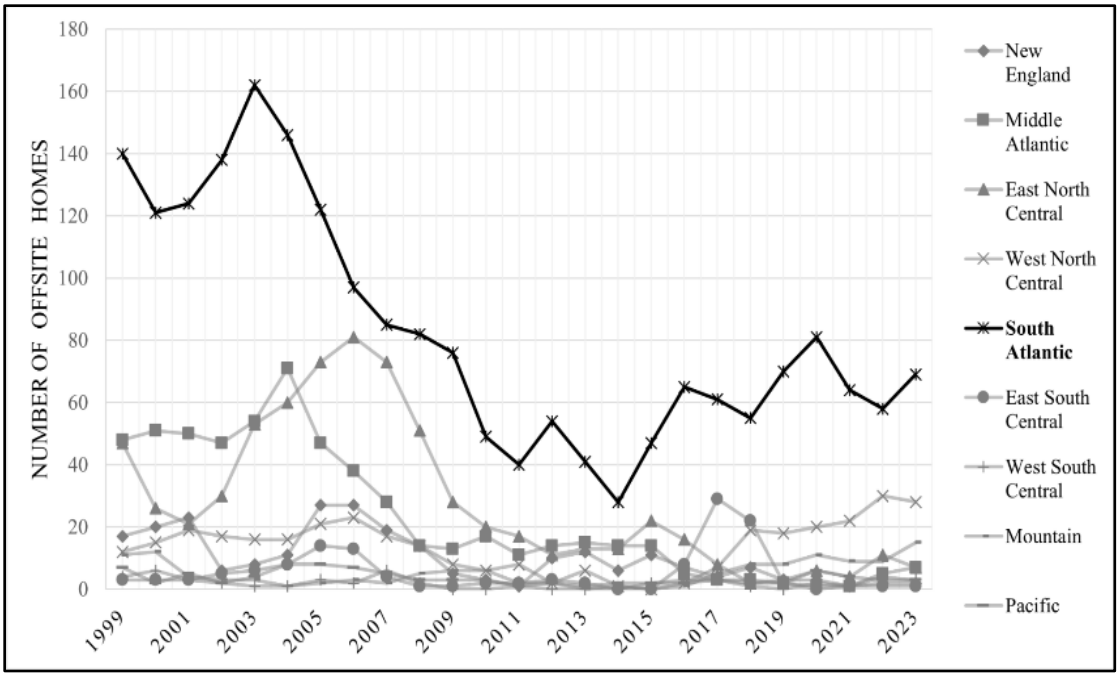

Figure 1. Number of attached offsite homes in each U.S. Census division between 1999 and 2023.

Nearly half (47.8%) of all offsite homes produced nationwide between 1999 and 2023 were in the South Atlantic division. As a proportion of total homes produced within each division, the South Atlantic division recorded the highest number of offsite homes (7.85%), nearly a full point higher than the next highest division, New England (Table 1). The West South Central division recorded the lowest rate (0.81%), approximately ten times lower than the South Atlantic division.

Table 1. Offsite Homes Produced in Each U.S. Census Division as a Proportion of Total Homes in the Division from 1999 to 2023.

Census Division	# Offsite homes	Total homes in each division (offsite and onsite)	Proportion of offsite homes in each division
South Atlantic	2075	26433	7.85%
New England	249	3565	6.98%
Middle Atlantic	573	8289	6.91%
East North Central	695	10386	6.69%
East South Central	134	2316	5.79%
West North Central	347	8502	4.08%
Mountain	129	9393	1.37%
Pacific	91	10005	0.91%
West South Central	50	6196	0.81%

Compared to all attached homes in all divisions nationwide (onsite and offsite), the division with the highest rate of offsite adoption was the South Atlantic division, producing 2.44% of all recorded homes (Table 2). The next highest producer was the East North Central division, producing 0.82% of recorded homes, approximately a third of the South Atlantic division. The lowest producer of offsite homes as a percentage of total homes produced nationwide was the West South Central division with 0.06%, roughly forty times less than the South Atlantic division.

Table 2. Offsite Homes Produced by Each U.S. Census Division as a Proportion of Total Homes Produced by all Divisions Nationwide from 1999 to 2023.

Census Division	# Offsite homes	Total homes in all divisions (offsite and onsite)	Proportion of offsite homes in all divisions
South Atlantic	2075	85085	2.44%
East North Central	695	85085	0.82%
Middle Atlantic	573	85085	0.67%
West North Central	347	85085	0.41%
New England	249	85085	0.29%
East South Central	134	85085	0.16%
Mountain	129	85085	0.15%
Pacific	91	85085	0.11%
West South Central	50	85085	0.06%

A single-factor analysis of variance (ANOVA) identified a statistically significant difference between the nine census divisions ($F(8, 216) = 54.82$, $P<0.000$). A post-hoc, two-sample t-test between the South Atlantic division and the next highest ranked division, the East North Central division, indicated a statistically significant difference between the two divisions ($P<0.000$).

DISCUSSION AND RECOMMENDATIONS

These results confirm findings from Assaad et al. (2022) and Rupnik (2014), who reported increased offsite activity in certain states in the South Atlantic division including Florida, North Carolina, and Virginia. They differ from some of their other findings that Pennsylvania, Texas, and California had similar or superior levels of offsite home production as those in the South Atlantic division. For example, the West South Central division, including Texas, was found by this study to have the lowest level of offsite activity in both count totals and proportionally within the division and nationwide. The reasons for these departures are possibly due to different methodologies. Assad et al. (2022) used survey data from a relatively small set of industry professionals to map offsite activity and openly acknowledged the limitations of the method to provide a comprehensive assessment of offsite home building. Rupnik's (2014) methodology—counting and mapping offsite companies by combining data from multiple sources—focused

more on examining offsite production facilities rather than the type and locations of the offsite units themselves. It is likely, even possible, that many of the offsite homes recorded in one state or census division were manufactured and shipped to other locations. Despite these differences, this research study and prior literature are in agreement that the South Atlantic division of the United States has consistently and disproportionately high levels of residential development for both onsite and offsite delivery methods.

To support the advancement of permanent offsite residential construction (PORC) in the United States the following recommendations are offered based on the findings of this research.

- **Home Builders**: PORC services are a rich opportunity for innovative and forward-thinking home builders to fulfill the potential of residential construction in the United States. Large and medium-sized production home builders—those with greater financial resources and stability—should lead the way by studying the South Atlantic division to identify which kinds of homes to build and where. One way to do this is to extend local or regional building networks to the South Atlantic to stay current with the construction methods and technologies of the busiest market of the country. Builders should also take advantage of current offsite market knowledge by looking to successful, often smaller and international, early-adopting companies for operational insights and best practices. Failed offsite ventures (e.g., Entekra, Veev, TopHat, L&G) should also be closely analyzed to avoid repeating their mistakes. Finally, home builders should use quality research from reliable sources to inform their business strategies.

- **Offsite Researchers**: Offsite researchers should upgrade and accelerate offsite publications with new and better research methods. Until standardized systems for tracking domestic offsite construction are instituted, researchers should make every effort to gather robust empirical data from reliable sources to verify or replace survey and interview data that have historically been the primary method for researching the market penetration of offsite construction.

- **Builder Associations and Local and State Governments**: The volume and velocity of residential development in the South Atlantic division relative to other divisions over the past quarter century has likely been one of the main forces driving home builders to search for new and innovative ways to deliver homes while maintaining acceptable standards of cost, quality, and production time. Stakeholders in the residential construction, specifically home builders associations and local and state governments, should work to replicate the market conditions that make the South Atlantic division prosperous and fertile for more innovations like PORC. Builder associations should also study the business environment in the South Atlantic with the express objective of lobbying their own local and state lawmakers for similar or better building conditions.

CONCLUSION AND FUTURE WORK

This study gathered source data from the U.S. Census's Survey of Construction to analyze the building methods used to deliver homes from 1999 to 2023 in the nine census divisions of the United States. It found that the South Atlantic census division performed significantly better than the other nine divisions in total offsite home counts (Figure 1). The study also found that the South Atlantic division had the highest proportion of offsite homes compared to all other divisions (Table 1). And it found that the South Atlantic division had the highest proportion of offsite homes compared to all homes from all divisions aggregated nationwide (Table 2). Considering these findings, more research is needed to understand why the South Atlantic division is doing better with offsite services. One theory espoused by this paper is that the high level of residential development in the area generally (onsite and offsite) has driven home builders to search for new and innovative ways to deliver homes and to distinguish themselves from the competition in cost, quality, and building-time. Future research should examine this theory and, if valid, should attempt to specify the market conditions that allowed offsite services to flourish in this area. Additionally, this study focused exclusively on attached offsite homes. Future research should include detached offsite homes (i.e., not connected to other dwellings either vertically or horizontally) to identify differences between markets, if any. Finally, more research is needed on mature offsite companies operating in European and Asian countries (e.g., Sweden and Japan) to better understand how their methods can be translated to American markets.

LIMITATIONS

The reliability of this paper depends on the micro data retrieved from the U.S. Census Survey of construction from 1999 to 2023 and is thus limited by the accuracy of those data. Also, this research focused specifically on permanent offsite residential construction (PORC) services and products as defined in the Introduction to the paper. Offsite definitions vary frequently in the literature (Smith, 2023) and care should be taken to avoid making incomplete or erroneous comparisons between, or assumptions about, various offsite products, services, or service providers (e.g., manufactured, modular, panelized, prefabricated, and others).

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Residential Construction Education and Architecture

Bridging the Gap: University-Led Partnerships Advancing Affordable Rural Housing in Indiana

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ABSTRACT

The lack of access to affordable, quality housing is an ongoing challenge in many rural U.S. communities. This paper details a collaboration between a university initiative, United States Department of Agriculture (USDA) rural development programs, local governments, and the National Housing Endowment to tackle rural housing shortages through a service-learning framework. This initiative brings together construction management faculty and students in a large-scale Midwestern university, county officials, and nonprofit housing providers to develop affordable, community-integrated housing solutions. Together with these, the initiative aims to identify potential funding sources, such as USDA and state grants, provide assistance in the grant application process, and leverage university resources throughout planning, design, and construction management. Participating in housing projects allows students to gain practical experience while assisting in the provision of necessary homes in rural areas with limited resources. In addition to construction efforts, this initiative emphasizes education and outreach to confront systemic barriers such as contractor shortages, aging housing stock, and community resistance to new development. This ongoing initiative explores how teamwork between academia, communities, and local and state governments can shape affordable rural housing models that are accessible and repeatable. The framework-building process aims to leverage the strengths of higher education, local expertise, and federal support to design a scalable approach

for improving housing access in underserved rural regions.

INTRODUCTION

Throughout the United States, significant challenges for rural communities persist with the ongoing lack of safe, affordable, and high-quality housing (Antin et al., 2024; Gershenson and Desmond, 2024; Staveski, 2024). The combination of an aging housing stock, a shortage of contractors, and the high cost of construction has left many low-income families in rural areas without access to adequate housing or the critical home repairs that they require. These existing challenges require innovative solutions and collaborative methods to leverage federal programs, nonprofit knowledge, and academic resources to fulfill housing needs and promote long-term community development (National Rural Housing Coalition, 2025).

Because of their unique position to serve local communities, land-grant universities are uniquely positioned to play a role in addressing these challenges. Universities can use construction management, construction engineering, and other programs to provide technical knowledge, engage students in service-learning projects, and build partnerships that integrate workforce development with community impact. This paper details a university-led initiative that aims to create a replicable framework for affordable rural housing repairs and construction by integrating federal and philanthropic resources with local nonprofit, academic, and government partnerships.

This initiative focuses on the USDA Single Family Housing Repair Loans and Grants (Section 504) (USDA, 2025a) and the Mutual Self-Help Housing Technical Assistance Grants (Section 523) (USDA, 2025b), which offer funding mechanisms for repairs and collaborative homebuilding efforts. The USDA Single Family Housing Direct Loan (Section 502) (USDA, 2025c) program provides a further opportunity for low-income families to achieve affordable homeownership. To develop and pilot this framework, the university is receiving support from the National Housing Endowment's Housing Education Leadership Program (HELP) Grant (NAHB, 2024), which is funding the discovery, conceptualization, and design of this university-led model.

To achieve this goal, the existing nonprofit infrastructure, which includes groups such as Habitat for Humanity and NeighborGood Partners, may be active partners in this process. Across the U.S., NeighborGood Partners and other non-profits listed in Table 1 oversee the mutual self-help model. This model strives to merge these resources with academic service-learning, developing a scalable model that will help rural residents while preparing construction management students for the housing sector workforce.

LITERATURE REVIEW

According to the U.S. Department of Agriculture (USDA) and housing research organizations, such as PEW, the National Rural Housing Coalition, and Housing Assistance Council, many rural families live in homes that require significant repairs or lack basic modern amenities (Cornelissen and Staveski, 2025; Lahr et al., 2023). The dispersed nature of rural populations

often complicates infrastructure development and increases construction costs, further limiting access to quality, affordable housing.

Fewer homes are being built per household than at almost any time in U.S. history, and it is even worse in rural communities (Cornelissen and Staveski, 2025; White, 2024). Developers in less populated areas cannot tap into the economies of scale available in urban centers, making materials and labor more expensive. Rural areas are also seeing their populations stagnate or decline as younger people opt for urban living, adding to the gamble involved in speculative building (Raice, 2018).

Studies show that collaborative approaches that integrate federal programs, nonprofit organizations, and local governments are among the most effective strategies for meeting these needs (Johnson, 2020; Jaques et al., 2023). In particular, partnerships that combine technical expertise with service-learning initiatives have demonstrated success in both addressing housing deficits and preparing future construction professionals (Hughes, 2025.).

Table 1 below highlights examples of nonprofit organizations that currently administer USDA Section 523 (Mutual Self-Help Housing TA Grants) and similar models across the U.S. These organizations, together with USDA Section 502 and 504 programs, form the backbone of a replicable university- led framework.

Table 1. Examples of Existing Nonprofit Organizations, Programs, and Their Locations Served.

Organization	Program Focus	Regions / States Covered
NeighborGood Partners	Section 523 TA grants	21-state Northeast region (e.g., MA, PA, CT, IN)
Rural Community Assistance Corporation (RCAC)	Section 523 TA grants (tech. assistance)	Western U.S. support for 46 active grantees
Habitat for Humanity (local affiliates)	Sweat-equity home builds often coordinate 523 self-help	Nationwide via 70+ countries; U.S. affiliates administer local builds.
NeighborWorks America	Technical assistance, training, community development	Over 240 organizations across all 50 states + DC + Puerto Rico
The Fuller Center for Housing	Home builds and repairs; sweat-equity; student engagement	Active in ~60 U.S. cities (e.g., Americus, GA).
Homewise (NM-based)	Home improvement, purchase financing	New Mexico (Santa Fe, Albuquerque) with consulting reach to OR, NC.
Community Action Agencies / RCAPs	Section 523 and self-help	Nationwide, via state/regional RCAP networks and local agencies.
South Central Community Action Partnership (SCCAP)	Section 523 TA and HUD self-help programs	Idaho region (e.g. Twin Falls).

UNIVERSITY-LED FRAMEWORK CONCEPT

Vision for the Framework

The university-led framework aims to connect federal housing programs, nonprofit expertise, and workforce education. The initiative strives to meet essential rural housing needs, while simultaneously training future construction professionals by utilizing the resources made available through the USDA's Section 502, 504, and 523 programs. Through the establishment of a model that is scalable and replicable, the aim is to facilitate collaboration between construction management faculty and students, along with local communities and housing organizations, to provide affordable home repairs and new housing projects.

This framework envisions the university as a technical resource and a facilitator of community-driven development with a service-learning model. Service-learning offers students practical construction skills and experience in budgeting, scheduling, and quality control, while communities gain access to an affordable housing solution and increased access to federal programs.

Core Components of the Framework

1. Integration of USDA Programs

• Section 504 (USDA, 2025a) funds are used to address immediate repair needs for low-income households, such as roofing, weatherproofing, and accessibility upgrades.

• Section 523 (USDA, 2025b) supports partnerships with nonprofits that provide technical assistance for mutual self-help housing construction. Students participate in these builds under faculty guidance, contributing to labor efficiency while learning essential project management skills.

• Section 502 (USDA, 2025c) loans offer opportunities for families to transition from renting to affordable homeownership, with university and nonprofit teams assisting in project feasibility and site planning.

2. Partnerships with Nonprofits and Housing Organizations

• Habitat for Humanity provides a proven model of community-based construction that complements USDA programs. Their affiliate network offers potential for collaboration, where student teams can assist with planning, labor, and technical expertise.

• NeighborGood Partners provides crucial support to mutual self-help grantees by offering both compliance expertise and effective training. The framework's foundation is fortified, and its impact is broadened through the partnership with NeighborGood Partners.

• Various other nonprofit organizations, including Rural Community Assistance Corporation (RCAC), Self-Help Enterprises in California, Community Action Agencies, and Rural Community Assistance Partnership (RCAP) affiliates, provide further examples that may be examined and modified for application at the local level.

3. National Housing Endowment HELP Grant

• The HELP Grant (NAHB, 2024) is instrumental in supporting the discovery and conceptualization phase of this framework. By supporting research into best practices, developing pilot project designs, and integrating curriculum, the program ensures its academic rigor and practicality.

Academic and Workforce Integration

The framework is both a housing solution and a workforce development strategy. Construction management students take part in all phases of a project lifecycle, including initial site evaluations and extending through scheduling, financial oversight, and actual construction activities. These service-learning opportunities help students understand the industry better and enhance their technical and interpersonal skills by bridging the gap between classroom instruction and workplace realities.

In addition, through their involvement with USDA programs and nonprofit models, students can gain knowledge in areas such as public policy, housing finance, and community engagement, which are usually not covered extensively in conventional construction studies. Therefore, the framework delivers a dual advantage, assisting with the requirements of rural housing while also fostering graduates who possess industry-ready skills and a high degree of social awareness.

Scalability and Replicability

This framework's central aim is to be replicated not only at other universities but also in a variety of rural environments. With the goal of creating an implementation guide that other institutions can use, the program intends to document the processes, partnership models, and lessons learned throughout the pilot projects. The collaborative effort of federal funding, nonprofit expertise, and academic involvement forms a lasting structure, capable of adjusting to the ever-changing requirements of rural communities. With additional support from organizations like NeighborGood Partners, this framework has the potential to become a model for university-led rural housing initiatives.

IMPLEMENTATION ROADMAP

A six-phase model is used in the implementation of this framework to ensure the process results in institutional readiness, encourages effective community engagement, and establishes long-term scalability. Securing grantee eligibility and getting program authorization are the initial actions that must be taken to begin the process. The process to manage programs such as Section 502, 504, and 523 begins with institutions assessing their eligibility by the standards set by USDA Rural Development and then completing the official application, this will require

submission of information like organizational capacity, financial systems, and proposed service areas. Upon approval, institutions are required to create internal compliance measures to manage federal funds well and satisfy reporting needs, common for academic institutions.

Following authorization, the next phase involves assessing community needs and aligning with key partners while simultaneously working through a feasibility handbook provided by NeighborGood Partners. This handbook may look different in regions of the United States not covered by NeighborGood Partners. Assessing community needs includes identifying rural areas with significant housing challenges through collaboration with local housing authorities and USDA field offices. Subsequently, institutions will formalize alliances with nonprofit housing developers, community-based organizations, and local governments, concurrently organizing funding channels to assist with project implementation.

The third phase focuses on program design and curriculum integration. Academic institutions align construction management coursework, such as capstone projects or service-learning, with the timeline and milestones of housing projects. Under faculty mentorship, students take on defined roles such as site supervisors, estimators, and schedulers, gaining hands-on experience in project planning, budgeting, and stakeholder coordination. This integration ensures that educational objectives are met while contributing to meaningful community development.

The fourth phase involves the pilot project's implementation, which initiates a couple of housing program options, for example, Section 504 home repairs or a Section 523 mutual self-help build. As proof-of-concept initiatives, these pilots include detailed documentation of workflows, costs, and any obstacles encountered, and the team is actively working to gather feedback from homeowners, nonprofit partners, and student participants in order to refine their implementation strategies, ultimately leading to improved outcomes.

The fifth phase focuses on evaluation and metrics. Quantitative data such as the number of homes repaired, student hours contributed, project costs, and timeline adherence are tracked. Simultaneously, qualitative assessments measure student learning achievements, the growth of leadership skills, and positive contributions to the community, which encompasses evaluations of homeowner satisfaction and improvements in their living conditions. These insights inform continuous improvement and guide future iterations of the program.

In the final stage, the framework is documented and prepared for expansion. A comprehensive playbook is developed, outlining operational procedures, funding alignment strategies, partnership models, and educational integration practices. Lessons learned from the pilot phase are used to refine the model, which is then positioned for replication in additional communities or states. This final phase ensures the framework's sustainability and scalability, enabling broader impact across rural America. Figure 1 below further illustrates this proposed roadmap.

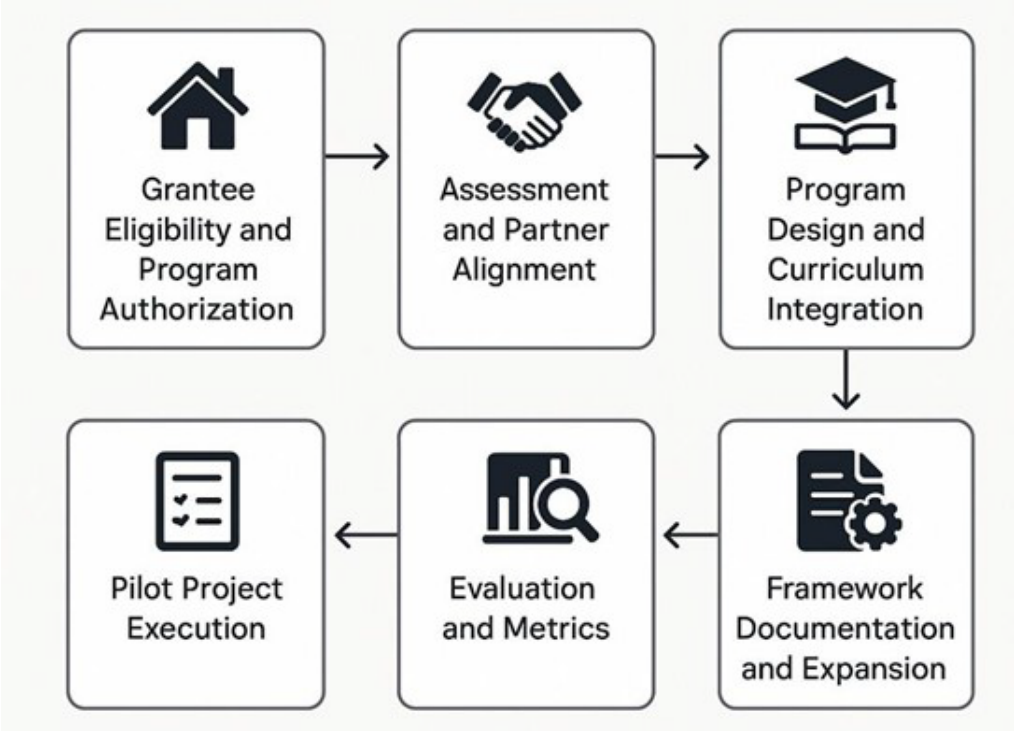

Figure 1. The proposed implementation roadmap for rural housing and construction management education framework.

CONCLUSION

Finding solutions for the affordable housing crisis in rural America requires innovative and collaborative approaches, such as connecting federal resources, the specialized knowledge of nonprofits, and programs for workforce development. By utilizing USDA programs such as Sections 502, 504, and 523, the university-led framework is being designed to create impactful housing solutions, and it will also involve collaborations with groups like NeighborGood Partners, as well as provide experiential service-learning opportunities for construction management students.

By incorporating academic resources and funds from governmental and charitable organizations, including support from the National Housing Endowment's HELP Grant, this specific model effectively demonstrates how academia can serve as a strong partner in both technical operations and initiatives centered on community involvement. The framework offers a model that is customizable and scalable, making it adaptable for other universities to address similar housing needs in underserved rural communities. Faculty have advanced through Phase 1 of the proposed implementation roadmap, which included involvement in a self-help housing orientation facilitated by NeighborGood Partners and the assessment of program eligibility criteria from the USDA General Counsel. The faculty members are presently progressing through the second

d phase of the suggested implementation roadmap, focusing intently on the feasibility handbook. Along with improving the standard of living for families in rural locations, the framework simultaneously furnishes students with the opportunity to develop practical skills, gain leadership experience, and to cultivate a more comprehensive understanding of the societal implications linked to construction initiatives. As the pilot projects progress and evolve, the knowledge gained and practical experience will serve as the basis for a detailed playbook designed for extensive implementation and approval, which will result in a long-term plan to improve rural housing and provide the next generation with the skills needed to succeed as construction leaders.

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The Forgotten Middle Child of the Industry: Low-Rise Residential Multifamily Buildings—Built Like a House, Expected to Perform Like a Tower

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ABSTRACT

In many areas of the United States, wood-framed, low-rise (four- to six-story) multifamily buildings make up a large percentage of the overall residential building stock. These buildings are relatively simple in nature, without the complex structural and building enclosure systems of urban high-rise towers. They share many common features of traditional single-family home construction, including wood framing, shingle roofing, and simple mechanical systems. Considering this, it seems easy to just "upscale" a single-family home to achieve a successful multifamily project. However, these buildings are truly the middle child of the building family, not as needy as the firstborn, not as self-sufficient as the youngest, but still requiring the same level of care and attention as both (even though they may not always get it).

In this author's experience, these apparently simple buildings require significantly more than just simple upgrades to a single-family design. Failure to properly design for the larger scale and complexity of a multifamily building can result in a wide range of problems, including water leakage, poor mechanical system performance (and the resulting comfort complaints), noise and odor transmission between units, and, as a result, costly litigation between residents, owners, and developers.

Complicating matters, the types of designers and builders with the experience to complete a successful multifamily project often do not seek this type of work, and highly skilled single-family home builders are rarely cost-competitive on multifamily projects.

This paper discusses the differences between single-family and low-rise multifamily construction and describes common issues that arise during both design and construction. The author will present examples from recent projects, including some under dispute, to highlight these issues. Lastly, the difficulty and expense of repairing these issues will be evaluated, further demonstrating the importance of quality design and construction for these building types.

INTRODUCTION

Low-rise multifamily buildings are often treated as scaled-up versions of single-family homes, leading many project teams to apply familiar materials, systems, and construction practices without fully accounting for the unique demands of the higher density and shared infrastructure that multifamily buildings entail. While these buildings benefit from faster construction and fewer code-mandated inspections compared to mid- or high-rise structures, this simplicity can mask critical complexities in design coordination, system integration, and long-term performance. Challenges such as inter-unit sound and odor transmission, mechanical system/airflow imbalances, and moisture control are amplified in multifamily environments. Small design oversights in these buildings can lead to significant and widespread consequences. Compounding the issue is the limited oversight required by building codes, or in some cases, the lack of adherence to these codes, which often do not require special inspections or performance testing for these projects. This paper draws on field experience to highlight common problem areas in low-rise multifamily building design and construction and offers guidance for improving outcomes through thoughtful planning, material selection, and QA/QC processes tailored to the multifamily context.

The observations presented in this paper are drawn from the authors' involvement in low-rise multifamily projects (four to six stories) across the United States market, mainly the East Coast, including new construction, post-occupancy investigations, and dispute-related forensic reviews. While individual project details are not provided, the recurring patterns discussed reflect systemic industry trends rather than isolated incidents.

Material Selection

In low-rise multifamily buildings, material selection is one of the most critical and underestimated decisions. Because these buildings are often framed with wood and appear structurally similar to single-family homes, builders and designers frequently default to the same materials that they have used for years in residential work. For buildings that are three stories or fewer in height, they may even be held to the same building code requirements (i.e., residential rather than commercial). However, the demands of a multifamily context, including higher occupant density, higher structural loads, greater exposure, more repetition, and shared systems, can cause these familiar materials to underperform or fail. What works on a house with four exterior walls and a single occupant group doesn't necessarily work on a 60-unit building, even if the building code technically allows it. Unfortunately, the building code rarely prohibits these choices outright, so it falls to the design and construction team to anticipate the risks. Here are three common examples of single-family materials that often cause problems in low-rise multifamily construction:

Fiber Cement Panels Without a Ventilated Rainscreen

Fiber cement cladding is widely used in single-family construction for its durability, fire resistance, and cost effectiveness. In small-scale applications, it performs well even when installed directly over house wrap without a dedicated drainage plane. But in multifamily buildings, especially over multiple stories and large elevations, the cumulative moisture load

behind the cladding is significantly greater. Without a ventilated rainscreen, typically a 3/8" to 3/4" gap for drainage and drying, fiber cement panels are prone to moisture accumulation, which can lead to staining, warping, cracking, and freeze-thaw damage. These issues often emerge within a few years of occupancy. While rainscreen assemblies are best practice and required by some jurisdictions (e.g., Canada's NBC or Oregon Residential Specialty Code in high rainfall zones), they are often omitted elsewhere to save cost or simplify details, leading to premature failure. When the same system is applied on a much larger scale, the number of untreated holes to install the planks increases proportionally and the probability of any accidental water leakage through these penetrations increases, especially if a "single-family" weather barrier is used (discussed in more detail in the following section). "Death by a thousand cuts" is an appropriate analogy to describe this phenomenon. On the other hand, the cladding systems in high-rise buildings are typically held in place with Z-girts or thermally broken cladding attachment systems that can be treated and sealed prior to installation of the cladding panels. Lastly, the general design of low-rise multifamily buildings is often more of a commercial appearance, with low-slope roofs and no roof overhangs. The humble roof projection on a single-family home is one of the best ways to manage moisture in the exterior walls, as it directly protects the top of the wall and greatly reduces wetting of the facade materials under most conditions. While wind-driven rain will still reach the majority of the wall surface, it will generally affect only the wind-facing elevations, and these events are much less frequent than vertical rainfall. This is a good example of a time-tested and effective design feature of wood frame construction that is widely ignored when these buildings are scaled up.

Conventional Housewraps in Complex Facade Assemblies

In single-family homes, mechanically fastened housewraps (spun-bonded polyolefin and similar synthetic membranes) are commonly used as water-resistive barriers (WRBs). These can be sufficient when applied behind siding or shingles in a relatively straightforward wall assembly. However, in multifamily buildings with complex geometries, deep window penetrations, and multiple facade transitions, these membranes become vulnerable, especially at horizontal projections or interruptions.

Lapping errors, fastener tears, and poor detailing around penetrations allow water intrusion. Housewrap-style WRBs provide little to no self-sealing at fastener penetrations, unlike thicker self-adhered or fluid-applied membranes, making them more vulnerable to leakage at cladding attachments where a large number of blind penetrations are made (as described above). When these systems are used without fully adhered flashings or transitions to other control layers, water intrusion can bypass the WRB entirely. Moreover, in taller buildings, wind pressures and stack effect can drive air and water into poorly sealed joints, where both can travel between the sheathing and the WRB. Unlike a small house, where minor leaks may be benign or quickly noticed, in multifamily buildings, they can go undetected behind finishes until systemic damage occurs. A fully adhered WRB or fluid-applied membrane can offer better durability, but these are often dismissed as "upgrades" rather than necessities. The installation of these "upgrades" often requires certification or training from the manufacturers, which makes them even less financially viable.

OSB Sheathing Without Moisture Management

Oriented strand board (OSB) is a staple in single-family construction due to its low cost and widespread availability. However, when used as exterior sheathing in multifamily buildings, particularly those with long construction schedules or delays between structural completion and cladding installation, it is highly vulnerable to moisture degradation. OSB swells, delaminates, and loses structural integrity much more quickly than plywood or treated sheathing. In multifamily projects, where framing may sit exposed for weeks or months during staging, this exposure is often unavoidable. Some codes require exposure-rated panels (APA Exposure 1 or Exterior), but many builders assume standard OSB will suffice or take the "everyone uses OSB" approach without considering project specifics. The decision may also be rooted in cost, since OSB will typically cost 50-60% more than plywood. While this may be an acceptable expense on a single-family house, when scaled up to a much larger development, the cost may become prohibitive for some budgets (despite being justified). Without aggressive moisture management, including WRBs installed immediately after sheathing goes in or suitable temporary protection, the results can include warped walls, buckling cladding, and weakened lateral resistance, leading to expensive remedial work before the building is even complete. There are various industry resources to provide guidelines to designers and builders to reference during design and construction processes. For instance, ASTM E2266 - Standard Guide for Design and Construction of Low-Rise Frame Building Wall Systems to Resist Water Intrusion is a guide that provides a common framework for evaluating the weather resistance, durability, and performance of building wall systems and related components, including decks, doors, windows, penetrations, and sealant joints, extending beyond the requirements of building codes. It serves as a versatile resource: public agencies may use it to establish performance standards; inspectors can reference it during construction oversight; architects and engineers can apply it to material selection, detailing, specifications, and submittal reviews; and contractors can use it as a checklist for field quality control. By supporting consistent practices across design, construction, and inspection, ASTM E226 helps ensure that building enclosures meet durability and performance expectations.

QUALITY ASSURANCE AND QUALITY CONTROL

In the transition from single-family to low-rise multifamily construction, one of the most overlooked yet critical shifts is the increased need for structured quality assurance (QA) and quality control (QC) procedures. While single-family homes typically rely on basic local inspections and builder knowhow, multifamily buildings, despite appearing "simple" in scale, have interconnected systems and shared boundaries that demand more rigorous oversight. Unfortunately, low-rise multifamily buildings often fall into a regulatory gray zone, with fewer mandatory inspections than commercial or high-rise buildings (especially those that fall under the residential code). This leaves quality almost entirely in the hands of the builder, which can be a risky proposition without a dedicated QA/QC program.

Under the International Building Code (IBC), multifamily buildings of Type V construction (common in four- to six-story wood-framed structures) are typically not subject to the special inspections requirements outlined in Chapter 17, unless they incorporate certain systems or

materials, such as structural steel, fireproofing, or post-tensioned concrete. For example, IBC Section 1704.2 requires special inspections only when mandated by Section 1705. For example, Section 1705.2 requires special inspections for structural steel connections such as welding and bolting, while Section 1705.3 mandates inspections for reinforced concrete construction, including verification of rebar placement, mix design, and placement procedures. In Type V wood-framed multifamily structures, many elements, such as framing, insulation, sheathing, roofing, and even many air and water barrier assemblies, do not require third-party verification under code. This can result in the enclosure being built and closed in without ever undergoing a detailed technical inspection.

In high-rise or more code-intensive construction (e.g., Type I or II), QA/QC is enforced through external pressure: curtain wall anchor tests, spray-applied fire-resistive material thickness testing, smoke control commissioning, and building envelope air leakage testing (per IECC or ASHRAE 90.1, 2019). However, for low-rise multifamily projects, the only required envelope performance test may be a blower door for the whole building and the dwelling units, and in some jurisdictions, even this is not mandated at the unit level if tested by sampling. For buildings covered under the residential code, the International Energy Conservation Code (IECC) allows for sampling in multifamily under certain size limits (IECC R402.4.1.2), which means problems can go undetected until complaints begin post occupancy.

This lack of mandated oversight is compounded by the fact that many developers assume that successful practices from single-family construction, such as relying on sporadic visual inspection and builder craftsmanship, are sufficient. But in a multifamily context, even small defects, for instance, an unsealed top plate or misaligned duct damper, may be repeated dozens or hundreds of times and lead to systemic failures affecting multiple units.

This lack of oversight is especially consequential when it comes to mechanical, electrical, and plumbing (MEP) systems. These systems are frequently designed for cost efficiency using decentralized equipment, such as unitary split systems and inline heat recovery units and or energy recovery ventilators, as well as centralized systems for kitchen or bathroom exhaust and sometimes ventilation air. But unlike in a single-family home, where one system serves one family, each unit in a multifamily building

interacts with others through shared shafts, plenums, or pressure relationships. Without rigorous testing and balancing (TAB) procedures, systems are often left improperly commissioned, resulting in widespread performance problems: over-ventilation in some units, under-ventilation in others, persistent negative pressures that draw in unconditioned or odor-laden air, and temperature imbalances between rooms or zones. These issues affect occupant comfort, indoor air quality, utility costs, and even building durability (e.g., through increased moisture loads or condensation on cold surfaces).

Unfortunately, formal testing and balancing are frequently deprioritized or eliminated in low-rise projects due to perceived cost savings or scheduling pressure (because, after all, “Who needs all this testing for a residential project?”). TAB reports, when performed, may be incomplete,

generic, or based on assumptions rather than actual measured airflow. Duct leakage testing and airflow verification are often performed on a sampling basis, leaving many units unchecked. Field fixes, such as blocking supply vents to "balance" temperatures, may go undocumented. These issues are rarely identified until tenants begin to complain or when multiple units show signs of moisture damage, pressure, related envelope failures, or persistent comfort issues. At that point, diagnosing the problem becomes difficult and expensive, often involving invasive inspection to access ductwork or equipment, as well as costly rebalancing efforts.

To address these gaps, project teams must adopt a QA/QC approach that includes not only building envelope detailing and sequencing but also performance testing of MEP systems. This includes ensuring that mechanical systems are installed per design, that duct leakage and airflow rates are actually verified unit by unit (not by sampling), and that all components are accessible for maintenance (an issue which has recently been added to some codes and standards such as ASHRAE Standard 90.1, 62.1, and International Mechanical Code, Chapter 3). Cross-trade accountability must also be built into the process; if a framing crew compromises an air barrier or a mechanical subcontractor shifts a duct riser, these issues must be documented and corrected before concealment. Without this level of diligence, what seems like a simple, code-compliant project on paper can quickly become a high-risk, low-performing building.

A robust QA/QC program should include design phase reviews (to catch coordination issues before bidding), pre-construction submittal reviews (including performance mockups of windows and walls), mid-construction inspections (targeted at transitions, penetrations, and sequencing), and post-construction testing (including blower door testing for each unit, duct leakage testing, and acoustic field testing). These steps are not always required by code but are essential to ensure that code-minimum design does not result in substandard performance.

SYSTEMS APPROACH

A single-family home is often considered as one singular mass and the interior space is treated as a singular volume where the occupants are in relatively similar schedules and have similar preferences on what the temperature should be and what the house should "smell" like. Often the same mentality carries over to mid-rise residentialbuildings, despite the reality of those buildings being extremely different. Every dwelling unit is its own habitat with different preferences in room temperature, daily schedules, and sense of what is a "good" or "bad" smell. In mid-rise multifamily buildings, dwelling units share demising walls, exhaust ducts, and sometimes even fresh air ductwork. These are all potential means of allowing the air in one dwelling unit to migrate into another if not designed, constructed, or optimized with the right tools and mindset.

One of the most commonly overlooked issues is the transmission of odor and sound between units, which is typically exacerbated by improper construction of demising walls and poorly designed shared ventilation systems. Demising walls, for instance, are frequently assumed to be sufficient if they meet the minimum fire and structural separation code requirements. However, without proper air sealing, insulation, and attention to flanking paths such as top plates, electrical penetrations, and floor-wall intersections, these walls, which may work well for a singular

volume, will fail to meet the specific requirements of a multifamily building. Sound travels easily through gaps, unsealed penetrations, or even continuous framing members. Likewise, cooking odors, cigarette (and more recently, given changes to legality, marijuana) smoke, and bathroom humidity can migrate into adjacent units through these unsealed gaps, driven by the pressure differentials created by wind, stack effect, or mechanical system imbalances. When shared exhaust ducts are installed without backdraft dampers or zone separation, air intended to exit one unit can be drawn into another, especially in low-rise buildings where vertical shafts are shorter and pressure control is less reliable. The design of duct systems can impact this, since the long and often complex runs of ductwork, including high-resistance elements such as fire and smoke dampers, needed to support multiple units are very different from the simple runs used in single-family homes. Poorly designed or constant-section ducts can result in significant imbalances in airflow (and by association, space pressures) as, in the example of exhaust runs, the units closer to the fan may receive a disproportionate amount of airflow while units at the end of the run might see no flow at all or backflow from other units. This is particularly problematic in kitchens and bathrooms, where high-odor or high-moisture air needs to be quickly and completely removed. In a single-family home, these pathways terminate directly outdoors, but in a multifamily setting, poor duct design can cause this air to recirculate into neighboring spaces.

Fresh air supply systems present a parallel problem (when not self-contained within units). Shared HRV/ERV ductwork or centralized supply systems, if not properly balanced, can allow odors or even noise to be pushed from one apartment into another. Additionally, if return and supply airflows are not matched, positive or negative pressure zones can form in individual units, effectively sucking air through any available bypass path, whether that be a shared soffit, a utility chase, or a poorly sealed electrical box in a party wall. All of these issues become magnified when builders apply single-family practices such as shared attic spaces, non-dedicated return pathways, or unbalanced supply ducts, failing to account for the number of connected units and the cumulative impact of small leaks or misalignments.

The result is a building that may pass inspection but fails to perform, leading to noise complaints, odor disputes, and eventual legal and reputational consequences for developers. Ultimately, success in low-rise multifamily buildings demands a mental shift from isolated homebuilding to systems-oriented construction that treats the building as an interconnected organism. Without that shift, these “simple” buildings can become surprisingly high-risk.

TRADE COORDINATION

In low-rise multifamily construction, successful project delivery depends not just on individual workmanship but on the seamless coordination between trades. While the basic systems, wood framing, batt insulation, membrane barriers, split HVAC systems, and plumbing risers are familiar to most subcontractors, the tight sequencing, repetition, and layering inherent in multifamily buildings create unique challenges. In many cases, one subcontractor’s scope becomes the substrate or dependency for another’s, meaning that a lack of coordination can compromise the performance of the overall assembly or result in substandard work by one contractor being concealed by another before it can be repaired. This is particularly true for

interdependent systems such as the building enclosure, where framing, sheathing, air barriers, penetrations, MEP rough-ins, and cladding all interface at the same location within a narrow construction window. In these situations, even minor oversights such as improperly routed ductwork, misaligned plumbing stacks, or unsealed penetrations can compromise the continuity of air, thermal, and fire barriers, often with long-term consequences that are difficult or impossible to trace after enclosure is complete.

A frequent cause of such failures is not outright negligence, but rather a lack of trade familiarity with adjacent systems and their functions. For example, framers or mechanical subcontractors may not fully understand the performance role of a fluid-applied air barrier and inadvertently puncture it during rework or layout changes.

Similarly, electricians may drill through fire-rated shaft walls or demising walls without restoring the firestop system, simply because they were not made aware of its sequencing requirements (which do not exist in single-family construction). These types of damages often stem from siloed scopes of work, incomplete handoffs, and schedule pressures that incentivize speed over coordination. In a multifamily building, where these interfaces are repeated dozens of times across units, balconies, shafts, and corridors, even minor coordination gaps can turn into systemic failures affecting comfort, safety, and code compliance.

Equally problematic is the lack of communication when damage occurs. All trades will, at some point, interfere with another's completed work, whether by accident, oversight, or out of necessity to complete their own scope. What determines the outcome is not the mistake itself, but rather how it gets handled. On well-run projects, subcontractors are trained and expected to report damage to previously completed

work, allowing for immediate inspection and repair before concealment. On projects without this culture of accountability or with minimal oversight, damaged insulation, compromised membranes, and displaced sealants are often buried behind drywall or cladding, never to be seen again, until they cause complaints, failures, or lawsuits.

Unfortunately, because low-rise multifamily buildings often fall outside the scope of special inspections (per IBC Chapter 17), there is little external enforcement to catch these issues before it's too late. This places the burden squarely on the contractor's QA/QC process and on-site supervision.

To reduce these risks, contractors must prioritize inter-trade awareness and proactive communication. This includes trade-specific coordination meetings, detailed sequencing plans, and clear accountability protocols for damage reporting and repair. Educating subcontractors on how their work interfaces with others, and how to flag problems when they arise, can be the difference between a functional building and one plagued with latent defects. In short, low-rise multifamily buildings require a shift from siloed execution to collaborative construction.

CONCLUSION

Low-rise multifamily buildings may appear simple due to their wood-framed structure and resemblance to single-family housing, but they carry complexities that are frequently underestimated. Their success relies not merely on code compliance, but on disciplined system integration, deliberate material selection, coordinated trade execution, and structured quality assurance processes. While building codes provide flexibility for these structures, that flexibility shifts responsibility onto the design and construction team. Without proactive oversight and systems-based thinking, these projects risk becoming sources of long-term occupant complaints, moisture-related failures, and costly litigation.

The recurring patterns that we observed across multiple projects are not isolated anomalies, but predictable outcomes of treating low-rise multifamily buildings as scaled-up houses rather than as a distinct building typology. Table 1 summarizes common failure patterns and corresponding best practices that can significantly reduce performance risk.

Table 1: Recurring Failures in Low-Rise Multifamily Construction and Recommended Best Practices.

Category	Recurring Failure	Root Cause	Consequences	nmended Best Practice
Cladding and Moisture	Rainscreen systems without a ventilation cavity.	Scaling single-family detailing to larger facades.	Water leakage, premature deterioration, trapped moisture, freeze-thaw damage.	Provide ventilated rainscreen cavity, include drainage detailing and flashing transitions.
WRB Selection	Mechanically fastened housewrap in complex assemblies.	Cost-driven substitution, lack of self-sealing at fasteners.	Concealed and visible water leakage, systemic sheathing damage.	Use fully adhered or fluid-applied WRBs, inspect transitions prior to concealment.
Sheathing	OSB exposed during extended construction.	Schedule delays, inadequate temporary protection.	Swelling, loss of structural capacity, cladding misalignment.	Install WRB immediately after sheathing, consider plywood or treated panels when exposure risk is high.
QA/QC	No structured enclosure inspection.	Reliance on minimum code inspections.	Repeated systemic defects across units.	Implement phased QA/QC plan, including mockups, mid-construction inspections, and post-construction testing.
Mechanical Systems	Incomplete TAB or sampling-based testing.	Budget and schedule pressure.	Pressure imbalances, odor transfer, condensation risk, occupant comfort complaints.	Require unit-by-unit airflow verification and full TAB documentation.

Demising Assemblies	Unsealed penetrations in party walls.	Trades unaware of air and sound separation requirements.	Odor migration, acoustic complaints, litigation risk.	Air-seal all penetrations, inspect before drywall, conduct field sound testing.
Trade Coordination	Damage to air and fire barriers during MEP rough-in.	Siloed scopes, no damage-reporting protocol.	Hidden defects, fire and life safety risk.	Hold pre-install coordination meetings, require documented damage repair sign-off.
Ventilation Systems	Shared exhaust without proper dampers or balancing.	Inadequate design for multi-unit pressure dynamics.	Backdrafting, odor cross-contamination.	Provide backdraft dampers and balance systems across full vertical stack.

Preventing these issues requires more than technical detailing; it demands structured coordination across all project phases. Low-rise multifamily buildings often fall outside the enhanced inspection frameworks applied to high-rise construction, making internal accountability even more critical. Table 2 outlines a practical stakeholder coordination framework that aligns responsibility with project phase.

Table 2: Stakeholder Coordination for Low-Rise Multifamily Projects.

Project Phase	Responsible Parties	Key Actions
Design	Architect, Envelope Consultant, MEP Engineer	Systems coordination review, interface detailing, enclosure risk assessment.
Pre-Construction	General Contractor, Trade Leads	Trade coordination meetings, sequencing plan, performance mockup planning.
Mid-Construction	GC QA/QC, Third-Party Inspector	Targeted inspection of transitions, implement damage reporting protocol.
Commissioning	TAB Contractor, GC, Owner Representative	Unit-by-unit airflow verification, blower door testing, acoustic testing.
Post-Occupancy	Owner, Property Manager	Track complaints early, implement corrective action before systemic spread.

When viewed collectively, these measures are not enhancements or “upgrades” but rather risk-mitigation strategies. The cost of implementing structured QA/QC processes, full commissioning, and coordinated detailing is modest when compared to the financial and reputational consequences of systemic building failures.

Ultimately, low-rise multifamily buildings must be treated as a distinct typology, one that occupies a unique position between single-family and high-rise construction. They demand the craft familiarity of residential building, the coordination rigor of commercial construction, and

the systems thinking of complex infrastructure. Recognizing this hybrid condition is the first step toward delivering buildings that not only meet code, but perform as intended over time.

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From GreenBuild to Garner Street: Decade of Student Engagement with the State College Community Land Trust (SCCLT) and Advancing Affordable High-Performance Housing

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ABSTRACT

Since 2013, Penn State students have collaborated with the State College Community Land Trust (SCCLT) to address affordable housing needs through sustainable design and performance-driven residential construction in State College, Pennsylvania. This program, which incorporates service-learning into architectural education, gives students hands-on experience designing housing that exceeds ENERGY STAR standards, enhances indoor air quality, conserves water, ensures material durability, and supports aging-in-place.

At the heart of this effort stands the Hamer Center for Community Design, which serves as an educational center and community design platform. The Center's mission is to build community through building knowledge and is realized through projects that promote socio-economic and environmental responsibility, empowering local stakeholders through teaching, research, and service. The Center provides a platform for students to explore real-world housing challenges and implement sustainable, equitable solutions rooted in Pennsylvania's unique regional contexts.

Projects to date include the GreenBuild duplex, completed in 2018 as part of the U.S. Department of Energy's "Race to Zero" design competition, the retrofit of existing housing, and the S. Garner Street development, which embodies responsible densification—an approach that increases housing density while protecting natural areas, reducing carbon emissions, improving affordability, and enhancing neighborhood vitality. Through these projects, students have contributed to producing research that addresses resilient, community-connected housing.
This paper will describe the methodological framework guiding student engagement across projects and offering a model for how university-community partnerships can help achieve permanently affordable, energy-efficient, and equitable housing through participatory research, policy awareness, and performance-informed design.

From Shelter to Smart Housing: Integrating Textile Architecture into Contemporary Dwellings

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ABSTRACT

Textile architecture offers a unique combination of structural efficiency, aesthetic versatility, material economy, and environmental sustainability, making it an increasingly compelling solution across a wide range of architectural applications. Despite its widespread use in large scale and iconic projects, textile architecture's potential in urban housing remains underexplored. Recent technological advances further demonstrate textile's capacity as a highly adaptive, multifunctional material, capable of addressing future smart building needs far beyond the role of passive shelter. This research investigates the integration of textile architecture within contemporary urban housing typologies and emerging lifestyles, emphasizing a hybridization approach that combines textile architecture with conventional building frame systems. The study adopts Brand's Shearing Layers of Change as a conceptual framework, highlighting its alignment with dwelling hybridization approach.

Keywords: Textile Architecture, Contemporary Urban Housing Typologies, Brand's Shearing Layers of Change, Smart Textiles, Building Frame Hybridization Approach.

INTRODUCTION

Textile architecture bridges nomadic traditions and high-tech innovation, offering answers for various applications including sport, transportation, commercial, industrial, landscape facilities, interior, and flagship buildings (Wang et al., 2015). Textile structures offer several advantages,

such as serving as both cladding and structure, which reduces weight, cost, and environmental impacts, while also enabling adaptive systems that respond to different environmental conditions and climate variations. They contribute to energy savings through natural light control, thermal regulation with translucent fabrics, and natural ventilation. Additionally, they allow for large clear-span coverage without rigid intermediate supports, which are relatively easy to construct due to partial off-site manufacturing. They benefit from flexible coated fabrics that enable sophisticated shapes and curves, easy transportation, acoustic control, fire retardancy, self-cleaning properties, and pleasant draping characteristics suited for complex three-dimensional forms. However, these materials also present disadvantages such as: compared with steel, concrete, glass, and other conventional building materials, membranes tend to age more quickly and are vulnerable to vandalism or accidental damage. Their design lacks established guidance, standards, and building code recognition, which means that each design must establish its safety through simulation and as needed special testing programs. They also require foundations and supports capable of resisting unusual multidirectional forces, and often involve higher costs due to the need for project-specific connections and additional patterning processes. Furthermore, structural elements used with membranes may require fabrication at awkward angles and positions (Berger, 1999). Collectively, these pros and cons demonstrate the successful integration of fabrics into permanent architecture and represent their potential for an even greater role in the future, particularly as material properties improve, costs decrease, and designers and engineers refine their expertise in textile architecture.

As cities continue to grow and diversify, architecture faces the challenge of delivering housing solutions that can flexibly adapt to evolving demands and long-term change. This paper explores the potential of integrating textile architecture into residential design, extending its application beyond its current limited use as roof gardens, swimming-pool canopies, playground shelters, and temporary houses. The conceptual framework draws on Brand's Shearing Layers of Change (Brand, 1994) to evaluate how various forms of tensile membrane construction such as textile buildings, secondary outer skins, inner skins, joint roofs, and membrane façades can be incorporated within contemporary housing typologies.

EVALUATION OF TEXTILE ARCHITECTURE UNDER THE SCOPE OF "BRAND'S SHEARING LAYERS"

Brand in his book How Buildings Learn (1994) classified building as a composition of shearing layers including site (the geographical setting), structure (the foundation and load-bearing elements), skin (the exterior surfaces), service (Wiring, plumbing, HVAC, tech systems), space plan (interior layout), and stuff (furniture, appliances, and personal belongings) with the life expectancy of eternal, 30-300 years, 20 years, 7-20 years, 3 years, or under 3 years. His approach is about building evolution over time as living systems to adjust to people's needs, environment and technology. A good design practice adopts the pace of evolution in layers from fast-changing to slow-changing layers. Table 1 outlines the key features required for shearing layers concept to function.

Table 1. Required Key Features Within the Shearing Layers Concept.

Feature	Explanation
Durability	The site and structure need to be strong, resilient, and long-lasting because they are difficult or impossible to change frequently.
Flexibility	Services, space plans, and stuff should be easy to modify, upgrade, or replace without major disruption.
Sustainability	Systems (especially services such as wiring or HVAC) should be designed in modules so they can be swapped out independently, allowing for modification and adjustment in response to seasonal and climatic variations.
Maintainability	Layers should be accessible for inspection, repair, and upgrades.
Adaptability	The overall system should allow layers to evolve at their own natural pace without locking each other in.

Modern textile architectural materials function as form-active structural systems, carrying loads through pure axial tension rather than bending. This behavior allows membranes to act not only as cladding but also as primary structural elements, forming roofs or walls that can span large areas and safely transfer wind and snow loads with minimal supporting framework.
Interpreted via Stewart Brand's Shearing Layers, textile architecture contributes to multiple layers simultaneously as:

1. **Site**: integration of lightweight fabrics has little impact on the permanent site layer, apart from reducing dead loads on foundations.

2. **Structure**: membranes become part of the load-bearing system, carrying roof or façade forces directly in tension.

3. **Skin**: textiles serve both structure and enclosure, lowering overall weight while allowing diffused daylight and reducing glare.

4. **Services**: fabrics can incorporate embedded sensors, lighting, or photovoltaic cells, merging some service elements into the structural surface itself.

5. **Space Plan**: moveable tensile walls and interior membranes blur the line between space planning and structure. They are lightweight, quick to install or remove, and can provide acoustic moderation while permitting light and air permeability.

6. **Stuff**: integration of textile architecture has minimal direct impact on the stuff layer, though their flexibility naturally supports temporary, movable, or modular furniture arrangements, enabling interiors to be reconfigured with ease.

Good architecture should be capable of performing multiple functions simultaneously by adapting to users' needs (Sylejmani, 2020). Within the structure layer, textile systems such as load-bearing membranes, tensairity beams, and cable–membrane roofs can act as primary or hybrid structural elements, transferring loads efficiently through tension while reducing material mass. Tensairity (Luchsinger, 2013) is a structural concept that combines tension, air pressure, and rigidity to create extremely lightweight yet strong structural elements such as beams, arches, columns. In the skin layer, textile architecture can function as a climate-adaptive envelope, for example through translucent membrane façades or shading textile skins that regulate daylight and solar gains. At the level of services, smart textiles allow the integration of photovoltaic elements, embedded lighting, environmental sensors, and ventilation control directly into the building envelope. Finally, in the space plan layer, movable textile partitions, retractable membranes, and acoustic textile curtains enable flexible and reconfigurable interior layouts. In this regard, textile architecture with its durability, flexibility, sustainability, and adaptability is uniquely suited to the gradual evolution of buildings. It allows long-life layers to remain intact while membranes, serving as skin, structure, spatial enclosure, and even components of the service layer, can be renewed or upgraded to accommodate occupants' needs as well as changing environmental and technological demands.

Historical Development of Textile Architecture

As described in Table 2, textile architecture has a long history, dating back to ancient times, as early dwellings evolved to respond to mobility and climate adaptability. Then over time, textile structures were developed as temporary but durable shelters for protection, which symbolized cultural identity. With the advancement of industrial revolution, portable fabric systems (e.g., circus tents, field hospitals) highlight the practical, repeatable, and adaptable nature of textile architecture. At the modern time, such structures were widely used for temporary dwelling and rapid-deployment shelters due to their speed of assembly and light transport weight. In the 21st century with the advancement of materials, computational design and simulations, robotic fabrication, and smart technologies, textile structures have changed to sustainable systems that bridge nomadic traditions and high-tech innovation, cf. Figure 1.

Table 2. Historical Timeline of Textile Architecture.

Date	Type
Ancient times	• Conical tents (Keti, Tupiq, Tipi) • Mongolian tent (cylindrical type (Kronenburg, 1995)) • Textile fabric tents: a. velum type: Bedouin black tent, Syrian desert (Kronenburg, 2015), b. Tibetan black tent (Zámolyi, 2016), c. Tuareg tent, African desert (Fiúza, 2016), d. Semi-vault tents: the Assyrian tent, ancient Iraq (Drew, 1979)

The classical and Roman period	• The retractable textile roof of the Colosseum (Retractable, foldable textile roof of the Colosseum, Rome, Italy (Monjo and Tejera, 2011)) • Military Tents: a. Trajan column, showing depicted drawings of military tents, b. Papilio tent (Drew, 1979)
The Ottoman period	• Tents were often linked to each other, forming complexes of interlaced tents of different purposes, sizes, and forms (conical, marquee, trapezoid, or circular (Kronenburg, 2015))
The Renaissance period in Europe	• The major tent consisted of a wooden circular structure with a central mast that rose up to 40 m high, to support a double skin membrane pitched roof and vertical walls (Kuusisto, 2010)
The industrial revolution age	• Circus Tents (Kronenburg, 2015) • Temporary Hospitals (Hobday, 2020) • Other Functions: acoustic membranes at the Crystal Palace (Zanelli, 2016)
The 20th century	• Tensile cable net structures (Milošević et al., 2013) • Tensile membrane structures (Fabric membranes (Milošević et al., 2013)) • Pneumatic structures (Air-structures (Lutes, 1971))
The 21st century	• Developments in design and manufacturing of contemporary structures (combination of modern designs, biomimicry, computational simulations, and robotic fabrication processes (Menges and Knippers, 2015)) • Developments in material technology: nanomaterials and nano-sensors, introduce additional multi-functions like thermal and sound insulating, ventilation controlling, sunlight controlling, air filtering, solar energy collecting, wind energy collecting or motion energy collecting

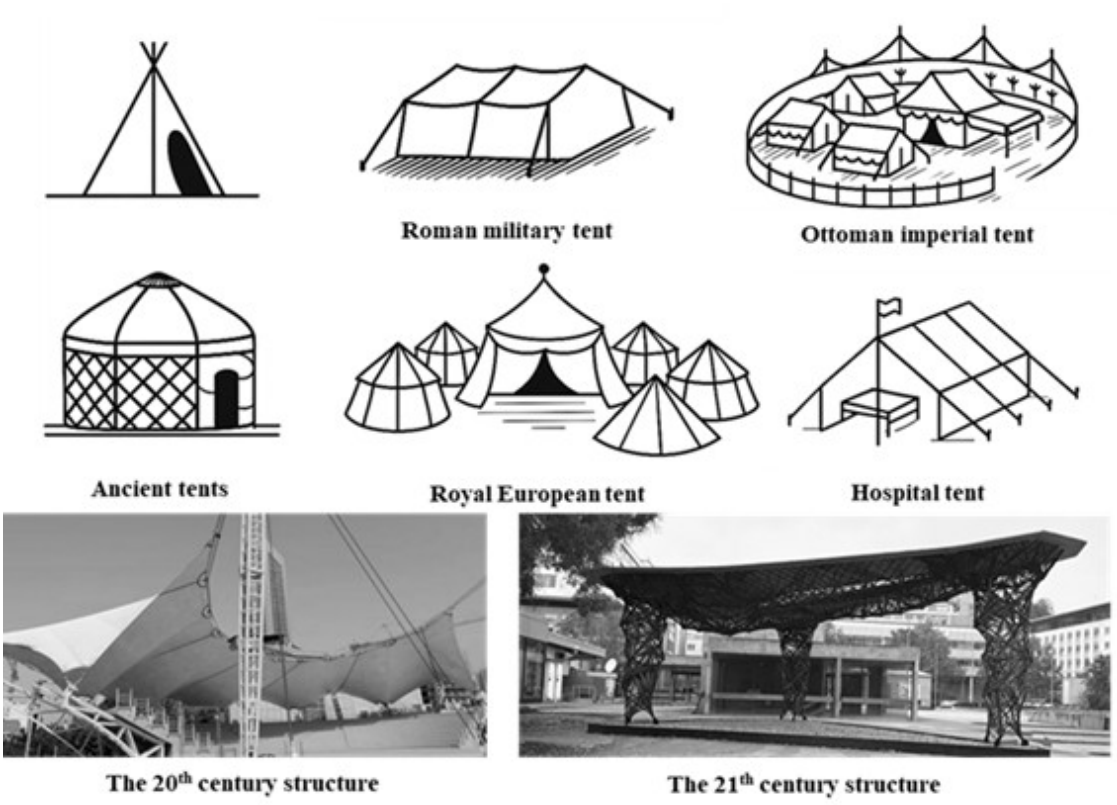

Figure 1. Textile architecture development (Shaefer and Al-Alwan, 2020).

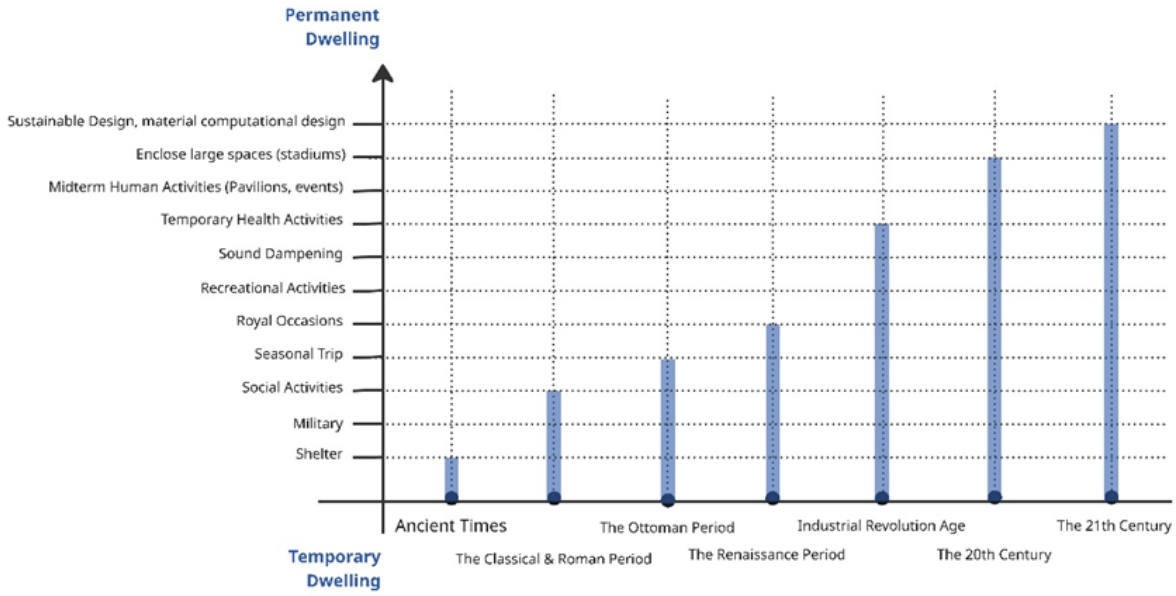

Figure 2. Functional transition of textile architecture over time, based on Table 2.

New generation of advanced architectural textile moves far beyond the level of passive sheltering by being able to sense the environment and adjust performance accordingly. As is the case for active façade, the new generation of textile structures can respond, react or adapt the suitable response to the stimuli that has been sensed (Heyse et al., 2016). Key areas of advancements are listed in Table 3.

Table 3. Key Technological Advancements in Textile Architecture (Brownell, 2012).

Advancement	Explanation
Energy Harvesting	• Photovoltaic Textiles: Organic photovoltaics (OPVs) can be printed directly onto fabrics using low-cost processes (inkjet or screen printing). • Piezoelectric Textiles: Nanofiber fabrics made of PVDF can produce electricity when twisted or moved, opening possibilities for wind-responsive building envelopes.
Light Emission and Visual Communication	• Light-Emitting Fabrics: Fiber optic woven materials provide low-energy illumination. • Color-Changing Fabrics: Smart fabrics change color through liquid-crystal inks and conductive yarns, enabling façades that display dynamic images or information.
Responsive and Smart Textiles	• Impact-Resistant Membranes: System stiffens instantly upon impact, improving structural resilience. • Climate-Adaptive Curtains: Use actuated louvers with shape-memory alloys to control ventilation, daylight, and even display patterns, offering real-time environmental control.
Sustainable Material Innovation	• Bio-Based Fabrics: Corn-derived polylactic acid (PLA) textiles replace petrochemical polymers and can be fully biodegraded, supporting closed-loop manufacturing. • Bio composites: Use plant fibers and soy-protein resins to create self-bearing, translucent panels with natural aesthetics and structural stiffness.

The already mentioned functional risks associated with textile architecture can be mitigated through the use of active and passive smart textiles, paving the way for the development of future smart houses as permanent dwellings.

HOUSING TYPOLOGIES

Urban housing typologies have evolved over time in response to rapid urbanization, population growth (Gür and Yüksel, 2019), and various cultural, environmental, and political developments (Jin and Bachman, 2022). Residential architecture encompasses a wide spectrum of building types, each offering distinct spatial and social qualities. Various types of urban housing are categorized as (Tomajian et al., 2024): 1. Stand-alone houses: single-family buildings, usually with a private yard that is not attached to any other buildings, 2. Urban villas and townhouses: typically, multiple stories, ample living space with private outdoor areas, 3. Row houses and terraces: series of connected single-family homes that are open on both sides while sharing separating side walls between units, 4. Slab blocks: multi-story and multi-unit structures with flat appearance consisting of a series of apartments stacked on top of each other, 5. Towers and high-rises: multiple stories apartments stacked vertically, 6. Perimeter blocks and courtyards: multi-family courtyard houses enclosing an open central courtyard with sense of community among residents, 7. Infills: narrow houses built within existing urban areas, 8. Stacked houses and clusters: individual housing units or apartments are vertically stacked on top of each other within a single structure in a complex intersected form.

INTEGRATING TEXTILE ARCHITECTURE INTO HAUSING TYPOLOGIES

Textile architecture can be applied to a wide range of buildings (cf. Figure 3), serving as textile buildings, secondary skins, inner skins, joint roofs, membrane façades, and even tensairity systems with various degree of enclosure (enclosed, adaptive, or open). Textile structures act as primary load-bearing systems made of tensioned fabrics or membranes where the fabric itself provides the main enclosure and structural stability. Buildings may also employ secondary skins, external fabric layers added as a second façade to enhance shading, thermal performance, or aesthetic qualities. Inside, inner skins can be introduced as lightweight textile layers that improve acoustics, diffuse light, or help regulate interior climate. Joint roofs extend the versatility of fabric by spanning and connecting separate building volumes, forming flexible, lightweight coverings for shared spaces such as courtyards or walkways. Finally, membrane façades use membrane materials as the main building envelope, creating exterior surfaces that combine structural performance with varying degrees of transparency, translucency, and dynamic visual effects.

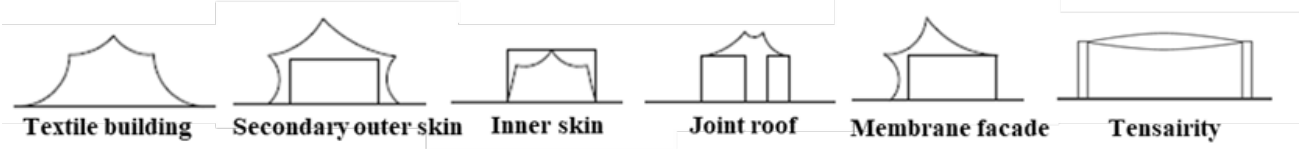

Figure 3. Classification of textile architecture (Forster et al., 2004).

Using conventional supporting frameworks across various housing typologies in combination with textile systems offers one of the most practical pathways toward textile-based housing. This hybrid strategy merges the strength and code-compliance of rigid frames with the lightness, adaptability, and environmental intelligence of multifunctional smart textiles, allowing urban dwellings to evolve over time in alignment with the shearing layers concept. Such hybridization can be realized through single or repeated modules of textile buildings, the full or partial application of outer skins, or the incorporation of membrane façades, see Figure 4. The figure is a conceptual design example demonstrating how the proposed framework can be translated into a hybrid textile–frame housing strategy. Modular textile systems refer to architectural components designed as self-contained textile buildings. These modules may function as complete volumetric structures or as subassemblies that attach to conventional structures. Full and partial outer skins denote textile membranes applied over an entire building envelope (full) or selectively over parts of it (partial), acting as continuous or segmented outer layers. Membrane façades are exterior wall systems that serve as the visible outer skin of a building, supported by a substructure. Importantly, this hybrid approach can be applied across all housing typologies previously discussed.

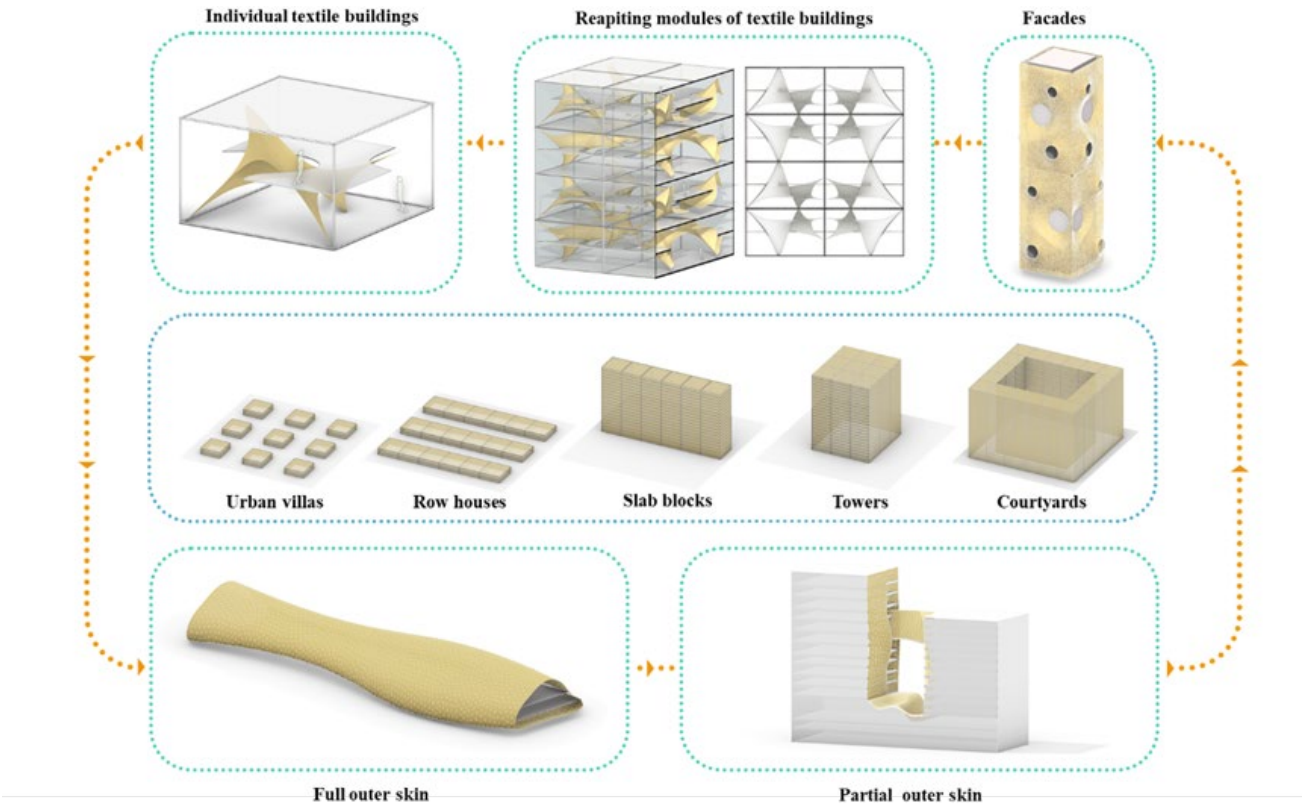

Figure 4. Illustrative design scenario for hybrid textile–frame housing.

Additionally, the use of textile architecture in residential applications introduces a set of formal qualities that distinguish fabric-based housing from conventional construction. Lightness and curvature emerge naturally, as tensioned membranes produce double-curved surfaces. Even when rigid frames fix the perimeter, the panels between supports settle into graceful double curved surfaces. This structural logic also encourages continuous skins, where walls and roofs merge into a single membrane. Corners soften and façades read as uninterrupted wraps rather than discrete, planar elevations. Together, these geometric tendencies transform not only the appearance of each housing type but also the way it is experienced and inhabited.

New models of living are emerging housing concepts, which move beyond conventional single-family homes or standard apartment layouts, see Figure 5. According to Bowes et al. (2018), these approaches respond to urban density, affordability pressures, lifestyle diversity, and shifting patterns of work and family by emphasizing flexibility, shared resources, and adaptability, rather than fixed ownership or static layouts. The first model, micro-living, features compact, highly efficient dwelling units designed to maximize functionality and affordability in dense urban contexts. The second, co-living/co-working, combines private rooms with extensive communal amenities and integrated workspaces, fostering both social interaction and collaborative work environments. Co-housing/communal living involves residents collectively planning and often managing clustered homes with shared facilities, encouraging social cohesion and participatory decision-making. Intergenerational housing is designed for multiple age groups to promote mutual support, companionship, and more balanced social structures. Finally, subscription-based dwellings offer housing as a service, where residents pay a flexible membership or “home subscription” to move between fully furnished units operated by the same provider.

Figure 5. The new models of living (Bowes et al. 2018).

Textile architecture can enhance these concepts by introducing lightweight, climate-responsive, and rapidly deployable membrane systems that support flexibility and energy efficiency, as summarized in Table 4.

Table 4. Potential of Textile Architecture in Emerging Living Models.

Living Style	Enhancements through architectural textile integration
Micro-Living	Continuous membranes stretched over building frames create curved external/internal surfaces, making very small units feel larger and more open, with the possibility of fast assembly and easy replacement.
Co-Living / Co-Working	Column-free surfaces span for events and workspaces, while retractable side panels allow seasonal opening/closing.
Intergenerational Housing	
Subscription-Based Dwellings	A series of membrane modules highlights mobility and adaptability, reflecting a lifestyle based on flexibility and service.

In micro-living contexts, textile membranes can enhance spatial perception through lightweight, continuous surfaces and daylight diffusion, making compact units feel more open while supporting adaptable interior layouts. In co-living environments, textile systems enable large-span, column-free shared spaces, where retractable membranes and movable partitions allow spaces to be easily reconfigured for changing social programs. For subscription-based housing, textile architecture supports modular and demountable strategies, using replaceable membrane skins to facilitate rapid adaptation and upgrading over time.

CONCLUSION

This research demonstrates that textile architecture offers a compelling pathway for the future of residential design. The key contributions of this study are threefold: first, it reframes Brand's Shearing Layers of Change from the perspective of textile architecture; second, it proposes a hybrid textile–frame integration strategy for residential design; and third, it demonstrates the relevance of textile systems for emerging housing models. In this context, textile architecture moves beyond novelty to become a meaningful tool in shaping adaptable and future-oriented residential environments.

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Collaborative Spaces

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ABSTRACT

Reducing the energy consumption of buildings and replacing fossil fuels with renewable energy or passive systems has now become an undisputed priority for authorities, for all human beings inhabiting the earth and, consequently, also for those who design living spaces.

Achieving these goals leads U.S. to reflect on events and transform our knowledge into positive innovation, forcing U.S. to initiate a process of "transition" in architectural design in which the relationship between space and energy is changing profoundly. Alongside and beyond a technological approach, is it possible to envisage an approach that involves the transformation of living spaces?

Recent research and projects identify a possible trajectory in which the concept of the boundary of living is redefined, interpreted as an interface between the interior and exterior spaces of the home, generating a new perceptual value and elements of energy containment/accumulation. A strip of overlapping cultures, ethnic groups, events and changing margins in constant discussion and mutation, requiring a reorganization of the interior and boundary space, which becomes the first architectural interface of the project: no longer impassable walls and boundaries, but a device capable of generating their expansion to include the connection between different spatialities. In particular, the expansion of the threshold space becomes an element of capture, mediation and accumulation of renewable energy and new relational forms of life and relationship.

A porous element subject to mutual influences between the interior and exterior, a thick wall/border is transformed into a fluid meeting point, where each part can benefit alternately or jointly from the other.

The aim is to demonstrate how, in contemporary design, this relationship between inside and outside has once again become fundamental and is being updated, adopting tools capable of creating new spaces for relationships and becoming an element of passive climate control, thus becoming an indispensable "collaborative" support for the sustainability of our living environment.

BACKGROUND

In January 1928, the first issue of the architecture magazine Domus opened with an editorial by Giò Ponti entitled La casa all'italiana (The Italian Home), in which he expounded a theory representing the Italian philosophy of living in relation to international modern architecture. Ponti emphasized the uniqueness of the Italian approach to the home, understood as a profound fusion between interior and exterior, in an architecture that is first and foremost an emotional and sensory experience of space and landscape. He described the Italian home not as a refuge from a hostile climate, but as a place chosen to fully and joyfully enjoy the natural beauty offered by the Italian land and sky throughout the long seasons of life.

"The Italian home is not a refuge, padded and furnished, for its inhabitants against the harshness of the climate, as is the case with homes beyond the Alps, where life seeks shelter from inclement nature for long months: the Italian house is like the place we choose to enjoy in our lifetime, with joyful possession, the beauty that our land and our skies offer U.S. in long seasons. In Italian houses, there is no great distinction between the architecture of the exterior and the interior: elsewhere, there is even a separation of forms and materials: in Italy, the architecture of the exterior penetrates the interior, and makes use of stone, plaster and frescoes; in the vestibules and galleries, in the rooms and staircases, with arches, niches, vaults and columns, it regulates and orders the spaces for our life in spacious measures.

From the inside, the Italian house is reborn outdoors with its porticoes and terraces, pergolas and verandas, loggias and balconies, roof terraces and belvederes, all of which are extremely comfortable inventions for peaceful living and so Italian that they are called by their local names in every language. [...] Its design (the house) does not stem solely from the material needs of living; it is not just a "machine a habiter". The so-called "comfort" in the Italian house is not only in the correspondence of things to the necessities, needs and comforts of our lives and the organization of services.

This "comfort" is something superior; it is in giving us, through architecture, a measure for our own thoughts [...] and it is, finally, in its easy, joyful and ornate opening up to the outside and communicating with nature, in the invitation that the Italian house offers our spirit to recreate itself in restful visions of peace, which is the full meaning of the beautiful Italian word, CONFORTO" (Ponti, 1928).

This thought leads U.S. to a continuous reflection on how we live together and how the home should be a relationship between people and the environment. Too often, the home is still thought of exclusively as a "machine a habiter", referring to the systems and canons of the Modern Movement, in which spaces are designed according to a system of requirements and using a technique that classifies the spaces of the home solely on the basis of technical performance parameters and not on the basis of their quality and richness, totally negating the experiences of living of the Italian Masters of Modernism.

The living space in which life takes place is articulated in a system in which the home is defined

by its position in a physical and social topography on which Western modernity has built its cultural and political system and translated the principles of democracy and unlimited progress, at the expense of resources, in the design of spaces and objects intended for strictly functional housing models that inevitably reflect the structure of the neo-liberal consumerist industrial society.

The housing model, organized around the hegemonic concept of function, is reduced to a series of performances that introduce greater monofunctional efficiency of spaces and building envelopes, continuously updating the technical variables that propose living systems increasingly oriented towards performance rather than relationships.

The technical dimension alone, although interesting for introducing new knowledge in the field of building design, has taken precedence over the quality of spaces, forgetting the lesson that Mediterranean architecture, and Italian architecture in particular, has provided a weave and variety of spaces that corresponds to the intertwining of cultures, histories and peoples of places. In this context, refocusing attention on the design of intermediate spaces, as well as continuing the tradition of Italian design, becomes fundamental in order to introduce an approach that is no longer solely linked to the performance provided by the technical tools most widely used today, but linked to the creation of passive elements, which we will define as “collaborative”, capable of connecting different spaces and providing performance without energy consumption.

AIM AND OBJECTIVES

Contamination, hospitality and inclusiveness, or “cohabitation in a world made habitable by a practice of conviviality” theorized by Paul Ricoeur (Ricoeur, 2001), i.e. the relational matrices that create infinite variations and compositions in Italian living, have completely disappeared in contemporary living.

This phenomenon, also linked to a transformation and dissolution of relationships within the family unit, has introduced a change in behavior in which the home is often represented as a safe haven where increasingly sophisticated digital technology and social media have only served to widen the isolation between families and between members of the same family, creating more and more walls, even immaterial ones (Vitta M., 2010) .

Much of the perception of the changing and fluid reality of our daily experience is attributed to the spread of television, mobile phones, the Internet, email and social media within the home environment.

Contemporary housing conditions appear to be marked by progressive fragmentation, which is reflected in an increasingly discontinuous and disjointed experience of living. This process is fueled by the emergence of a paradigm based on complexity and constant change, which destabilizes traditional references and redefines users’ expectations of domestic space.
In the face of this evolution, the market tends to propose standardized housing models that are unable to respond to new needs. The spatial configurations proposed are often inadequate for

today's variety of lifestyles, which are distinguished by diversity of use, relationships and social practices. Added to this is the novelty brought about by technological progress and the post-pandemic situation, which has led to a changed and rapid approach to reality, understood as a mode of expression of the real (Benesayag, Cany, 2025), and to the emergence of a demand for greater richness and articulation of living spaces, capable of reflecting the plurality of experiences and adapting to constantly evolving living conditions.

The objective is therefore to activate project structures that implement the concept of boundary/threshold, no longer understood solely and exclusively as the relationship between internal and external space, but as a tool for defining passive, "collaborative" technical and spatial elements capable of improving the spatiality and comfort of housing in order to make it more sustainable overall.

METHODS

Operating in the contemporary world through a sustainable vision leads U.S. to make an initial choice that aims to work on what already exists rather than on something new. The gap, or rather the building stock that is no longer able to meet the needs of its inhabitants, becomes the field in which to intervene.

Action then shifts to the plane of existence, understood as the dimension in which the project "blends" with an existing, "situational" condition in which a new adaptive and additive level is "syntagmatically overwritten" onto what is already present, so as to include both the existing and the new. Operating with an overwriting means that the project is configured as a system that does not separate, list and recompose, but seeks comparison in a single environment, in which each part exists in relation to the other: the whole is included in each part. In this context, architectural and urban design become an act of "situational design", which works with what is given, accepting the limited nature of each intervention and renouncing the illusion of being able to dominate the evolution of situations. The project thus fits into a situational present that is layered, not static, and whose depth is the result of the complex and contradictory construction of the identity reality in which it operates.

Central to the methodological framework is the concept of reinterpreting the architectural "border" or border—the interface between interior and exterior—no longer as a rigid division but as a dynamic, porous, and hybrid threshold merging private and social realms (Castiglioni and Mariotti, 2019). This shift responds to the need for architectural devices that promote interaction, energy exchange, and relational complexity.

Gianluca Favetto, Italian writer and journalist, in his article 'Se il confine è un sentiero della mente' (If the border is a path of the mind), defines the border as follows: "Borders are nothing more than the kiss of two lands, of two things... A situation of shoreline [...]. The shoreline is a condition that exists everywhere, even high in the mountains. It is something that, in the same place and at the same time, holds together land and water, sand and waves. In the same space, it recognises the other, the different from itself, ascertains and accepts the variety and complexity

of the world. While striving to separate and distinguish, it compares and confuses. That is, it blends together, amalgamates, unites without reducing to one" (Gian Luca Favetto G.L., 2016). Contemporary architecture is therefore increasingly configured as a practice centered on relationships rather than on the mere definition of functional objects; a space in continuous transformation, oriented towards interaction and the dynamics of uses, rather than the composition of static and self-referential scenarios.

In the design field, this represents an opportunity to mend spatial fragmentation and redefine the sequence of environments, orienting design towards a greater capacity to accommodate indeterminacy and design spatial and physical relationships between level 0, the basement level and the building, between spaces dedicated to the private sphere and semi-private and/or outdoor spaces, between public and private functions, between what is open and what is covered, between natural and man-made elements. The profound meaning of the project lies precisely in these connections, which constitute its primary and structuring significance.

The investigation adopts a multi-scalar approach combining theoretical analysis, case study examination, and design experimentation. Key references include classical architectural theory (Ponti, van Eyck, Hertzberger, Tschumi) and contemporary reinterpretations emphasizing spatial hybridity, threshold dynamics, and interstitiality.

This occurs both at the residential level and at the urban or landscape design level, since working on the theme of thresholds often translates into a search for “hybrid” relationships between “different sedimented layers” (Enzensberger, 1998) imposed above or below level 0, capable of creating new possibilities for living that incorporate the random and the unpredictable.

The redefinition of the margin is even more interesting today if we deal with spatial areas of waste to be regenerated with a ‘syntagmatic overwriting’ (Gaiani, 2017) in which adaptive and additive tools are used to connect history and new systems of life through the manipulation of the existing, hybridization, stratification, insertion and contamination.

The theme of intermediate space is certainly not new in architectural debate. As early as the 1950s, Aldo van Eyck had intuited its potential, introducing the concept as an integral part of a broader reflection on the continuity between opposites. This intuition was subsequently developed by Herman Hertzberger, particularly in his book Lessons in Architecture, where intermediate space becomes “the threshold that constitutes the key to transition and connection between areas with different territorial vocations and, as a place in itself, essentially constitutes the spatial condition for encounter and dialogue between areas of different orders” (Hertzberger H., 1996), i.e. an entity capable of connecting different areas through the mixing of space, belonging simultaneously to two distinct realities.

An analysis of the works of Dutch architects highlights how this threshold space is not limited to a function of passage, but acts as a relational device, capable of connecting interior and exterior, private and public, natural and built, generating an osmosis between the different dimensions of the project (Bevilacqua M.G., 2014).

More recently, the concept has been reformulated by Bernard Tschumi through the idea of the in-between, a space “in and between things” (Guiheux A., Tschumi B., Abram J., Lavin S., Fleischer A., Pelissier A., Rouillard D., Agacinski S., Descharrieres V., 1999). which is not only a physical interstice, but also a theoretical and design condition.

The edge, transformed into a margin and threshold, then becomes an element that refers to a variety of situations that are adjacent to something that is physically recognizable: it is an area of proximity, a hybrid interface, where social and intergenerational encounters take place. It is also the tool that captures which elements of permanence and memory to privilege, substantiating them with new ones through which the project will develop.

The Threshold/Margin thus becomes the first architectural interface of the project, no longer walls, insurmountable boundaries, but a tool that allows their expansion for different spatiality and sociality.

In addition to the spatial aspects, we must not forget how this “collaborative space” is also useful for improving the efficiency of buildings by enhancing solar gains in winter and mitigating them in summer.

In the contemporary landscape, a significant contribution to the reflection on intermediate space is offered by the work of the Lacaton and Vassal Architecture Studio with the redevelopment project of a residential building from 1959, designed and built according to monofunctional standards and constructed with a prefabricated building system that has no spatial interface with the outside, located in the inner suburbs of Paris (Lacaton and Vassal, 2021).

The project involves adding a new self-supporting structure to the outer edge without projections, which will expand the living space towards the outside by inserting an “intermediate” space that can be used in different ways, creating a new porous interface margin. This added space, hybrid in nature, is located between the interior and exterior, acting as a filter zone capable of extending the quality of living without compromising the existing structure. It can be transformed into an extension of the interior space, a loggia, a bioclimatic greenhouse, an autonomous space, etc.

The methodological process for the case studies (Figures 1-4) involves:

- Identification of sites exhibiting spatial “threshold” conditions or potential for boundary redefinition.

- Application of adaptive design strategies—such as additive, layered, and hybrid interventions (Gaiani, 2017)—to enhance spatial coupling between inside and outside and generate new relational interfaces.

- Observational and participatory research involving social stakeholders, as in the Riesi project (Figure 3), where community engagement supports spatial and social reclamation.

• Integration of architectural and urban scales, exemplified by the Pilastro housing regeneration (Figures 1-2) and the Bologna military museum project (Figure 4), employing transparent and porous interface elements that introduce continuity and expand inhabitable zones vertically and horizontally.

• Evaluation of environmental and energy performance improvements enabled by intermediate spaces, “collaborative spaces” supporting sustainable design goals.

The choice of projects serves to demonstrate that collaborative spaces can be introduced at different scales and in different situations and uses.

This methodology balances theoretical rigor with empirical experimentation, validating the relevance of selected case studies as exemplars of threshold redefinition in contemporary habitation.

Figures 1 and 2 illustrate the Pilastro residential public housing regeneration project in Bologna, Italy, project by Alessandro Gaiani, “Collaborative spaces”, where new “box” structures and intermediate threshold spaces extend existing apartments outward. The project hybridizes the residential building typology, emphasizing variability and adaptability, and mediation with inhabitant needs through social facilitators, establishing mutable spatial relations beyond repetitive façades.

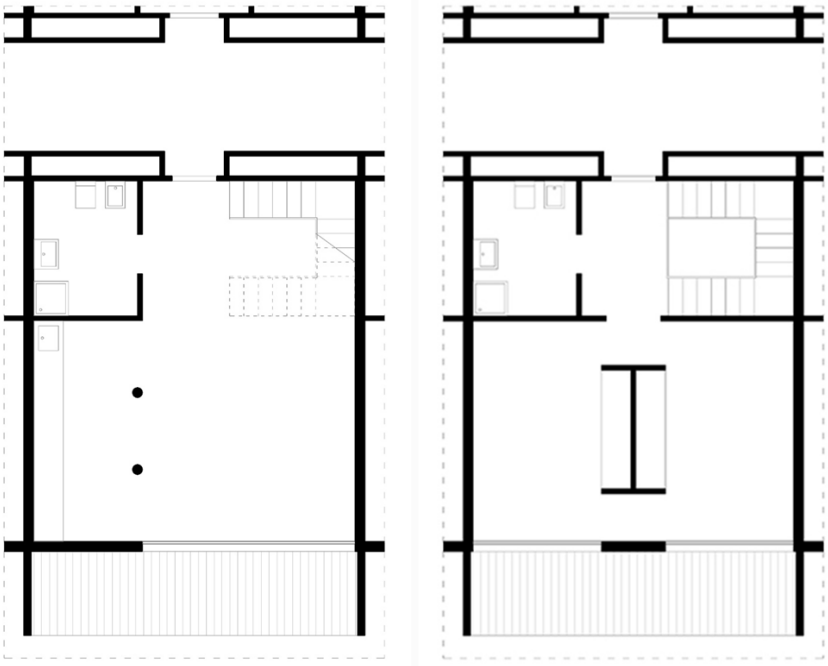

Figure 1.

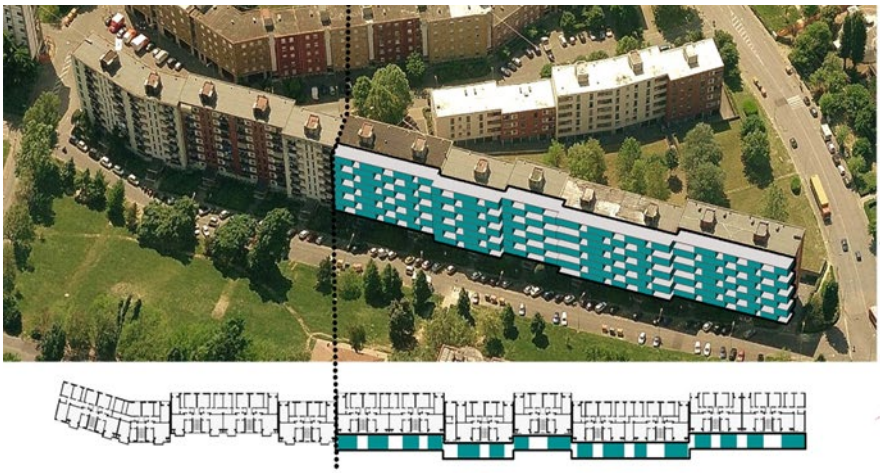

Figure 2.

Figure 3.

Figure 3 documents the Riesi, Sicily urban transformation led by the Orizzontale collective and Flora La Sita (foto foto.rmedium_emanuele_piccardo). Here, a confiscated mafia property and adjacent street were converted into youthful, playful, and communal spaces, redefining the street façade through vibrant color coding symbolic of new urban proximity and public space recuperation.

Figure 4.

Figure 4 presents the design for the adaptive reuse of the "Starmoto" former military barracks in Bologna, proposed as part of the fourth-year architectural design workshop at the Department of Architecture in Ferrara, carried out by students Gregorio Fagotti, Esther Jiménez Martín and Davide Lattanzio, repurposing underground areas with translucent interface elements to create unusual threshold conditions between ground level and subterranean spaces, integrating spontaneous natural growth with new architectural insertions.

The collective approach to these examples demonstrates the capacity of contemporary architectural practice to embrace and manipulate spatial thresholds, shifting from barriers to relational, porous interfaces contributing to social, environmental, and experiential complexity.

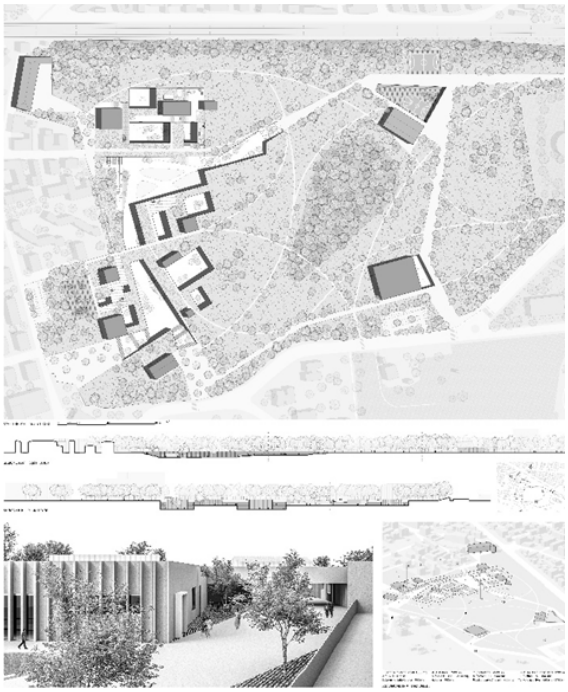

Figure 5.

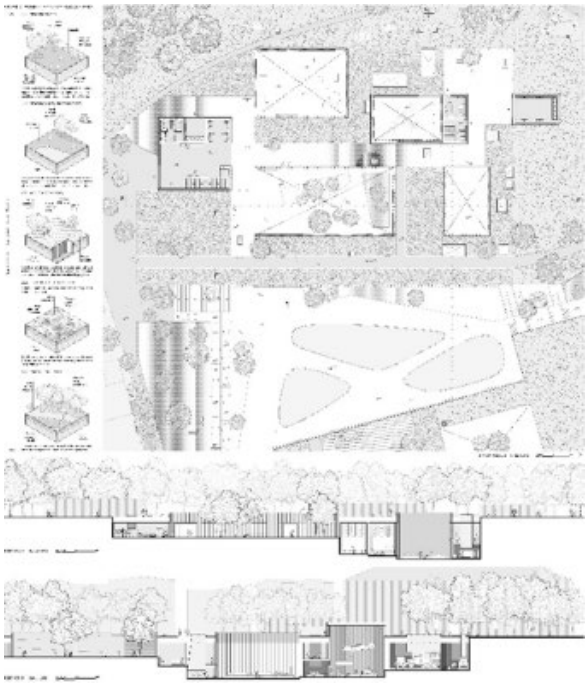

Figure 6.

EXPECTED RESULTS

The concept of "threshold as a collaborative zone" has always been addressed in research and design topics in the world of architecture. We have sought to address this topic from a perspective that takes into account the complexity of our era, in which technological acceleration and diverse lifestyles increasingly compel U.S. to reflect on the changes taking place in living, where multiple practices and temporalities prevail, changing the well-defined rules of the past.

Exploring spatial phenomena through time challenges a static view of space, emphasizing the importance of Kronos as a cornerstone in the interpretation of change, maintaining the essential link between space and time, but favoring an analysis and design guided by the latter. Since we are called upon to reconcile the accelerated pace of society with the slower pace of physical change, we propose a vision in which it is possible to associate a "culture of becoming" with a dynamic spatiality based on different temporalities, in which the threshold is the interface element capable of assuming changing configurations.

Intervening on existing structures through passive systems, “collaborative spaces”, not only linked to high-tech machinery that produces performance but also energy consumption, seems to U.S. to be an approach that, in the contemporary world, can no longer be postponed. For this reason, in contemporary design, especially when working on existing “obsolete” structures, the use of “collaborative spaces” seems to be an essential approach.

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Impact of Organizational Structure on Architectural Production, and Its Implications on Academic Education (Design-Build: "Undercover Architect")

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ABSTRACT

Housing is essential, not only as a socio-cultural asset, but also in the world of architecture in pursuit of beauty, originality and everyday inspiration. However, much of it is not very inspiring at all. In New York at least, much of the visible housing, predominantly apartment buildings, either seen from walking on city streets or from glancing at real-estate websites, is rather repetitive and based on marketing formulas and return on investment (Fig. 1).

As an architect and a professor of architecture, I am always wondering, why the out-put is so predictable. This is not a technical issue, but an issue of logistics and organization, and, of culture and education. Being involved in the production of architecture, I believe that the organizational structure of how such buildings are created, is inefficient and actually detrimental to our profession. The role the architect plays is uncommitted within that structure and thus doesn't give much space for tangible creativity.

Being involved in the education of aspiring Architects, I witness often that common concepts of identifying ourselves within the professional field, are questionable: Commonly, conceptual thinking is overemphasized, without preparing students how to translate an idea into built form so to become proficient "players" in the field, where they could showcase extraordinary talents in a highly competitive market.

What is needed, is to blend the creative qualities that we, as architects, could bring to the table with the necessary skills of management and logistics. In order to do so, the self-conception of the profession has to change. For a truly applied process, the profession requires wearing many different "hats."

In this paper, I will discuss how architects could rearticulate their role in the organization of construction and how better education could lead to a stronger generation of architects, who might be able to realize the dream of reviving architecture as an applied art.

INTRODUCTION

How the creation of sophisticated architecture is taught in academia and how this knowledge then connects to the professional environment is inefficient overlooks the fact that architecture,

as an applied art, constitutes “the only activity that involves imaginative conception of ideas, leading to artifacts that are realized as actual constructions …” (Illies and Ray 2018).

Figure 1. NYC: Riverside Blvd.: Industrial Reproduction in Architecture; © by author.

Any architecture, as actually constructed, operates within highly competitive and economically challenging constraints, often undermining its potential of being imaginative in its intrinsic nature. We, as architects, must improve on how to influence the way extraordinary design can be implemented, leading to better application and to better fitting into an ordinary system of production.

The understanding of how to get from good design proposals to control over realization (in a highly regulatory context) is seldom taught. Built work therefore often stops short of its ambition and doesn’t develop its potential, which should be to create socio-cultural traction and also beauty.

The field of construction is one of the three most significant economic sectors in NYC. Construction spending in 2023 reached a record high of $68.2 billion; $22.8 billion of that

money was spent in the residential sector (Jain 2025).

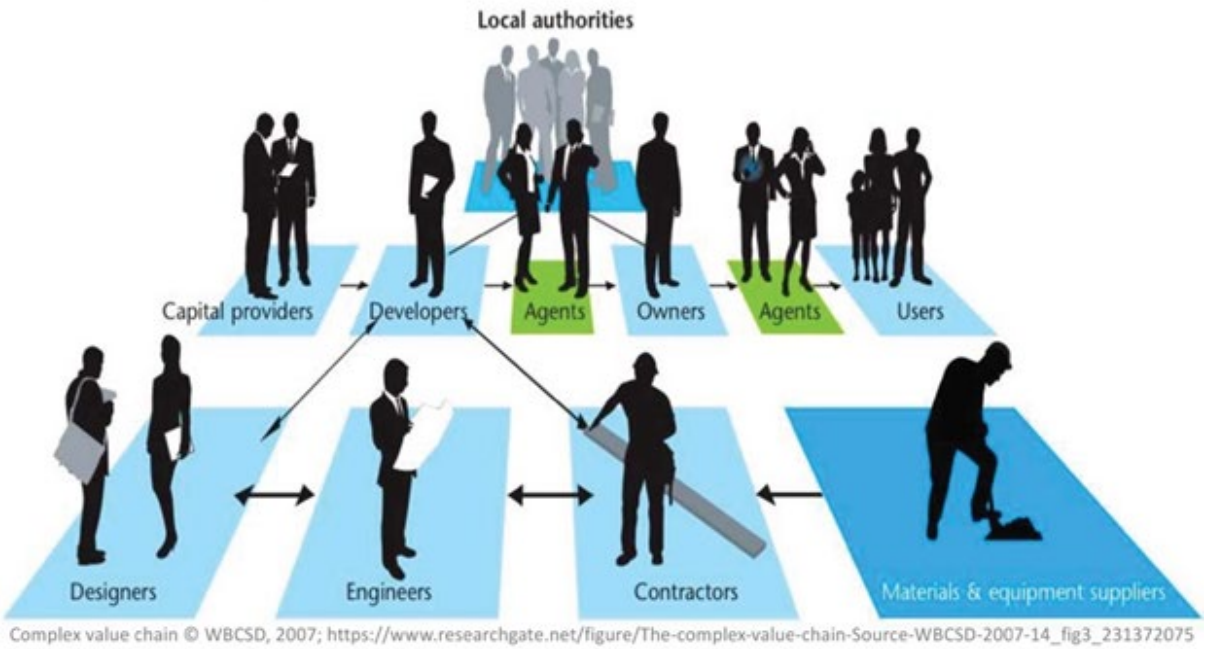


Figure 2. Complex Value Chain; © by WBCSD, 2007 (fig3_231372075).

Typical organizational structures in construction often reflect the economic value chain, while sidelining the creative contributions (Fig. 2). Any construction of a building requires the following players to do their work (Fig. 3):

A) Developer

B) General Contractor + Builders

C) Architect + Engineers

D) Code Consultant + Authorities; and

E) (being a complicated discipline): the Teacher + Trainer.

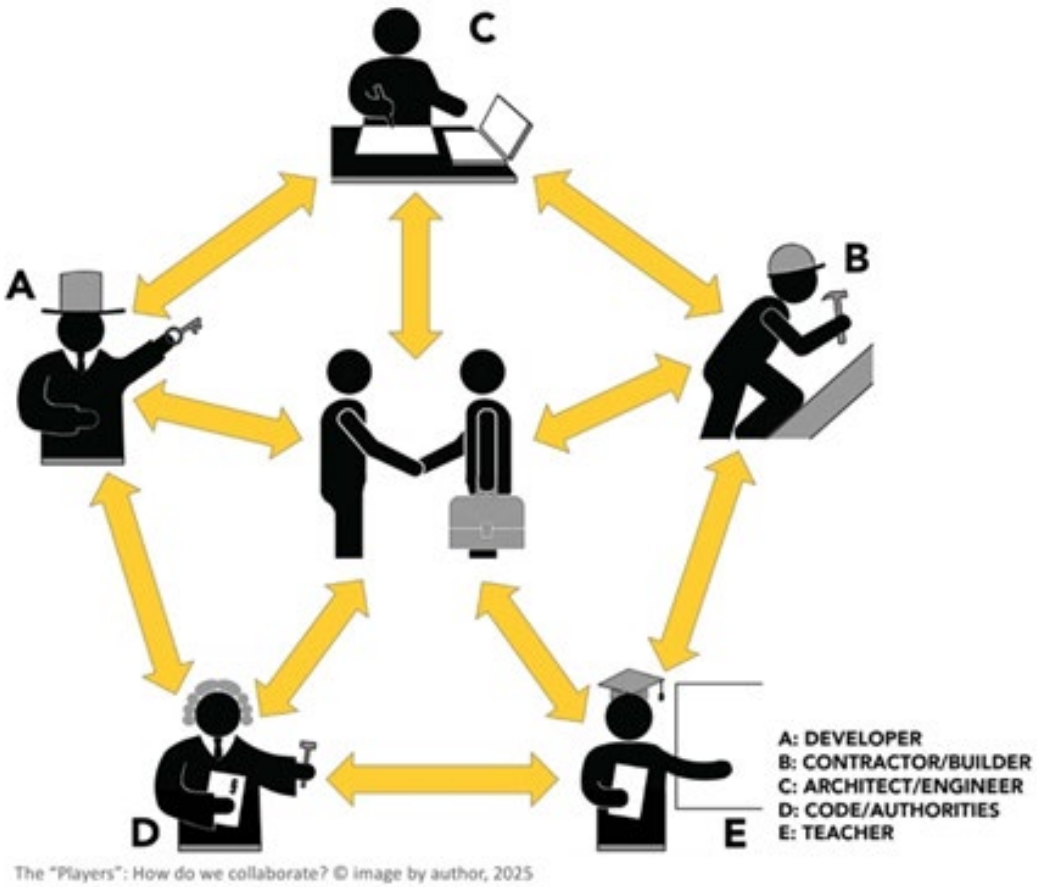


Figure 3. How do we collaborate? © by author.

There are, of course, redundancies and omissions. In any case, players at work need optimized teamwork. Common models of project organization exist, but what are good analogies for smooth and efficient teamwork?

Like in an orchestra, one should be deeply aware of all substantial instruments that are played. Like in an orchestra, teamwork is key. It is significant how the players communicate with one another in order to make good progress.

The Architect usually claims to not be involved in making the music, but being the conductor instead. However, a good conductor has to know his/her instruments, not only in terms of how they sound, but also in terms of how they are played. It is actually said that a good conductor can therefore play several instruments for that reason. The question then is, whether we, as architects (and conductors), know the instruments that are played, or better said, the typical players serving construction.

A) The Developer: According to U.S. Green Building Council, developers "oversee a project from start to finish: selecting a site, securing the finances, overseeing design and construction, and managing or selling a property. The developer, sometimes with the help of a builder, is responsible for forming a team of professionals to implement his or her vision within a certain budget and schedule, all the while following applicable codes, ordinances, and policies" (U.S. Green Building Council, 2019). Anything mentioned here, an architect should be capable of doing as well (except maybe managing/selling a property);

B) The General Contractor: Usually, the General Contractor doesn't do the physical work. He/she coordinates the scope of work with the diverse trades involved and translates the architects' drawings into understandable action for the builders;

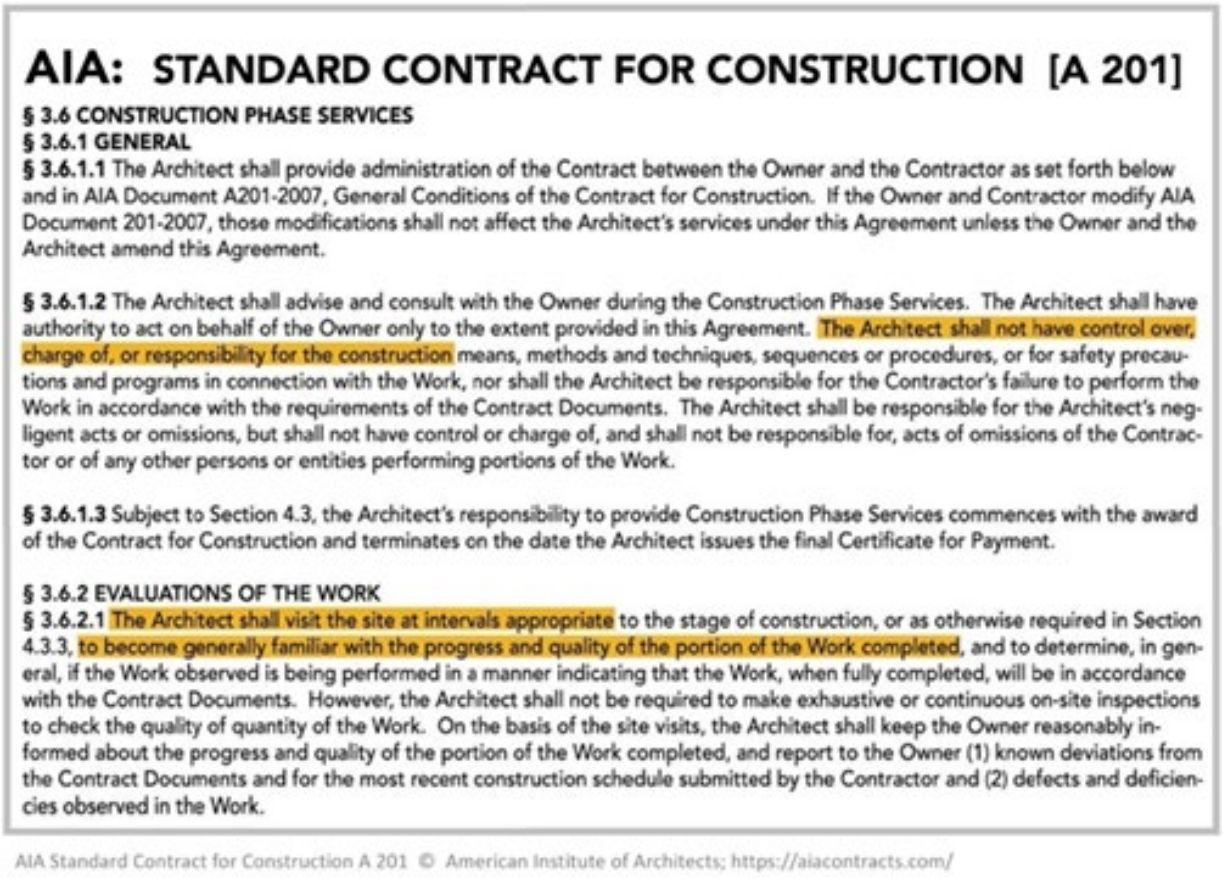
C) The Architects + Engineers: They are usually office workers, seldom seen at construction sites (why? this will be explained later.);

D) The Expeditor: Also at an office: knowledgeable about NYC building codes and processes that are unnecessarily complicated and difficult to navigate; and finally:

E) The Teacher: Not much of a practitioner anymore (also this must be explained).

These players seem to be disconnected and the self-appointed conductor, the Architect, and maybe the teacher (preparing the next generation) seem to be sidelined in the process. Surprisingly, we yet adhere to the status-quo of how a construction undertaking should be structured. We also have not changed the way we educate our students.

The reasons for preferred organizational structures are manifold, but it is important to understand how we arrived at this position: One of the indicators is a commonly used document provided by the American Institute of Architects (AIA) for their Contract for Construction (A201). Within that document it is stated: "The architect shall not have control over, charge of, or responsibility for the construction means and methods…. The architect shall visit the site at intervals appropriate … to become generally familiar with the progress and quality of the portion of the Work completed …" (Fig. 4) (AIA, 2017; Gluck, 2013). It practically denies the architect the influence of his/her own creation on the jobsite. It separates the "player," who is in need of hands-on knowledge in order to produce drawings that are meaningful to the builder, and therefore deprives him/her from a crucial technical learning experience.



AIA: STANDARD CONTRACT FOR CONSTRUCTION [A 201]

§ 3.6 CONSTRUCTION PHASE SERVICES

§ 3.6.1 GENERAL

§ 3.6.1.1 The Architect shall provide administration of the Contract between the Owner and the Contractor as set forth below and in AIA Document A201-2007, General Conditions of the Contract for Construction. If the Owner and Contractor modify AIA Document 201-2007, those modifications shall not affect the Architect's services under this Agreement unless the Owner and the Architect amend this Agreement.

§ 3.6.1.2 The Architect shall advise and consult with the Owner during the Construction Phase Services. The Architect shall have authority to act on behalf of the Owner only to the extent provided in this Agreement. The Architect shall not have control over, charge of, or responsibility for the construction means, methods and techniques, sequences or procedures, or for safety precautions and programs in connection with the Work, nor shall the Architect be responsible for the Contractor's failure to perform the Work in accordance with the requirements of the Contract Documents. The Architect shall be responsible for the Architect's negligent acts or omissions, but shall not have control or charge of, and shall not be responsible for, acts of omissions of the Contractor or of any other persons or entities performing portions of the Work.

§ 3.6.1.3 Subject to Section 4.3, the Architect's responsibility to provide Construction Phase Services commences with the award of the Contract for Construction and terminates on the date the Architect issues the final Certificate for Payment.

§ 3.6.2 EVALUATIONS OF THE WORK

§ 3.6.2.1 The Architect shall visit the site at intervals appropriate to the stage of construction, or as otherwise required in Section 4.3.3, to become generally familiar with the progress and quality of the portion of the Work completed, and to determine, in general, if the Work observed is being performed in a manner indicating that the Work, when fully completed, will be in accordance with the Contract Documents. However, the Architect shall not be required to make exhaustive or continuous on-site inspections to check the quality of quantity of the Work. On the basis of the site visits, the Architect shall keep the Owner reasonably informed about the progress and quality of the portion of the Work completed, and report to the Owner (1) known deviations from the Contract Documents and for the most recent construction schedule submitted by the Contractor and (2) defects and deficiencies observed in the Work.

AIA Standard Contract for Construction A 201 © American Institute of Architects; https://aiacontracts.com/

Figure 4: AIA Standard Contract for Construction A201 © by American Institute of Architects, 2017

Accordingly, as soon as the work becomes tangible, the architect loses control, based on how the system is set up. The issue (and current professional weakness) lies in the transfer of information, translating an imagined construct into a built construct. This has been detrimental to our profession.

The reason can be extrapolated from the above: The Architect is not a risk-taker and has been prepared by documents such as the A201 not to engage into financial peril. While the Developer's and the General Contractor's performances are based on finishing on-time and on-budget, the Architect's role during that crucial phase seems to be rather that of a by-stander. Therefore, two main detrimental developments for the Architect are detected:

#1) Underdeveloped hands-on knowledge

#2) Uninvolved, or avoided risk-taking.

As a consequence, due to the financial pressure and the lack of team-integration, the Architect's

role (as the conductor of the oeuvre) has deteriorated.

BACKGROUND + PROFESSIONAL GROWTH

Originally, I aspired to become a carpenter, which didn't happen due to concern to enter a blue-collar profession. I was often suspicious about separating the world of "making" from the world of "thinking" in architecture. There are certain connections that I experienced while studying architecture in Europe. For instance, at the Technical University Berlin it was a requirement to document proof of several weeks of internships spent on construction sites, before being eligible to an academic benchmark called "Vordiplom" (Pre-Diploma). Reason for this was "to give students an early insight into the fields of activity of the other people responsible for the implementation of a construction project and to give them an impression of the complexity and dependencies of the necessary work processes" ("Richtlinien zum Pflichtpraktikum," 2019).

As a student, I have worked with masons and I have worked in a construction management firm, both during summer breaks. After graduation, I have worked in several offices on tangible projects. However, in one of them I was warned that as an Architect you should never be caught with a hammer-at-hand. This was decades ago, but it stuck with me as a negative example.
I believe that it is fundamental to engage in craftwork if you want to be specialized in thinking creatively. It is necessary in order to create good architecture.

I have had my own practice for the last 25 years. For my projects, there are many special things I have done hands-on so to drive a project forward and to engage into teamwork with the crews onsite, and, subsequently, to learn from them. This is crucial for professional development in architecture.

I am teaching this as well: I have been the PI for one of CCNY's most prestigious Design-Build projects: The Solar RoofPod, which was a contestant of the 2011 Solar Decathlon exhibited at the National Mall in Washington D.C. in order to build a net-zero residential unit. It had ~300,000 visitors (Figure5). It is now permanently installed on top of the roof of the CCNY Spitzer School of Architecture as a sustainability hub and classroom. I documented the research that led to this student-driven project in my book: "Prototyping Architecture" (Volkmann, 2016).

See "PROTOTYPING ARCHITECTURE – THE SOLAR ROOFPOD", Oscar Riera Ojeda Publishers 2017, ISBN# 978-9881619402 © by Christian Volkmann

Figure 5: Prototyping Architecture: The Solar RoofPod: Students being proud of physical architectural work, 2011; CCNY.

Through all of these experiences I am covering point #1 (mentioned above): Develop hands-on knowledge. Especially the RoofPod project opened my eyes in order to change teaching strategies. I will explain now, how I have engaged in Point #2: Develop risk-taking skills.

THE PROJECT

Frustrated by the lack of professional opportunity as an architect, I decided to put a new premise to the test: I chose to run my own construction firm and develop a new 4-apartment townhouse from the ground up, right in the heart of Harlem. To prepare, and to make the project as economically viable as possible, I trained in multiple disciplines. I first qualified as Construction Superintendent, a certified position required by the NYC Department of Buildings. I coordinated all building trades, commissioned all subcontractors directly, and maintained full control over scheduling and logistics. I served as one of my own subcontractors, working hands-on and

participating across many trades: steel structure, concrete work, framing, drywall, tile, and daily site cleanups. I didn't mind the physical labor, it was a financial necessity at first, but over time, I realized that the architect should be closer to construction responsibilities. That proximity enhances understanding and enables better control of design execution, in collaboration with the construction team (Fig.6).

See "UNDERCOVER ARCHITECT – TOWNHOUSE DESIGN-BUILD IN HARLEM NY", Oscar Riera Ojeda Publishers 2026, ISBN 978-1964490427 © by Christian Volkmann

Figure 6. Harlem Townhouse: Discovering the architectural detail tangibly, 2021; Harlem NY,

Beyond construction management, I also took on financing, budgeting, and code compliance. As the Architect of Record, I handled the entire design process, from initial concept through construction documents. I managed much of the administrative work as well, far beyond the typical scope of an architect. What began as a financial necessity, gradually became a preferred mode of operation. I came to understand that true control over design requires serious day-to-day hands-on participation.

Throughout the process, I wore many different hats: designer, builder, manager, and laborer. This experience gave me a new perspective on integrating design and construction, and on developing a more cohesive, strategic practice. This practice allowed me to dive deeper into assembly strategies: I installed curtain- wall systems with glazing, rainscreen siding, my own stair system, offset pivot doors, kitchen islands, etc. I learned more about the particular, sometimes complicated assembly methods than I would have learned from catalogues and drawings. (Fig.7)

Figure 7: Harlem Townhouse: Custom floor plan compared to typical developers' floor plan strategies; by author.

What is most important is that this changes the architectural "ball game": As mentioned at the beginning, the way our cities look is very repetitive, without much articulation of conceptual idea and without love for the detail. The same façade systems are regularly used for expedient installation purposes, the same floor plans are used for smooth marketing, always with similar

strategies: maximizing number of bedrooms, even though demographics for Manhattan say otherwise: roughly 80% of households are non-family, occupied by one or two persons (Fig.8) (“Statistic Atlas,” 2018).

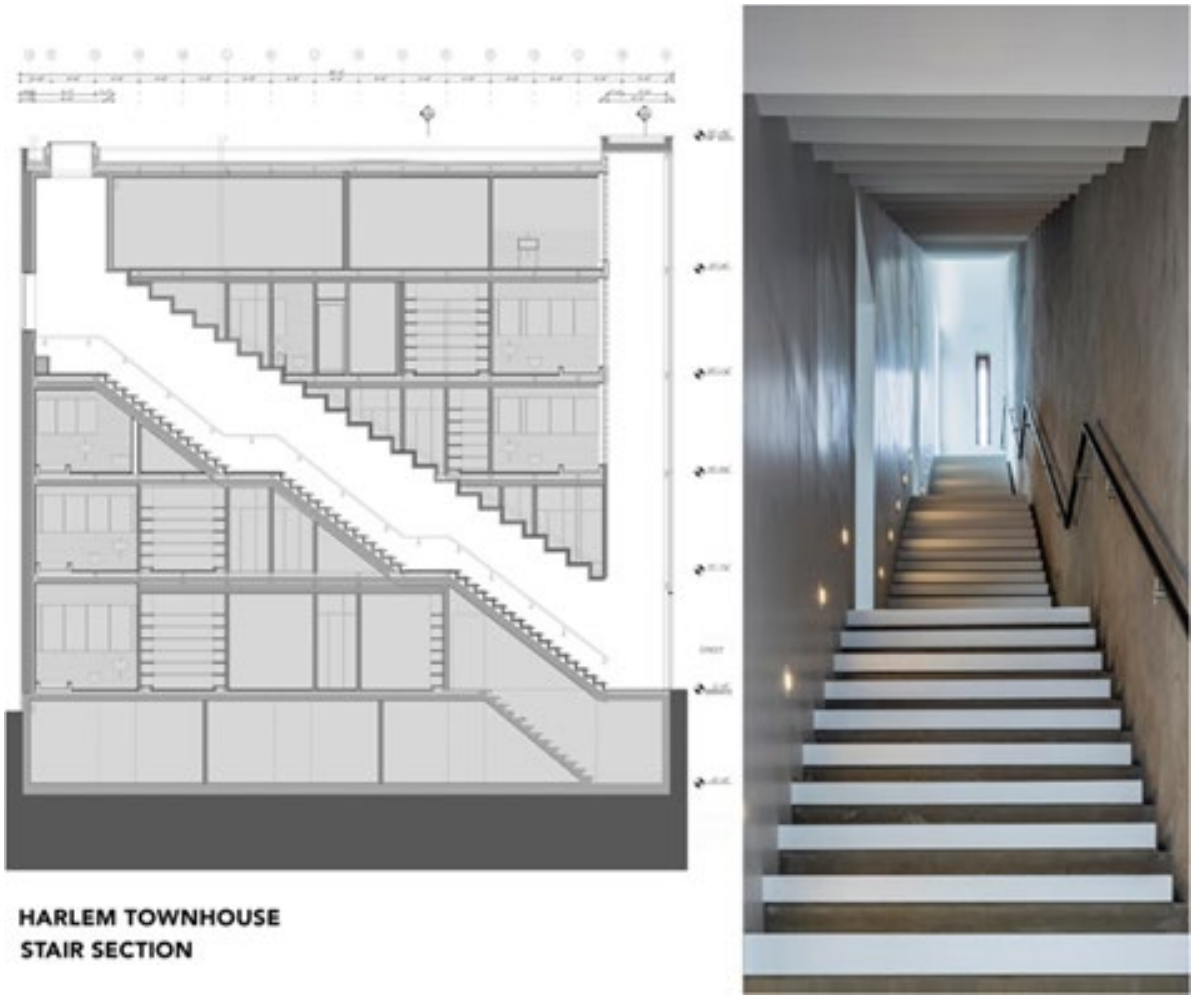


Fig.8: Harlem Townhouse: Section, related to spatial thinking and Design-Build construction strategies; by author

Developers are prone to use an idea of mass-fabrication, in order to maximize return-on-investment. If architects could build more creative “applied art” solutions in a cost-effective way, our cities would look different. This could be achieved by change of education, by not following the conventional organizational structure anymore, but by involving the Architect as a true “conductor”, with expertise in the field of design-build processes.

In German culture the Architect’s profession was once called Baumeister (which translates to

Masterbuilder). The Masterbuilder always engaged in meaningful communication and seemed to know as much as the trades people about their craft, maintaining parallelly the vision and idea of the artifact. Knowing and communicating the bigger picture all the while understanding the diverse techniques of building was the way how sophisticated construction was undertaken. “In traditional society, the builder combined the functions of design and construction that are now assumed by separate professionals, and the system of apprenticeship taught people to take these functions on in a way that combined thinking and doing. The word architect, when it was used up to the eighteenth century, usually referred not to an architect in the present-day sense of the word but to someone who assumed overall responsibility for design and construction. Almost invariably, [these masterbuilders] came out of the building trades, and their responsibility lay not only in the production of drawings but also in work on the building site … Their work was in fact an extension of the role of the craftsman.” (Davis, 2006). This might seem a bit nostalgic, but I believe that we have to have a holistic understanding of the building processes, from concept to completion, and oversee all aspects, including material selection, techniques, details, structural and mechanical integrity, artistic elements and spatial assets, financing, code compliance … and much more. There is competition in the process of taking the field of this integrated role: The Developer, who is controlling many of the players we started with. The role of the specialist for the architect has to be reconsidered, because the separation of professions lead to our isolation. The integrated All-rounder is in an economic sense less vulnerable than the No-risk-bystander, as suggested by the AIA’s A201. The architectural profession must be recalibrated so to develop better skills of control and collaboration in the process of building and making.

EDUCATION

Any recalibration of the current system will take many years, because we use to follow what is an established path. An architectural career usually begins in an academic setting, meant to serve as the foundation for learning. It is thus clear that any effort of recalibration has to start at that level. The objective should be to better integrate the profession into an organizational structure that is about translating creative thinking into actual construction.

Students have to learn how-to-play-the-game and how to fit into a complex environment with manifold skills, focused on producing a better product, that is not only functional but inspiring. This raises the question: Does the academic curriculum truly prepare students with such a range of integral skills? Are we, in fact, prepared and equipped to teach how to do applied art, working hands-on, in a team with others?

In my more than twenty years as a professor of architecture, I have seen that most curricula do not cultivate such skills. They are largely focused on the solitary acts of thinking and representing. Few very good design-build programs stand out: Auburn University’s Rural Studio program, University of Kansas DesignBuild program, the Yale Architecture Building Project, but it seems that such programs are isolated.

Design-Build programs require more time for teaching, for procurement and for construction.

They carry greater risks than projects that remain on paper, since things can go wrong during execution. As a result, many faculty members avoid such projects, often also lacking the professional experience needed. Academic demands reinforce this tendency; a published book can count more toward academic career advancement than the realization of a built project. It should be the opposite, since the tangible creation of imaginative conception lies at the heart of the discipline. Students must be brought closer to understanding architecture through hands-on experience, to give them the skills necessary to interact in-the-field, to foster teamwork and leadership skills.

There are two essential elements in an architectural education when it comes to producing tangible architecture: process and product. The product is well covered in most academic architectural programs: We focus on architectural narratives, typologies, and the articulation of final appearances. We are analytical on paper, and we know how to represent ideas precisely. However, we are far less effective at teaching how to integrate the conditions of process and production. We, as teachers, often leave the students with the impression that someone-else-will-figure-it-out. Process is problem-solving, related to communicating with players that are involved in construction. The way we teach process in academia is suppressed, making it difficult to grasp the essence and detect its crucial connection to the product. To truly understand process, one must enter the world of the builder and experience firsthand how things are made.

Artefactory Lab: Design-Build Studio at City College of New York: collaboration w/ Associated Brick Mason Contractors of Greater New York and Concrete Masonry Check-Off program; see also: https://www.bizjournals.com/newyork/news/2025/09/01/design-build-ccny-industry-future.html

Figure 9. Artefactory Lab: Design-Build Studio at CCNY, w/ABMC Local 1 and Concrete Masonry Check-Off, 2025.

An example for Design-Build implementation and understanding of process: Last semester we did a Design-Build studio sponsored by the Concrete Masonry Check-Off program, where students first designed on their own, than after six weeks in teams, with consultation of masons and contractors, which then ended in a two-day construction workshop with union masons collaborating to constructs a space composed of two structures. Students were in charge of detailed drawings, mock-ups, take-offs and cost calculations and, of course of realizing beautiful ideas. (Fig.9, Fig.10) There are opportunities to broaden the academic curriculum and strengthen how we teach the significance of process. This is one of many, which my team and I conducted.

Figure10. Artefactory Lab: Design Build Studio at CCNY, after end of semester, 2025: "Lessons learned" © Fion Li.

The most important step (for me) would be to establish a permanent design-build program within the curriculum. The best chance to develop such program is to invite the building world into the school's environment on a consistent and long-term basis. This means forming lasting partnerships with construction industry stakeholders and integrating these collaborators into an academic strategy.

Where better to plant the seeds of a tangible literacy than at the cradle of education? The larger payoff comes afterwards, when students enter their profession. Their ability to use skills related to process will continue continuously, compounding for a lifetime and connecting to the practitioners' typical challenges.

CONCLUSIONS

The intention must be to reform the profession by overhauling an organizational structure, related to construction, that has been inefficient and detrimental for meaningful architectural output, and for creating applied art. The role of players must be recalibrated. Architects have to address the question on how to conduct their business in terms of logistics and supervising the process of creating their product.

What is crucial in that process is finding the right approach, determining what additional roles the Architect could potentially take on in all niches of construction, with the objectives to keep the budget slimmer and the output more beautiful. The Architect has to discover new haptic responsibilities to make meaningful connections between a desired product and a feasible process. To be deeper involved in the process of construction requires the ability and the skill to take risks, which we are advised to avoid.

In order to learn how to evaluate real-life situations, we must be exposed to real-life conditions, early on. That clearly means that we have to implement them in our educational system. As teachers of architecture, we must be interested in teaching students how to apply learning to real-life production conditions. This is not necessarily related to specific topics of design.

The entrepreneurial qualities of the Architect must include discovering synergies and innovative collaboration models. The results are probably much more interesting in terms of output of production than the typical model-T strategy developers often apply. It is also about developing confidence: Understanding the conditions, but thinking independently, from a standpoint that is based on strategizing in the world of architectural making.

My aim, as Architect, is thus to become better in the management of process, comprehending specific conditions that apply and then, taking advantage of them in favor of the artifact, meaning the product. If we combine the two ends of thinking, we can define a better role in the system of construction logistics.

The subtitle: Design-Build – “Undercover Architect” relates to a book that I just finished about the Harlem Townhouse 10. It points to my conviction that certain necessary skills for making architecture can only be understood practically. It is much more likely that you uncover them in in a construction environment, which I therefore infiltrated. My role model is that of the Masterbuilder, who is focused on becoming knowledgeable in establishing a tangible connection between the world of thinking and the world of making. This comes with the realization that our profession is likely a hybrid: a “blue-and-white-collar” profession, with one foot placed firmly in each field.

Reforming an approach (and a profession) means to foster the next generation of architects to understand their conditions differently. We must communicate in a more comprehensive way, focusing on crucial roles essential in construction and management that the architect potentially could fulfill. The aim is to foster synergies between parties involved in construction, so to be

more efficient, but also, to develop mutual compassion for an architectural artifact, with buy-in from all sides.

The architect must be a team builder. This, as a significant objective, would mean that we have to achieve more opportunities of exchange, forming stronger communities of stakeholders. Many processes could be improved by practicing together, meaning that business and management skills of the developer, the craft and techniques of the builder, the understanding and application of code experts, the general legal conditions specific to New York and the design and communication skills of the architect would have to become part of a more comprehensive model.

That, ideally, would mean that we should attempt integration efforts: developers, general contractors, craftspeople and architects creating a platform of education together. Crucial information must be exchanged, by establishing partnerships and overlaps between industry and academia. Changing the architectural education requires introducing topics to the curriculum that develop entrepreneurial qualities. Tangible skills basic to craft, art and technology must be practiced hands-on.

Architects have to learn to wear many different “hats” in a specific profession that requires versatility. The “players” in the world of architecture and construction are known. The conditions of interaction are however ambiguous. Interaction is key to making progress. The opportunity is to reinvent the profession: We should be masters of interaction, in all different realms that determine the construction site. We should awaken from the office slumber and understand the profession comprehensively, by engaging with the world that shapes the product, which means to verify it in field (V.I.F.).

My hope is that many aspiring architects of coming generations will be more passionate about embedding themselves into field operations. I started with the analogy of the orchestra: Everybody likes to listen to good music. Music is related to architecture in many ways, in terms of the compositional logic and also in our appreciation for beauty. We are experiential beings. We love thoughtful auditory sensation, and we love the stimulation of our visual senses, the thoughtful compositions of light, geometry, material and space. It influences our thoughts, our feelings, our culture.

If architecture is purely related to return-of-investment, to technical application without meaning and to scaled management of mass production, the world would become a sad place. What it takes is that we, as Architects, improve our position in the organizational structure of construction, to create formidable tangible artifacts, which are stimulating and beautiful. Design-Build strategies might be the key in re-discovering such assets.

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Learn by Doing: Using the Gateway Decathlon to Enhance Experiential Learning in a Residential Construction Course

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ABSTRACT

The Gateway Decathlon student competition is a design-build challenge that engages interdisciplinary student teams in the creation of prefabricated, high-performance housing solutions. Focused on sustainability, affordability, and real-world impact, the competition spans multiple stages encouraging collaboration across architecture, engineering, and construction management disciplines.

In 2023, Cal Poly's Construction Management Department entered the competition with the goal of designing and developing a mass timber prefabricated residential unit. The primary objective was to explore high-speed construction methods and improve transportation efficiency by combining flat-pack systems with modular construction techniques, an approach aligned with current industry demands. The resulting design features a modular central core unit, or "wet pod," which houses the mechanical room, bathroom, and kitchen. This core is complemented by prefabricated mass timber components for the floor, roof, and walls.

To support the Gateway Decathlon project and expand "learn by doing" opportunities within current undergraduate construction courses, the decision was made to construct the wet pod on campus. As a result, students in the "Residential Construction Management" course were given the opportunity to build a fully modular pod that would be delivered to the Cal Poly campus assembly/exhibition site (and designed for later shipment to the final competition exhibition location) upon completion. To prepare for the final pod, the authors collaborated to develop mock-ups to understand tool and material needs, length of time for instruction and installation of the different components and ensure equitable learning opportunities for students in alignment with course learning outcomes.

This paper will detail the pod's design process, curriculum modifications, and the integration of hands-on learning modules. The focus will be on the types of classroom activities involved, lessons learned during the development and implementation phases, student learning outcomes,

and recommendations for incorporating similar interdisciplinary, project-based experiences in construction education. This paper will help educators incorporate project-based experiences into the curriculum and take advantage of the unique opportunities presented by real-world projects.

INTRODUCTION

The Gateway Decathlon was a three-year competition that focused on innovative, sustainable housing design and construction. This design-build, multi-staged, multidisciplinary event brought together teams of students, guided by faculty members and industry partners, to collaborate on housing design and construction projects. It was an exciting opportunity for collegiate teams to showcase their skills in designing and building cutting-edge housing units. The competition emphasized creativity, innovation, and sustainable solutions, with a particular focus on industrialized and off-site residential construction methodologies. The project was designed to be built and exhibited on the Cal Poly campus and then disassembled to be shipped to another location for final assembly, for a 10-day installation and a month-long public exhibition.

The Cal Poly Gateway Decathlon (CPGWD) team included faculty from the College of Architecture and Environmental Design, industry partners across the Architecture, Engineering, and Construction (AEC) sectors, and second- through fifth-year students representing diverse disciplines such as Architecture, Construction Management, Civil Engineering, and Business Administration. The initiative emphasized interdisciplinary collaboration, project-based learning, and curriculum integration to create a robust foundation for designing an advanced and unique housing prototype. This educational model reflects Cal Poly's "Learn by Doing" philosophy, which is particularly emphasized in programs such as Construction Management, Architecture, and Architectural Engineering, all of which were strongly represented within the CPGWD team. Sustainability, affordability, and resiliency were central drivers of the team's design approach. To address these priorities, the project adopted mass timber as its core material strategy, due to its environmental benefits, potential for innovation, and compatibility with industrialized construction methods. Beyond structural performance, mass timber enabled rapid assembly, design for disassembly, transportation efficiency, and modularity—concepts that framed the team's design process. A hybrid construction approach was employed, combining flat-pack systems with modular construction techniques to align with contemporary industry practices. The resulting design incorporated a modular central core unit, or "wet pod," housing the mechanical room, bathroom, and kitchen, complemented by prefabricated mass timber floor, wall, and roof components (Figure 1).

The Cal Poly team chose mass timber as the primary structural material because it works well with prefabrication and a hybrid flat-pack/modular strategy for industrialized delivery, while also supporting the project's sustainability goals. The design combined flat-pack systems with modular construction, centered on a "wet pod" (mechanical room, bathroom, and kitchen) and prefabricated mass timber floor, wall, and roof components to streamline logistics and allow efficient assembly, disassembly, and reassembly after campus exhibition. In addition to these constructability benefits, mass timber can store biogenic carbon in wood products over the

building's service life (Kouhirostami and Dharmapalan, 2026).

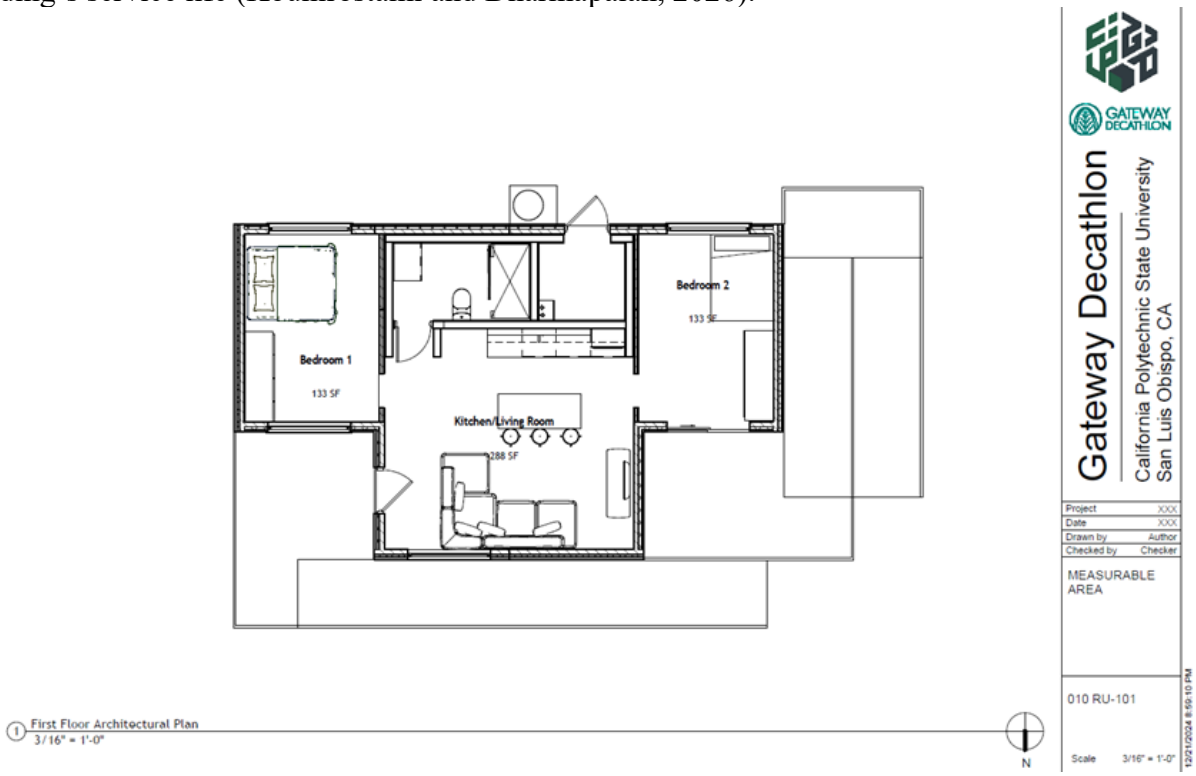

Figure 1. Architectural plan.

To expand "Learn by Doing" opportunities within the construction curriculum, the decision was made to fabricate the wet pod on campus, integrated within an existing core course's curriculum. Students enrolled in the Residential Construction Management – CM 214 (RCM) course participated directly in building a fully modular pod, which was later delivered to the project site. Prior to final fabrication, the instructional team developed mock-ups to evaluate tool and material requirements, estimate instructional and installation durations, and ensure equitable learning opportunities in alignment with course outcomes.

This paper presents the design and implementation of the wet pod as both a competition deliverable and an educational innovation. Specifically, the paper highlights the design process, curriculum modifications, and integration of hands-on learning modules. The discussion focuses on classroom activities, lessons learned during development and implementation, observed student learning outcomes, and recommendations for embedding similar interdisciplinary, project-based experiences into construction education. The intent is to provide educators with practical insights for leveraging real-world projects to enrich curricula and enhance student learning.

LITERATURE REVIEW

Student competition opportunities are abundant for students in the fields of architecture, engineering, and construction management. These competitions range from being discipline-specific to interdisciplinary, allowing students the chance to focus on real problems they might encounter when they graduate and start working in industry. Students join these competition teams for hands-on, practical experience and exposure to complex real-world problems (Letdin et al., 2025), with students identifying design competitions as one of the top three activities that helped them gain relevant skills (Rottmann et al., 2016). They also participate in competitions to make an impact on the community in which they serve, to learn "the value of collaboration and transmission of design intent" (Weber, 2015, p. 4) and to develop team and leadership skills to help them enter industry well-equipped. Faculty members also notice that competitions can also heighten student's "emotional interest, motivation, and involvement engaging students in an exciting and open-ended, multidisciplinary project and encouraging creativity and innovation" (Gadola and Chindamo, 2019, p. 19).

One of these competitions, the Solar Decathlon -which served as the inspiration for the Gateway Decathlon- has been around for more than 20 years. Since its inception in 2002, it has involved nearly 790 teams from universities worldwide and has trained over 25,000 students, whose projects have pioneered the development of energy-efficient, renewable-powered homes, positively impacting communities by demonstrating scalable, sustainable, and affordable housing solutions (DOE, 2022). Students from several disciplines including architecture, engineering, and construction work together to solve a problem, and have to coordinate not only the design but the logistics. Students who have participated in this competition have been excited to be recognized for their work on the project and have reported increased multi-disciplinary skills, knowledge and abilities as a result of participation, enhanced their teamwork skills (Baier and Tao, 2007; Chuku et al., 2003), and were provided employment and entrepreneurial opportunities.

In 2024, the Gateway Decathlon embraced goals similar to the Solar Decathlon—not only to advance innovative techniques in prefabricated residential design and construction, but also to create a platform for training future industry leaders with deep knowledge of off-site and modular design and construction. These aims directly address documented gaps in workforce skills for off-site design and construction and the need to modernize industry practices to fully realize design, productivity, cost, and schedule, and other benefits and differences (Assaad et al., 2022). GWD aimed to prepare students for the future by equipping them with the knowledge, skills, and interdisciplinary experiences needed to become the next generation of industry leaders in off-site and sustainable housing.

Integrating experiential learning in classroom activities has been perceived by students as the most effective way to learn the material (Kolegraff et al., 2021). Students have ranked it as the most effective way of learning the course material, and it provides additional advantages of gaining empathy for workers, better understanding scheduling and coordination. Although traditional teaching methods provide foundational knowledge, experiential learning enhances "skill acquisition [and] foster[s] critical thinking and adaptability" (de Costa, 2025, p. 7).

Although some schools provide class credit for students to participate in competitions, the learning is only achieved by a limited number of students - only those members who are a part of the competition team. However, competitions have been leveraged by faculty as a way to undertake comprehensive curriculum and pedagogy redesign and ways to investigate student learning engagement to cultivate competencies in emerging trends like technology integration and sustainable practices (Wu and Hyatt, 2016).

Limited literature addresses the expansion of learning and problem-solving from competition into the integration of classroom activities in parallel courses, which could support both the overall competition and enhance learning experiences. This paper aims to fill this gap by reviewing the Gateway Decathlon competitions and identifying how the design of the structure and a portion of the construction were integrated into a separate class. This approach expanded hands-on learning opportunities across multiple classrooms. Not only did it provide additional chances for students to explore alternative systems, but it also offered design and construction students leadership opportunities to develop a design that other students had to understand and follow.

POD AS PROTOTYPE: DESIGN, CONSTRUCTION, AND INNOVATION

The design process for the Gateway Decathlon (GWD) began with the integration of the competition into the curriculum through an Architectural Design studio - ARCH 452 in collaboration with a service experimental Construction Management course - CM 420 during the Winter 2024 quarter. Cal Poly's curriculum is based on a quarter system; therefore, all the classes meet for 10 weeks. ARCH 452, supervised by Bryan Shields, adopted the Gateway Decathlon design concept as its studio project, in which five student groups developed multifamily residential concepts for the International Energy Conservation Code (IECC) Climate Zone 4. The primary design concept focused on revitalizing an abandoned industrial building into a multifunctional, mixed-use structure utilizing prefabricated construction strategies.

Students in ARCH 452 collaborated closely with CM 420 to ensure that their designs met the competition's technical and logistical requirements, resulting in a cohesive design documents' package. CM 420, designed as a project-based service-learning course, provided students with hands-on experience in bridging theoretical design knowledge with practical application. Students from different built environment disciplines collaborated to support ARCH 452 students. Throughout the winter session, students not only developed the predesign and conceptual design drawings (Figure 2) but also managed the project's social media presence, learning to communicate their design process effectively and engage with broader audiences, which is essential for real-world project promotion and stakeholder engagement.

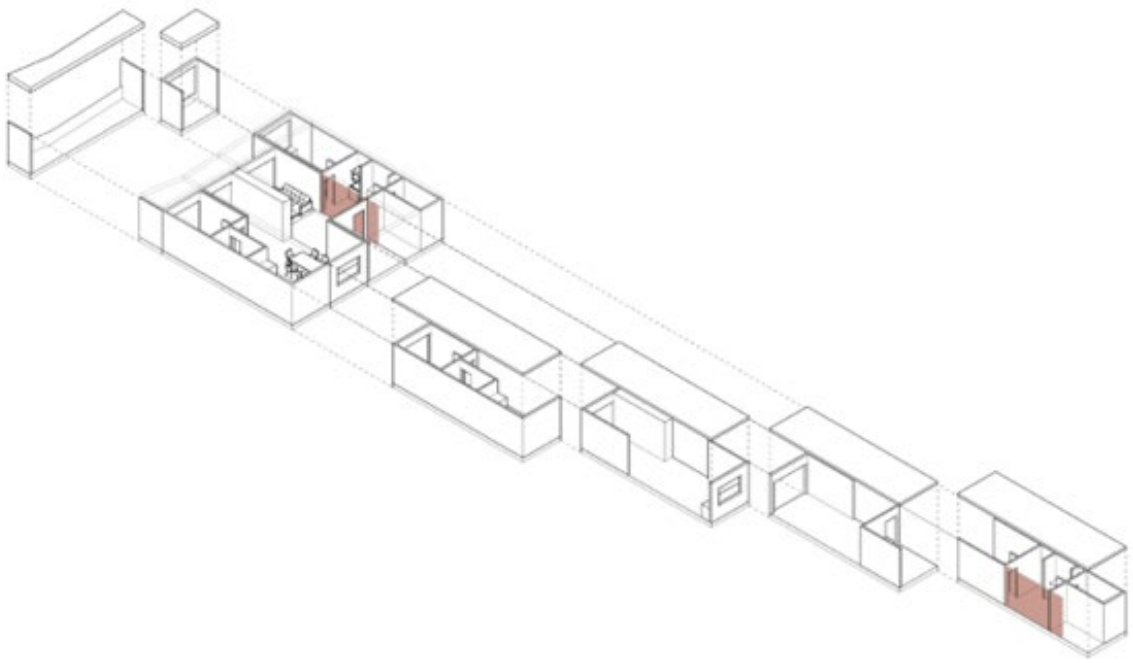

Figure 2. Exploded axon – design developed by a team from ARCH 452.

The design development advanced in subsequent quarters, with a strong emphasis on producing comprehensive deliverables and integrating advanced construction management practices. In the Spring quarter, Special Studies in Architecture – ARCH 480 collaborated with Special Problems for Advanced Undergraduates – CM 400 to complete the Design Document package. The process continued through the summer quarter, as CM 400 students worked alongside peers from Construction Management and Architecture to refine the design and ensure alignment with both the project's goals and the competition requirements. Throughout the entire process, industry partners played a critical supervisory role, reviewing the work to ensure constructability and feasibility, while addressing material availability, transportation constraints, and installation limitations by in-person and virtual meetings and design charrettes.

These reviews and collaborative efforts ultimately led to the adoption of a hybrid system that combined modular and flat-pack strategies. This approach was recognized as the most viable solution and was selected for development into the final design submitted to the competition. To validate the feasibility of this concept and test its constructability, the team made the strategic decision to build the "wet pod" (Figure 3) within a Residential Construction Management – CM 214 course. This hands-on activity not only provided proof of concept for the hybrid system but also gave students invaluable experience in translating a competition design into a buildable product, reinforcing the project's emphasis on interdisciplinary, experiential learning.

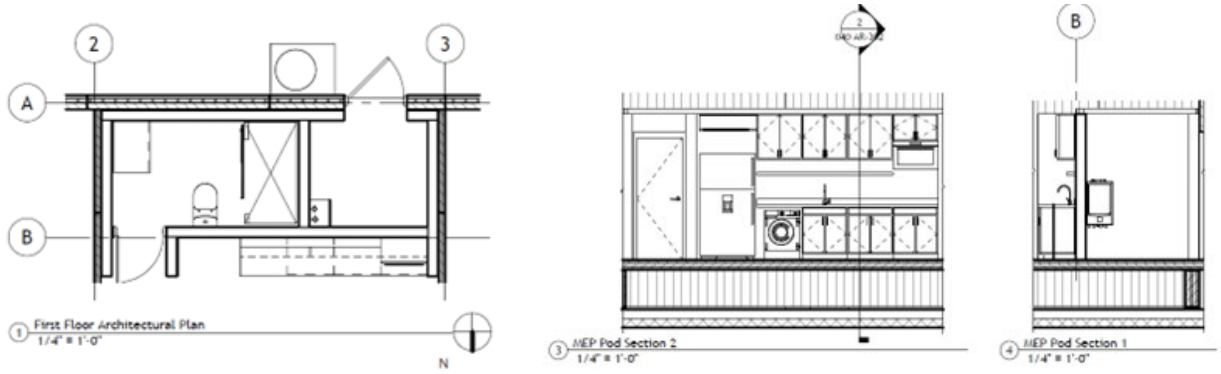

Figure 3. Wet pod–plan and sections.

POD AS PROTOTYPE: DESIGN, CONSTRUCTION, AND INNOVATION

Standard Class Format

As mentioned, Cal Poly's curriculum is based on a quarter system, and the Residential Construction Management – CM 214 (RCM) course meets for ten weeks to go over all aspects of residential construction – from foundations to close of escrow – including a discussion of the team players, setting up the construction site for efficiency and safety, building methods and materials, scheduling and coordination of trades, quantity take-offs of all parts and pieces in a home, and a financial analysis of a production homebuilding project. For two weeks each quarter (approximately 26 hours), students put their learning into practice by building a 48 square foot wood framed tiny home structure. Construction includes floor, wall, and roof layout and framing, waterproofing exterior walls and roofs, installing siding and roofing materials, and installation of doors and windows.

Planning for Adjustments

However, the authors of this paper met during the summer of 2024 to discuss the opportunity to adjust the activities so students could construct a wet pod for the solar decathlon project in AY2024-2025. The construction would be for the wet pod and include all the rough-in installations for the back-to-back kitchen and bathroom/utility room areas and could include floor, wall, and ceiling joist framing, electrical, plumbing, and exhaust systems in fall and winter quarters, with finishes installed in spring quarter. The deadline for the wet pod was June 2025. Since the quarter system allowed for three quarters, the following schedule was decided:

- **Fall Quarter**: Practice installations (students in this residential course would work on the mock-up but everything would be disassembled at the end of the quarter. This was our learning curve quarter. The goal of this construction was to teach building systems construction but also provide the instructor with a way to practice the installation and understand how long it would take to install each component, so adjustments could be made in the following quarter if necessary to make the building more efficient.

• **Winter Quarter**: Complete wet pod construction. Using lessons learned from Fall Quarter, the instructor could adjust the building day activities and schedule for greater efficiency of installation to ensure all necessary components were installed.

• **Spring Break**: Finalize all rough-in installations students could not complete (ie. Mini-split rough-in)

• **Spring Quarter**: Install all interior finishes, including drywall, cabinets, flooring, and finish mechanical, electrical, and plumbing (MEP)

The authors met to review the plans, decide on the materials to be used, and clarify the systems to be installed (i.e. future water heater to ensure correct wiring). From this, the RCM professor split the work up into four separate areas with each area including framing, electrical, exhaust, and plumbing to ensure equitable learning experiences for each student team (Figure 4).

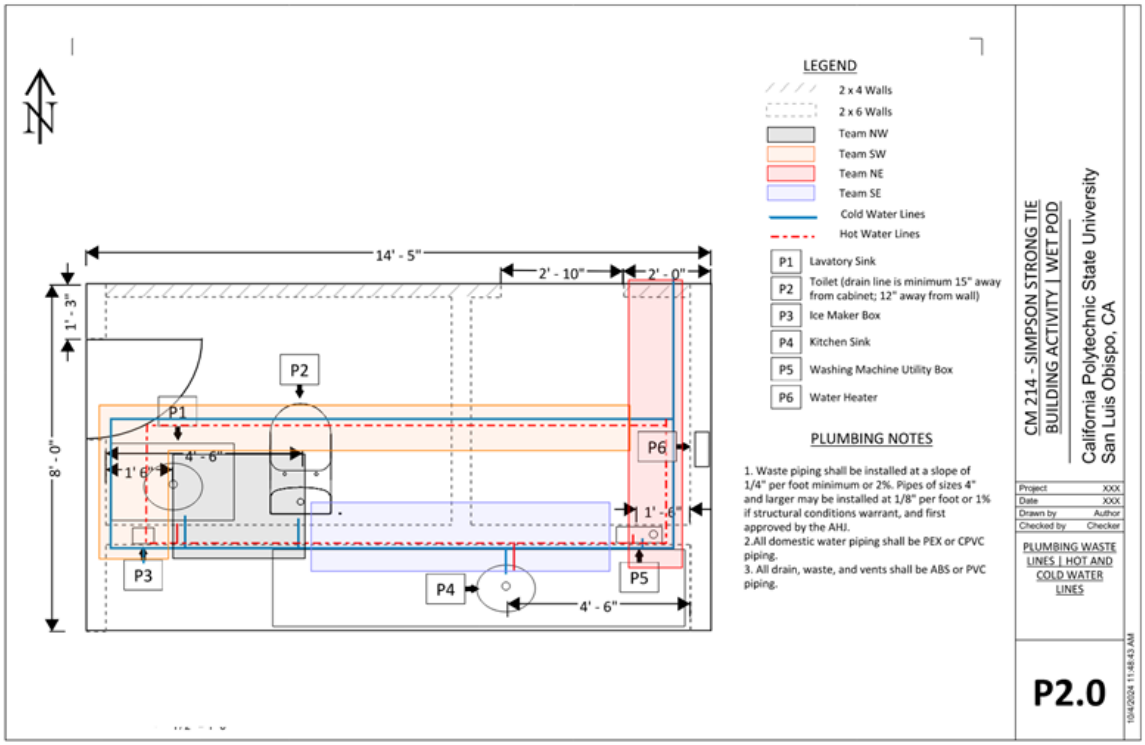

Figure 4. Wet pod construction drawing.

Integration into the Classroom and Pivots Made

All construction materials were purchased during the first few weeks of the fall quarter. Students began construction in week 4, following a lecture on framing. The course is structured around the spiral learning framework discussed by Cleary (2022). This approach allows students to first

learn fundamental concepts in lecture, then apply that knowledge through actual construction and building. Finally, they extend their understanding by completing quantity take-offs for the items they have just learned about and installed.

Fall quarter installations were definitely a learning curve for both the students and the RCM professor. For instance, all four teams started on their activities at the same time – so when it was time to complete the plumbing drain lines, all four teams all started at once and, since they were all working on something slightly different, they each had questions for one single instructor. This resulted in a lot of waiting around for guidance – or rework for students who tried to figure it out independently but ended up installing fittings in the wrong directions or using the wrong-sized pipe. Also, the small size of the pod created space conflicts with students working in the same area (Figure 5).

Figure 5. Working area.

Prior to winter quarter, the authors learned that the timeline had been extended for the competition, so the wet pod no longer needed to be completed by June. With this knowledge, the RCM professor took advantage of this opportunity to split the building into four separate wall areas, each with similar MEP items, to better refine teaching and coordination of the different teams for a more efficient build. For example, for the plumbing drain line installation, only two teams worked simultaneously at alternate sides of the pod, allowing the professor to split their time more effectively and reducing space conflicts. While two teams were building, the other two teams completed estimates independently, and then the next day they switched roles. This allowed for greater efficiency of the students' time and installation.

By the end of winter quarter, the wet pod was completed through wood framing and partial MEP rough-in. While the team was on track to deliver the project on time, a leadership change within the competition and uncertainty around the updated plan and requirements created a moving

target for spring-quarter execution. For that reason, Cal Poly chose not to continue with the project into the spring quarter.

Lessons Learned

First, while there are clear learning benefits to having students design projects, challenges arise when those designers are not involved during the construction phase. Implementing and constructing a student-led design project in the following quarter can be difficult, as the student designers may have graduated or moved on, leading to gaps or unanswered questions in the design.

Space and sequencing of students is crucial with 24 students in a small space. Since the wet pod did have a small footprint, and since the RCM professor wanted to ensure equitable learning experiences for all students, teams were able to interact with each building component (all teams did some framing, electrical, plumbing, and HVAC), it is critical to coordinate and communicate each team's location, limits of work and connection to other team's systems, and stagger training to maximize learning and efficiency of the install.

Students enjoyed greater exposure to the MEP items and earned a better understanding of how the different trades are sequenced, how buildings go together, and what the different components are so they have increased understanding of what the different parts and pieces are when looking at a drawing and performing a quantity take-off. However, they would have preferred a complete set of plans, including isometric drawings, single line diagrams for electrical, product data sheets, and measurements for all components being installed. Although the wet pod plans were completed prior to the RCM class, not all materials were specified (like the water heater or appliances), so it became a design-as-you-build project, which is challenging for students who are just learning these systems. Although this doesn't always happen in the "real world," not having this included leads to frustration and makes it less of a learning experience than an exercise in futility.

Opportunities and Challenges Going Forward

One limitation for construction was having only one RCM professor for 24 students on build days – and that instructor had more management knowledge than construction expertise. One opportunity could be inviting specialty trades workers to the classroom on build days to help with construction training and standard installation practices.

Cal Poly is currently converting for a 10-week three-quarter system to a 15-week two-semester calendar. Additionally, the CM program has adjusted its curriculum to include an additional MEP fundamentals lab, which is a prerequisite for the RCM course. As a result, students will have a greater understanding of MEP systems and how to install them, so students will enter the RCM course with a greater understanding of theses systems, allowing the RCM class to be more of a refresher, which will mean less time required for lecture and training of these systems and more time to build.

Although the RCM course typically includes experiential learning activities and supports the costs for these activities, the wet pod construction was substantially more expensive than the typical wood-framed structure constructed each quarter – and the higher-cost items weren't yet included like the mini-split heat pump or cabinets and appliances. Additional fundraising may be necessary to sustain this as an ongoing project.

Although the Gateway Decathlon competition provided a very specific use for a wet pod, there are few instances where this type of installation will be used. However, this model could be modified to build tiny homes over two quarters with the intent to auction them off at the end of the school year, providing a way to generate revenue for the continued funding of the project. Additionally, as noted by Weber (2015), having a year-long project just steps from other classrooms where other construction management courses are held, this project would give students the joy of seeing the work produced and other students could visit the progress and "understand the reality of the construction process" (p. 10).

REFLECTION AND STUDENTS' OUTCOMES

The integration of the Gateway Decathlon pod construction into the Residential Construction Management course demonstrated both the opportunities and limitations of embedding competition-driven projects into formal curricula. Students consistently highlighted the value of engaging in hands-on, interdisciplinary work, reporting that their exposure to MEP systems deepened their understanding of trade sequencing, constructability challenges, and coordination requirements. These outcomes echo findings from Gadola and Chindamo (2019), who emphasized that competitions heighten student motivation and promote systems-level thinking, and are consistent with Wu and Hyatt (2016), who observed that project-based competition models improve communication and problem-solving skills within building information modeling (BIM)-intensive contexts.

At the same time, several challenges tempered the experience. Students expressed frustration with incomplete design documentation and "design-as-you-build" adjustments, a scenario that aligns with workforce reports identifying gaps in off-site construction training related to incomplete information flows and change management (Assaad et al., 2022). The absence of complete isometric diagrams, product specifications, and prefabrication details limited the educational benefits for novice builders, suggesting that experiential learning models require careful scaffolding to ensure equitable and meaningful engagement. This observation supports da Costa et al. (2025), who argue that without structured guidance, green-skills education risks reinforcing confusion rather than building competency.

The course also exposed organizational limitations. With only one faculty member supporting 24 students during complex installations, instructional bandwidth emerged as a constraint. While Cal Poly's planned semester conversion and prerequisite MEP fundamentals course may mitigate this in the future, the findings underscore the need for faculty-to-student ratios and industry participation to be strategically calibrated. Construction related studies on project-based curricula

note similar concerns, where instructor workload and expertise influence the degree to which experiential learning translates into professional readiness (Cleary et al., 2022).

Despite these limitations, students valued the opportunity to translate conceptual competition designs into tangible construction outcomes. The pod prototype offered a visible, testable proof of concept, reinforcing Cal Poly's "Learn by Doing" philosophy while also preparing students for the complexities of off-site, modular, and sustainable residential construction. Compared to more traditional laboratory or capstone projects, the competition-driven prototype provided a higher degree of authenticity and industry alignment, albeit at higher cost and logistical complexity.

CONCLUSION

The integration of the Gateway Decathlon pod into the Residential Construction Management course demonstrates a replicable but resource-intensive model for enriching construction education. By leveraging a real-world competition deliverable, the course successfully advanced student learning outcomes in trade coordination, constructability assessment, and interdisciplinary collaboration. However, this case also highlights critical gaps between educational aspirations and industry realities. The reliance on incomplete design documentation, the need for greater instructor support, and the challenges of scaling experiential learning across large classes underscore that competition integration must be carefully designed to balance educational benefits with feasibility.

For construction education, the findings suggest three key implications. First, industry partnerships should be expanded to provide technical expertise during complex build phases, mitigating faculty capacity limitations. Second, experiential modules must be supported with robust, industry-standard documentation to reinforce learning rather than introduce unnecessary ambiguity. Third, future competition integrations should consider financial sustainability, potentially by exploring revenue-generating models such as tiny home auctions or sponsored build initiatives.

Ultimately, while competitions like the Gateway Decathlon offer powerful vehicles for advancing workforce readiness in off-site and sustainable construction, their curricular integration demands intentional planning, resource alignment, and a commitment to critical reflection. When designed with these considerations, competition-based experiential learning can serve as a bridge between academic preparation and industry innovation, equipping students with the competencies necessary to lead the future of residential construction.

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The Tuscanization of South Africa's Residential Landscape

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ABSTRACT

The demands for decolonizing academic curricula, the constraints imposed by Black Economic Empowerment legislation, and a trend toward Afrocentricity in every conceivable sphere, including marketing, sport, and consumerism, are prominent features of life in South Africa. For that reason, the conspicuous preference in the black community for freestanding houses with pitched tiled roofs, patios, and faux classicist columns, generally referred to as the Tuscan style, is puzzling. How did a residential aesthetic that imitates that of Greco-Roman antiquity, the ultimate Eurocentric expression, become so popular among the black population? This study is deductive, relying on observation and literature for its information. The analysis of the phenomenon applies criteria derived from two esteemed American scholars, namely, Amos Rapoport (1929—), from Milwaukee, and Denise Scott Brown (1931—), from Philadelphia. The findings provide evidence of a dominant trend in the aspirations of most black households that is largely ignored by architectural schools, a shortcoming that contributes to the increasing irrelevance of the profession in the residential field.

Keywords: Afrocentricity, Amos Rapoport, Denise Scott Brown, Tuscan Style.

INTRODUCTION

Since the advent of democracy in South Africa in 1994, there has been constant pressure to decolonize curricula, including those of architecture schools. At the same time, academics and practitioners continuously debated the issue of architecture with an African identity. During the 1990s, as a Postmodernist manifestation, a building style of pitched roofs with Mediterranean tiles, patios, and columns with bases and capitals somewhat resembling the Tuscan orders became fashionable in (at that time) mostly white upper-income gated estates. That trend was short-lived, but in a movement that took the architectural fraternity by surprise, it has since become the dominant residential style on the less-regulated urban fringes and rural communities. It is replacing traditional homesteads, and even rural villages are rapidly morphing—mostly without official intervention—into suburban neighborhoods consisting almost entirely of these Tuscan-style houses. This study aims to determine how a house style that is clearly the antithesis of Afrocentricity became the prevalent residential preference. The findings indicate a disconnect between cultural aspirations and academic dogma.

METHOD OF STUDY AND SOURCES OF INFORMATION

Methodologically, the study flowed from in situ observation to a review of relevant literature, that of two American architects and educators, both instrumental in formulating cohesive theories of perceptions and tastes in vernacular and popular cultures. They are Amos Rapoport (1929—), professor emeritus at the University of Wisconsin-Milwaukee, and Denise Scott Brown (1931—), architect and educator (partly trained in South Africa), and principal of the firm Venturi, Scott Brown and Associates in Philadelphia. She (Denise) was married to Robert Venturi, and collectively, they changed the course of architecture, setting the stage for much more variety in architectural expression than that offered by modernism.

Amos Rapoport's seminal work, entitled House Form and Culture (1969), suggests a nexus that served as the research perspective. It is also almost impossible to engage in qualitative architectural research without deferring to Henri Lefebvre (1901–1991), the French philosopher whose The Production of Space (1974) provides valuable insights.

SOUTH AFRICA'S RESIDENTIAL LANDSCAPE

Until around the mid-twentieth century, the dwelling types of black and white households in South Africa were identifiable. As Maré (2013: 119) highlights: "These two groups dwelt and built differently in the same land" (Figure 1). The transformation of the black rural compound began with the introduction of flat-roofed rectangular rooms and has accelerated since.

Figure 1. Early homesteads of black and white communities respectively (photos by the author).

After that, the landscape was characterized for many decades by the traditional thatched-roof dwellings, called rondavels, usually combined with these small rectangular houses and often also with metal-clad shacks (Figure 2).

Figure 2. Typical rural homestead (photo by the author).

Following the advent of democracy in 1994, we found the gradual appearance of rather modest houses with prominent columns in the historically black townships, the first examples of what became known as the "Tuscan" style in South Africa (Figure 3).

Figure 3. A Tuscan house and additions in a historically black township (photos by the author).

Then, rather suddenly and quite unexpectedly, huge houses that can only be described as mansions in this Tuscan style started to appear in rural areas. Tuscan houses are being built among traditional and "ordinary" buildings (Figure 4) in ever-increasing numbers, replacing them until they morph into a homogenous Tuscan suburb, albeit without paved roads and often without engineering services (Figure 5).

Figure 4. Rural villages then and now (photos by the author).

Figure 5. Italianate houses in the North West Province (screenshot from Sithole 2021).

THE TRANSFORMATION OF RURAL VILLAGES INTO SUBURBS

The percentage of formal dwellings in South Africa have been increasing steadily from 65.1% in 1996 to 88.5% in 2022 (Stats SA 2022: 68). South Africa is a suburban nation, and approximately 80% of the formal dwellings are freestanding houses (South African Market Insights 2019), which includes the so-called Tuscan houses under discussion.

Formal dwellings were most common in Limpopo (94.7%) and Mpumalanga (92.2%) (Stats SA 2023: 69). Even though these provinces are not economic hubs, they have far less informal dwellings than South Africa's major economic area, Gauteng, with 2.7% and 5.8% respectively compared to 11.0% (Stats SA 2023: 68). Over the same period, traditional dwellings, mostly thatched mud huts, have declined nationally from 18.3% to 3.1%. In Limpopo and Mpumalanga, traditional dwellings now constitute only 2.2% and 1.8% respectively. Perhaps not surprisingly, the highest proportions of traditional dwellings are found in the Eastern Cape (11.7%) and KwaZulu-Natal (8.0%), where the Xhosa and Zulu nations are known for protecting their indigenous cultures.

This author previously found that black households often work in urban centers, particularly Gauteng, where they would live in rented apartments, often shared with others, and even in shacks. They spend weekends and holidays in their ancestral homelands, where their actual homes are to be with family and the clan (Steyn 2024).

ORIGINS OF THE TUSCAN STYLE

It has been suggested that the Tuscan trend in South Africa started with Montecasino, the gaming, shopping, and restaurant complex north of Johannesburg that was built in 2000 as a replica of a typical Tuscan village (Brulliard 2009). It was an example of commercially driven historic revivalism, a trend extensively described by Charles Jencks (1939–2019) in his The Language of Post-Modern Architecture (1977). Tuscan style houses appeared in large numbers, mostly commissioned by white homeowners, especially in high-income, gated estates (Figure 6). Numerous estates still allude to their aesthetic program with names such as "Tuscan Gardens" or advertisements claiming to be "A magnificent Tuscan-inspired estate." While wealthy white households currently favor boxy concrete-and-glass architecture, black homeowners across the income spectrum are enthusiastically embracing the Tuscan style.

Denise Scott Brown's Learning from Las Vegas (1972, with Robert Venturi and Steven Izenour) and her Architectural taste in a pluralistic society (1980) arguably contributed to what David Michalski (2015) calls the "Tuscanization" of taste in "the construction of Tuscanesque spaces, textures, and flavors in architecture, [and] home design". In South Africa "Tuscanization" is clearly not exclusively the prerogative of Michalski's "taste elite".

Figure 6. A Tuscan house in a gated estate in Pretoria in the late twentieth century (photo by the author).

Debbie Whelan (2020: 61), an anthropologist and architect, was the first academic to study the Tuscan style phenomenon. She observes: "It is only relatively recently, with the emergence and establishment of a strong Black middle class, that homes of complex ancestry – Italianate [and here read 'Tuscan'], Balinese and neo-colonial have begun to dominate the fabric of the suburbs and the rural areas, and areas under traditional authority."

Pamela Kimario (2016), in a YouTube video entitled "South African Cultural Houses," shows examples of Zulu, Xhosa, and Sotho-Tswana dwellings, as well as an Ndebele home. She then illustrated her concluding comments that "We don't all live in Rondavels" with an aerial view of an extraordinary lavish villa (Figure 7). "We've got beautiful homes in South Africa as well," she exclaims! Google Images provided evidence, though, that the illustration was of a mansion in the Hamptons, a summer destination for affluent New York City residents, which was on the market for US$69 million!

Figure 7. An example of a contemporary South African villa (screenshot from Kimario 2016).

Although the image was factually incorrect, it nevertheless revealed the aspirations of the author. However, she is not an isolated case. Velile Sithole (2021) produced a large number of YouTube videos with titles such as "Tuscany Estates and High Boundary Walls in Rural South Africa" and "Beautiful Tuscan Style Houses in Rural South Africa." She writes:

Villages in the rural areas in the North West Province look like Italian villas with Beautiful Tuscan inspired houses […] Everything is Tuscan. Tuscan buildings all over the village […] Everybody is building in the same style […] It is a Tuscan-inspired village.

One viewer commented: "Spot on, the houses in Rustenburg villages look the same. The roof must be tuscany [sic] with mixed tiles and you must also have pillars on the garage doors and verandas" (Figure 8). Building on tribal land, rather than the suburbs, is much cheaper, and there are no rates and taxes. While many architects have been appalled at the demand for Tuscan houses, draughtspersons readily filled the vacuum. Fees are minimal: standardized Tuscan construction drawings are available online for $275 to $550 (Figure 8).

Figure 8. An advertisement for Tuscan building plans on the internet (screenshot from one of hundreds of similar advertisements on Facebook).

Tuscan-style houses are found in affluent suburbs all over Africa, for instance, on Zanzibar Island, Nairobi, and Kampala (personal observation). Kenyan architect, Francis Gichuhi (2011), laments that "[t]he emerging black middle class is quick to follow the fashions of the

international arena to position themselves as citizens of the world." However, this is not a uniquely African trend. Even in Australia, Italianate villas have been popular since the nineteenth century. While vernacular forms used to be ethnic markers (Rapoport 2006: 192), Paul Oliver (2006: 265) suspects that, due to globalization, "the distinction between the world's cultures will cease to have relevance. The relationship between culture and aesthetics is nevertheless irrefutable. Even Lefebvre (1974/1991: 230) refers to "cultural models" as associated with their "attendant imagery." It can be argued that the black South African middle class is not simply following the style of white people. Instead, like European, Middle Eastern, and Asian people, they follow an architectural trend globally considered a symbol of prosperity and sophistication.

Apart from the car, the single dwelling – the private, freestanding home – is arguably the most tangible self-expression of a household's identity. The topic of architecture with an African identity features prominently in academic discourse, although homeowners' preferences are not on the agenda. This is the main cause of the schism between the public and the architectural profession in South Africa. After all, as Oliver Marc (1972: 122), author of Psychology of the House, emphasizes, suburban homes are built "as [the owners] see it, and not as others would make them see it."

HOUSING STYLE AND CULTURE

Apart from places of worship, housing is unquestionably the most culturally sensitive building type. As Rapoport (1982: 14-5) stresses: "A dwelling is not just a structure; it is an institution, a social and cultural unit of space created to support the way of life of people." For him, the concept of culture has two dimensions: the one based on world views and values is manifested as a person's lifestyle, while the other is based on social variables concerning family roles and kinship. Ethnicity, race, and class are considered "less useful," whereas lifestyle is "more useful" in determining what is culture-specific.

According to Rapoport's theory, there is no conflict between a lifestyle showcasing a Tuscan home that is intended to communicate success and achievement, and an Afrocentric worldview. Apart from clan and kinship affiliations that tie black people to their ancestral lands, tradition and customs, such as how rooms and spaces are used and understood, determine spatial organization, but rarely aesthetics. For example, in Tswana culture, dining is preceded by what Paul Mmolotsi Rantau (2006: 26) calls the "communal washing of hands." A washbasin inside the dining space would accommodate this ritual. Also, as part of the Tswana funeral ritual, the dead lie in state in their house before the coffin lid is closed and sealed (Rantau 2006: 83). Therefore, it should be possible to carry the coffin out of the house with dignity. This function influences the position and width of doors and the layout of corridors. These are detailed considerations and do not affect the aesthetics of the home. Rather, black households often assert their African identity by collecting and displaying African crafts such as beadwork, cloth and carpets, and work by black painters and sculptors.

In the authoritative The Harvard Architecture Review, Denise Scott Brown (1980: 41-51) relegates socio-economic background (upper-, middle-, and lower-class), as well as race and ethnicity to the level of sub-cultures, concluding that sub-cultural planning has limited use and that "taste cultures" should rather be considered, subtly implying that cultural preferences can change. She writes of "parallel and noncompeting taste cultures." Her "high culture" stresses the achievement of the individual and is subject to frequent swings in fashion, such as currently being manifested by the popularity of Tuscan motifs. "Folk culture," on the other hand, stresses "historical antecedents, … neighborliness and … the individual as part of the community," and changes only slowly. She adds, significantly, that a person can "participate in two or more taste cultures," a principle she calls "straddling." Essentially, she confirms Rapoport's thesis.

The unremitting suburbanization of rural villages is unquestionably irreversible. Newly acquired wealth enables families to establish a strong presence in their ancestral lands. It seems reasonable to suggest that Tuscan populism – the Tuscanization of the residential landscape – is simply a current fashion. However, classicism in its various manifestations, albeit more refined than contemporary Tuscan, has been producing buildings of great dignity for millennia. In the public perception, Tuscan houses achieve the same and could prove to be resilient.

There is no evidence of the formalism or "double-coding" (as coined by Jencks) associated with Postmodernism in the houses under study. Rather, an expression of aspirational tastes that respond to developer- and media-driven messages about what "luxurious" housing looks like. This seems to be less about joining a "high culture" of the taste elites, but the self-expression of the nation's new middle class.

CONCLUSION

Since 1994, the South African architectural fraternity, including schools of architecture, has anticipated a strong demand for Afrocentric buildings. The briefs for institutionalized design competitions, such as for the Pan African Parliament in 2007, required evidence of African identity. Some participating architects achieved that by skillfully and subtly applying critical regionalist principles. However, almost nowhere have owners of freestanding, private homes insisted on Afrocentric aesthetics. Italianate styling emerged as the preferred choice for many South Africans, regardless of color.

While dense, walkable mixed-use typologies dominate Western Europe, the single dwelling is the most prevalent dwelling form in South Africa. Since this represents a massive portion of the market, architectural schools should not ignore this trend under their social contract. Although the tastes and preferences of black consumers are continuously being researched in the retail market, their preferences in the housing market remain largely unexplored. The architectural community must address this pertinent shortcoming if it hopes to retain its professional credibility and relevance.

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Technologies for Sustainability | Renewable Energy

Advancing Mass Timber Buildings: Novel Methods Improve Thermal Assessment and Material Use

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ABSTRACT

For nearly a century, thermal demand calculations for buildings have relied on simplified models developed to match the technical constraints of their era. The first standards, introduced in Germany and Austria in 1929, established climate zones and material conductivity coefficients that, with only incremental updates, still underpin many current assessments. Yet, methods such as Hot box testing, originally designed for lightweight insulation, continue to be applied for mass timber buildings, overlooking thermodynamic characteristics confer real-world advantages. Recent research at Oak Ridge National Laboratory incorporates updated methodologies, aligned with ASHRAE Standard 55 (ASHRAE, 2023) accounting for factors such as thermal inertia, inner surface temperatures, emissivity, solar gains, and dynamic outdoor conditions. These factors better reflect observed heating and cooling loads and highlight opportunities for efficient use of materials in mass timber construction. This work provides a framework for designing comfortable, resilient, and resource-efficient buildings while aligning with performance expectations in energy codes.

INTRODUCTION

Efforts to demonstrate the benefits of mass wood construction date back decades, with momentum increasing after the Carter-era oil embargo prompted new building energy conservation requirements. The first national model building energy code in the United States was developed following the passage of the Energy Conservation and Production Act (ECPA). In

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In 1975, the National Conference of States on Building Codes and Standards (NCSBCS) introduced the Model Code for Energy Conservation in New Building Construction (MCEC). This code provided states with a standardized framework for regulating energy efficiency in new buildings.

In 1992, CABO Model Energy Code (MEC) was developed to address residential buildings. In 1998, the International Code Council (ICC) published the first edition of the International Energy Conservation Code (IECC), which incorporated and replaced MEC. The log home industry, in particular, faced growing challenges in complying with evolving insulation requirements under these model codes.

A turning point came with a study based on six small structures built in Maryland (Childs et al., 1983), which provided a methodology for integrating mass (concrete, wood, etc.) into energy code compliance calculations. These findings were integrated into later versions of the MEC and, subsequently, into the IECC. However, many building officials found the mass wall provisions difficult to interpret and apply to submitted plans, limiting its practical use in permitting. In response to such concerns, the U.S. Department of Energy issued the 2004 IECC Supplement to simplify. Unfortunately, this streamlining effort reduced mass wall classifications to a generalized category, diminishing recognition of the distinct thermal performance advantages of mass timber.

While the many subsequent IECC publications (updated on a three-year cycle) have not significantly revised requirements for mass walls, the problem of compliance with insulated frame requirements grew. The industry responded with trade-offs for greater insulation in roofs, better glazing, and greater mechanical efficiency. Code updates removed those trade-offs by raising roof insulation to R-49, Energy Star minimums became code requirements for glazing, and the mechanical trade-off was eliminated altogether. This put the focus on mass wood walls, with no consideration for the fact that log homeowners reported greater energy savings than contemporary wood framed homes of their neighbors. At roughly 1.5% of U.S. new home starts or 7% of custom homes starts, the log wall market was too small to move the codes.

In Europe, the story was similar but the support for mass wood was evolving. The industry developed cross-laminated timber (CLT) technology to build large panels of mass wood. Assembly of buildings became faster and more efficient. The first sizable innovation of wood products in decades exploded and gradually found its way to North America. Incredible investments in building new manufacturing facilities and operations began in Canada and then

the U.S. The U.S. Softwood Lumber Board formulated an agenda to maximize the impact of CLT, funding fire testing, seismic and wind load testing, and answering a multitude of questions about how CLT solves life safety building code requirements. Their effort does not look at thermal performance.

Currently, the U.S. residential mass wood industry is composed of buildings with log walls (including floor and roof timber frame structures with wood decking) and a growing list of CLT building systems. Forty years after the initial mass wall studies, the codes haven't found a way to match static thermal properties of wood to that of rated insulation products. But that's the rub! Mass walls are dynamic, responding to conditioned interiors vs. exterior climate conditions and humidities with the mass as a buffer.

With the introduction of ICC's Standard on the Design and Construction of Log Structures (ICC400-2022, International Code Council, 2022), the log building industry has a unified consensus document. This standard incorporates the same fundamentals as the IECC, resulting in only a slight impact on energy conservation measures. Despite promising advancements, it has become evident that current energy codes do not fully recognize the potential energy savings that mass timber can deliver. Many studies have documented how mass timber systems can offer superior thermal performance compared with traditional materials – particularly regarding peak demand and energy consumption. For instance, prior research highlighted that when mass timber blocks are utilized, cooling energy use could decrease by up to 50% during peak periods (Salonvaara et al., 2022). Hygroscopic materials such as wood were found to balance indoor humidity and help cool the room (Simonson et al., 2001). Such reductions could lead to substantial cost savings under time-of-use billing, while also significantly decreasing peak cooling loads, thereby potentially alleviating pressure on the electrical grid.

OVERALL GOALS OF THE STUDY

The primary objective of this study is to thoroughly assess and depict how the thermal performance of mass timber constructions can enhance building envelope efficiency. By generating empirical data on energy consumption patterns, this research aims to not only improve simulation capabilities for heating and cooling energy requirements but also emphasize the noteworthy advantages of utilizing mass timber over traditional framing techniques. Furthermore, we attempt to illuminate the mechanisms through which mass timber positively influences indoor climate control leading to both financial savings and significant reductions in peak energy demand, ultimately benefiting the electrical grid. This study is crucial as it seeks to bridge the gap between outdated thermal performance assessments and the dynamic realities of modern mass timber structures. As we quantify the thermal performance of mass timber systems under varied climatic conditions, our findings are expected to inform future building designs and optimize resource use.

FIELD TESTING

The project has constructed two test cubes (10’ x 10’ x 10’) in three different climate locations. One cube was built with lightweight framing (2 x 6) and one with a single layer of mass timber (6 7/8” CLT). All six sides of the cubes have the same structure and materials except the floor that has a floor OSB instead of drywall. The cubes were assembled side by side in Oak Ridge, TN, Golden, CO, and Nacogdoches, TX. Figure 1 shows how the cubes were placed in the north-south axis to avoid shadowing at any time of the year, and the picture shows the lightweight and mass timber cubes with mini-splits and doors on the north side of the cubes. The last two cubes were constructed and instrumented in Nacogdoches, TX, late June 2025. The cubes are intentionally simple with only opaque envelope components focused on walls. Each test cube has a one-ton mini-split for heating and cooling. The cubes have been instrumented to monitor indoor air temperature and operative temperature, air humidity, moisture contents of CLT, temperature and relative humidity in the wall cavities (lightweight cube only), interior and exterior surface temperatures, heat fluxes through the interior surfaces of walls, and electricity consumed by the mini-splits.

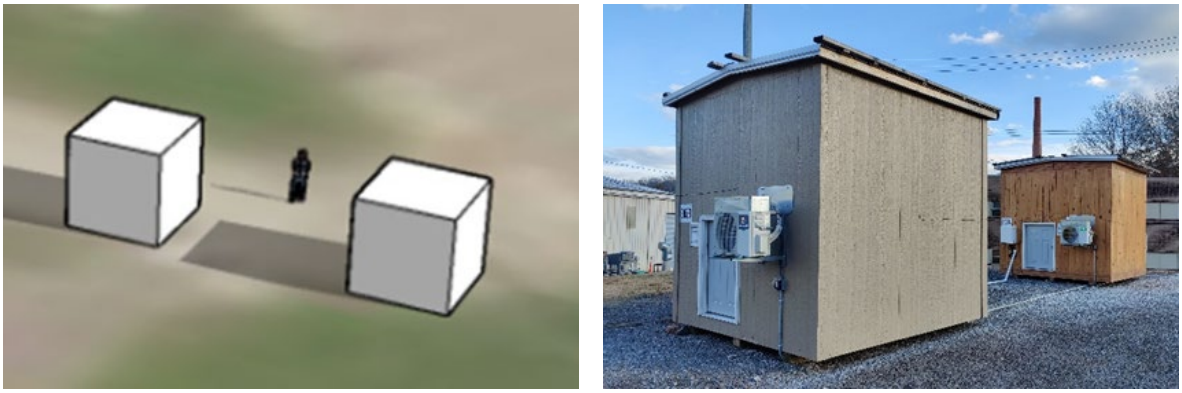

Figure 1. Field test cubes in Oak Ridge, TN. Image on the left shows shadowing analysis, and picture on the right the lightweight cube and the CLT cube.

The lightweight cubes feature the same siding (LP® SmartSide®) at all locations. In Oak Ridge, TN, the CLT cube was finished with a clear coat, whereas in Golden, CO, and Nacogdoches, TX, the CLT cubes were stained to achieve a solar absorption coefficient comparable to that of lightweight cubes. The solar reflectance of the siding is 0.29. For the CLT panels, the reflectance values are 0.45 in Oak Ridge (clear-coated), 0.19 in Golden (stained), and 0.27 in Nacogdoches (stained). The lightweight cubes are constructed with standard 2x6 framing at 16 inches on center, using oriented strand board (OSB) with a built-in water-resistive barrier (WRB) and taped seams. The wall cavities are insulated with fiberglass batts rated R-19 in Oak Ridge and Nacogdoches and R-21 in Golden. Interior finishes include 0.5-inch gypsum board in the lightweight cubes only. In contrast, the CLT structures consist solely of a 6 7/8-inch-thick CLT layer. The doors on all cubes measure 35 inches by 49 inches and have an R-value of 5

h·ft²·°F/Btu. The framing fraction of the lightweight cubes is approximately 23%, which aligns with typical values found in conventional construction.

The cubes were tested for air tightness and adjusted to ensure that both cubes at each location had comparable levels of air leakage. The test huts in Oak Ridge, TN, achieved an air leakage rate of 3 ACH50, while the huts in both Golden, CO, and Nacogdoches, TX, measured 6 ACH50. Although these values may seem high, when expressed as air leakage per envelope area, the rates range from 0.1 to 0.2 cfm/ft² at 75 Pa. These values are well below typical air leakage limits, such as the 0.25 cfm/ft² at 75 Pa required by the USACE (U.S. Army Corps of Engineers, 2012). It is important to note that air tightness expressed in air changes per hour (ACH) is influenced by the volume-to-surface-area ratio, which differs between small and large buildings. Therefore, ACH is not a reliable measure of envelope air tightness for comparison across building sizes. Instead, air leakage per unit of surface area provides a more appropriate metric.

Simulations

The collected data will serve to confirm the modeling capabilities of tools like EnergyPlus™ (U.S. Department of Energy, 2024) and WUFI®-Plus (Fraunhofer Institute for Building Physics, 2024) for analyzing energy, thermal, and moisture conditions. Once validated, these modeling tools will be utilized to extend the findings from the small cube studies to entire buildings situated in various climates. This expanded analysis will enable U.S. to assess the performance of building envelope standards for mass timber walls in comparison to lightweight wall systems.

TEST RESULTS

The monitored test results were analyzed to compare the average energy consumption and hourly energy use to demonstrate the thermal inertia effects. Additionally, indoor temperature was monitored during a simulated power outage to evaluate resilience of the test cubes against high temperatures.

Energy Use

The test cubes in Golden, CO, were controlled to 23°C (73.4°F) in March 2025. Figure 2 shows the hourly energy use of the mini-splits for three days.

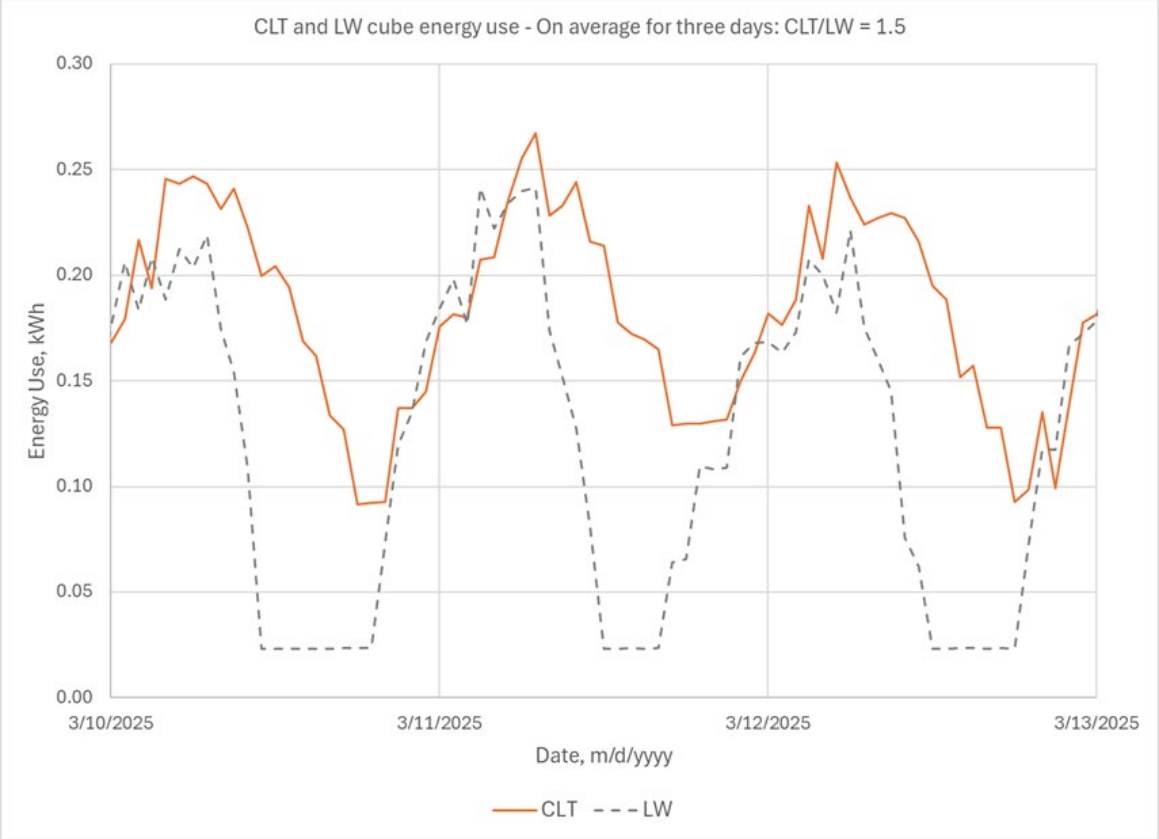

Figure 2. Hourly energy consumption of the mini-splits in the lightweight (LW) and the mass timber (CLT) cubes in Golden, CO, in the spring.

The peak demand in the lightweight and CLT cubes are almost the same and occur between 5:00 a.m. and 7:00 a.m. depending on the day. The mini-split in the CLT cubes heats all day whereas the lightweight cube does not need heating during the afternoons. Over the three days, the CLT cube consumes about 50% more energy than the lightweight cube, less than would be predicted based on the effective U-values. Figure 2 also indicates that the lightweight cube, even though better insulated, has almost the same peak demand as the CLT cube. The CLT cubes have consistently consumed about 50% more energy than the lightweight cubes in the three locations, which is less than expected based on envelope R-values. Based on in-situ heat flux measurements and surface temperature readings, the effective R-value of the CLT panels is approximately R-8.2 $h \cdot ft^2 \cdot °F/Btu$ for the 6 7/8" thick layer in the Golden, CO cube, corresponding to R-1.2 $h \cdot ft^2 \cdot °F/Btu$ per inch. This value aligns well with typical R-values for wood. Additionally, the average area-weighted effective U-value of the framed cube is 56% of that of the CLT cube in Golden, CO, and 60% in Oak Ridge, TN, and Nacogdoches, TX.

Figure 3 shows the energy use for cooling in the cubes in the summer. From 8:00 a.m. till 6:00 p.m. on July 9 the lightweight cube uses more cooling energy than the CLT cube. The CLT cube

demonstrates the thermal inertia of mass timber by balancing and shifting heat gains into the cube between day and night.

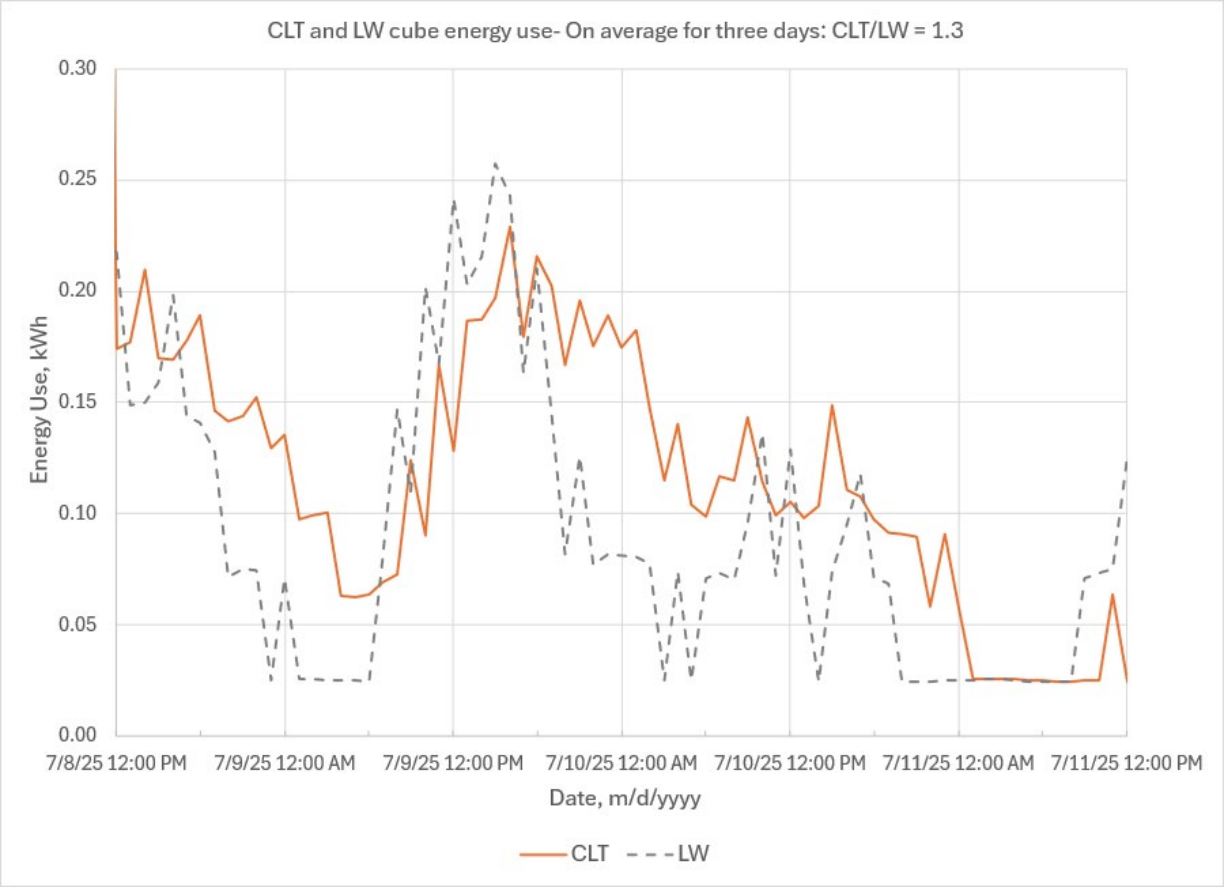

Figure 3. Measured hourly energy consumption of the mini-splits in the lightweight (LW) and the mass timber (CLT) cubes in Golden, CO, in the summer.

Predicted Performance with Simulations

Figure 4 presents preliminary results from a hygrothermal whole-building simulation comparing the test cubes in Golden, CO, using typical meteorological year (TMY) weather data as the boundary condition. The simulation indicates a greater delay in the onset of cooling demand for the CLT cube compared to the lightweight framed cube, a delay that is not reflected in the on-site measurements. In the simulation, the cooling peak for the lightweight cube occurs around 5 p.m., while the CLT cube peaks approximately four hours later, around midnight. At a component level, the 6 7/8" CLT panel provides 6-7 hours shift in the peak heat flux. The agreement between the simulated and measured results needs to be confirmed before proceeding with broader whole-building simulations. The simulation results depend heavily on the thermal capacity (density, specific heat) and the thermal conductivity. Wood is a hygroscopic material,

and these properties are influenced by its moisture content (Flechas et al., 2025). Thermal mass increases notably with moisture content. Thermal conductivity increases modestly but can be significant for detailed hygrothermal modeling. For building energy modeling, adjusting these properties based on expected moisture content can improve accuracy, especially for unconditioned or high-humidity environments.

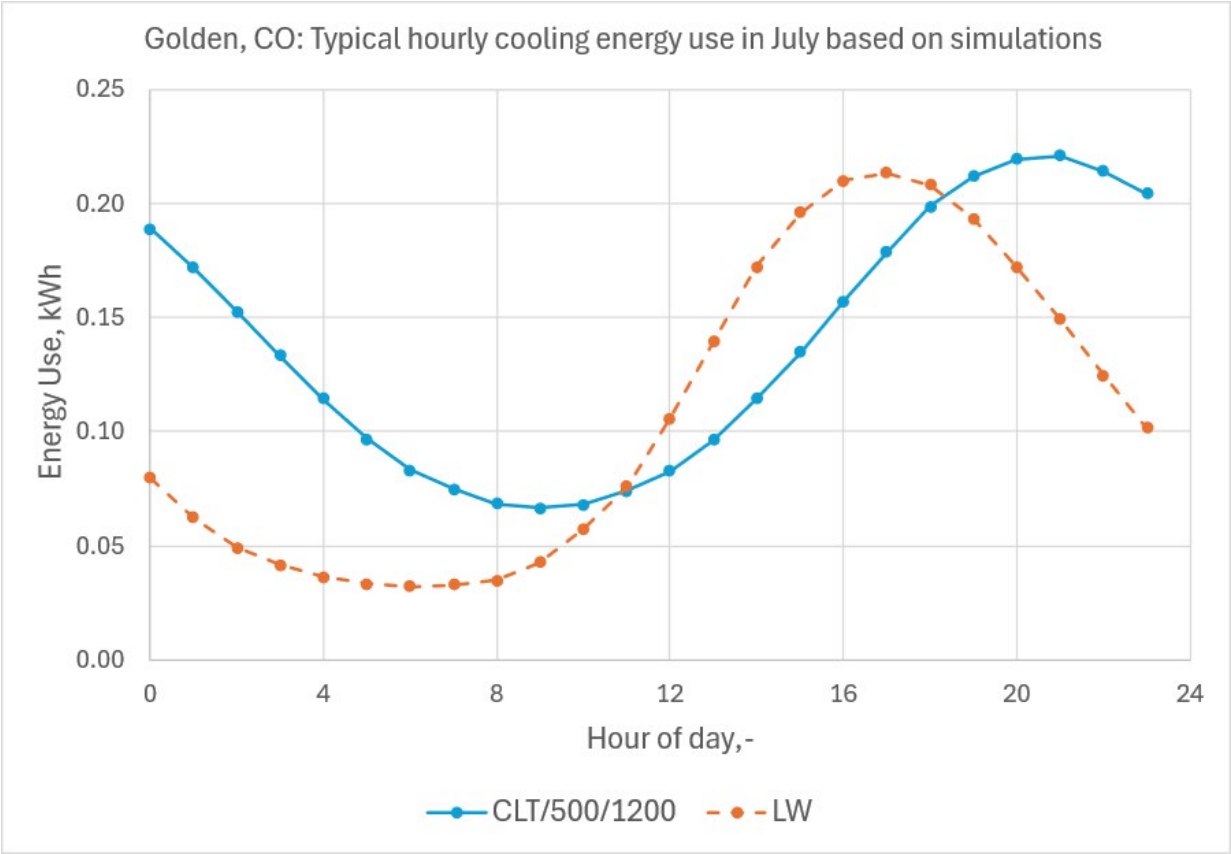

Figure 4. Typical (monthly average) simulated hourly energy consumption in the lightweight (LW) and the mass timber (CLT) cubes in Golden, CO, in July.

Resilience During Power Outage

A power outage situation was simulated in Golden, CO, during hot days in July of 2025 by turning off cooling with circulating fan still running. Figure 5 shows the course of operative temperature inside the cubes during those days without cooling. On July 8th the cooling was turned on again. The lightweight cube reaches up to 94.5ºF operative temperature whereas the CLT cube goes up to 87.9ºF during the hottest day. Thus, the mass timber cube maintains more livable conditions during power outages. The indoor air temperature is not shown but it followed very closely the operative temperature.

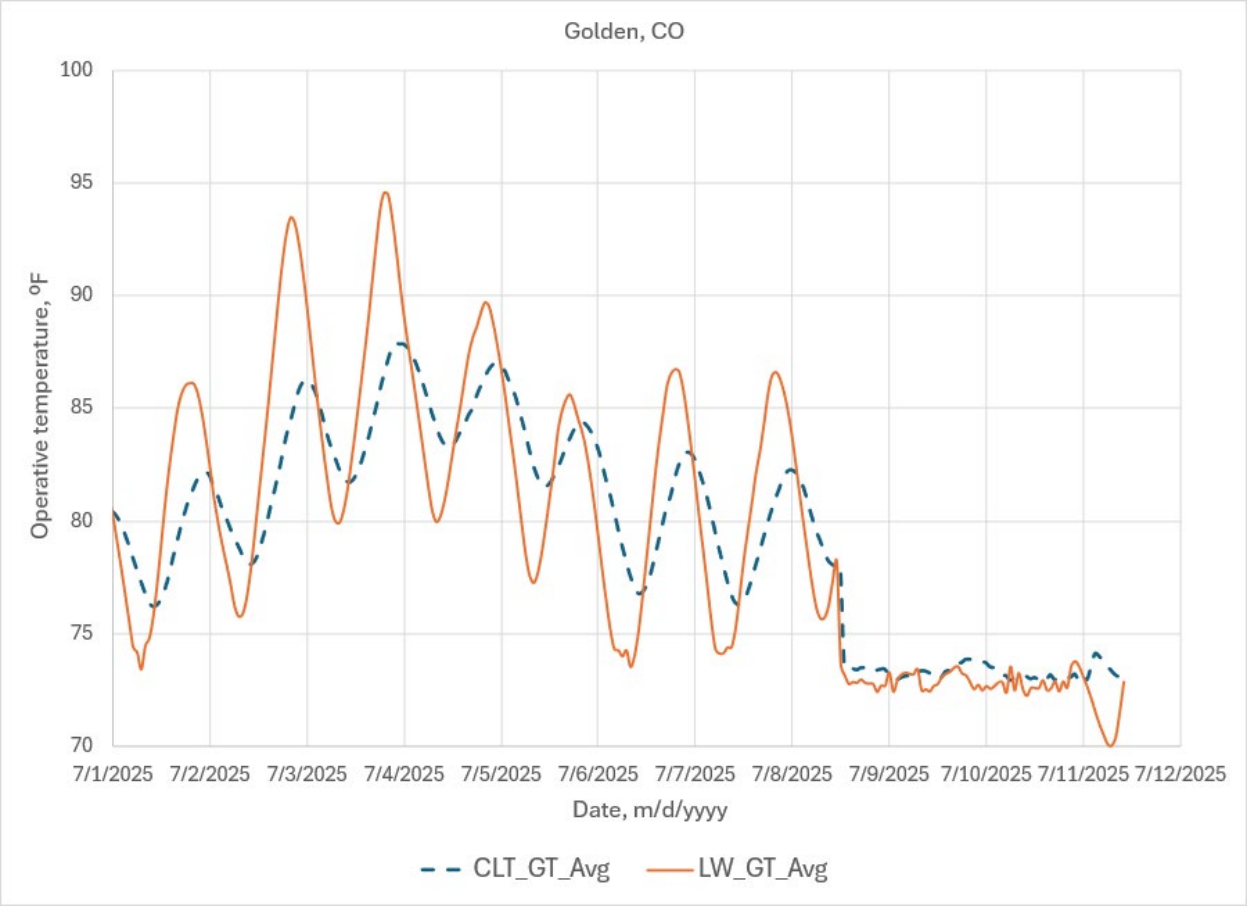

Figure 5. Measured operative temperature in the CLT and Lightweight cubes during a simulated power outage lasting eight days.

DISCUSSION

Prior to CLTs entering the market, log home producers increasingly turned to energy audits for compliance with building codes since this option was incorporated into the IECC. In the early stages, finding accredited third-party services for reliable energy audits meant searching through organizations like RESNET (resnet.us, RESNET, 2019) or BPI (bpi.org). While today there are multiple options available, skepticism regarding the energy performance of log homes persists. For instance, a member of the International Mass Timber Alliance (IMTA) lost a sale because the local authority having jurisdiction refused to consider the design of a log home, outright declaring, “Not in my county.” Such misinterpretations of building codes, coupled with this deep-rooted mindset, pose significant challenges to log home builders.

Additionally, there is a common misconception that log homes are prone to leakage. This perspective may have been more accurate in the past, before building practices mandated tighter

construction. Just as builders of lightweight wood frame homes have adapted to enhance envelope performance, log home builders have learned to implement similar strategies. In fact, both types of homes tend to experience air leaks in the same areas – primarily at the top of the foundation, the junction between walls and roofs, and around wall openings.

This paper aims to focus the research on demonstrating that mass timber homes can achieve energy performance comparable to that of traditional frame houses when both are equally sealed and insulated. One potential avenue for addressing concerns might involve introducing a new term in energy codes to represent this dynamic performance, yet designating something like Rmass or Rlog may lead to confusion rather than clarity.

To effectively communicate these concepts within the context of new code development, we need to adopt a relatively simple approach. The following steps could serve as a foundation for our approach:

Performance Comparison
Demonstrate that mass timber walls can match the performance of insulated lightweight wood frame walls. Since a mass wood wall functions as a continuous assembly, its performance may effectively be compared to that of continuous foam insulation products which are currently in high demand. Furthermore, it is crucial that the maximum allowable air infiltration rate remains consistent for both wall types.

Design Considerations
Assess the ratio of thermal buffering materials, taking surface area into account, in relation to the enclosed conditioned space. This analysis can be streamlined by concentrating on the square footage of the floor area, which facilitates easier calculations. While smaller homes typically require less energy for conditioning, they may consume more resources per square foot of building area. This brings forth the question: how should design factors be incorporated into energy codes?

Glazing Limitations
Glazing has been a significant topic in code development for many years. However, the current approach frequently overlooks the fact that many purchasers of mass wall homes prioritize views, often choosing to replace entire walls with large windows and patio doors. Alarmingly, while building codes may allow for glass-walled residences, they often exclude mass walls from similar considerations. This inconsistency prompts the need for a new metric that compares the "center of mass wood wall" to the "center of glass."

The project progresses by collecting performance data and comparing it with simulation results. These simulations will inform the development of design guidelines that consider the thermal inertia effects inherent in mass timber.

PRELIMINARY CONCLUSIONS

This study highlights significant advancements in the thermal assessment and material use of mass timber buildings. Our research demonstrates the dynamic behavior of mass timber and lightweight construction and a more accurate alignment with actual heating and cooling needs. Field tests have validated that these structures can effectively reduce energy consumption and peak demand compared to conventional lightweight systems, making a strong case for their adoption in construction. Additionally, by addressing common misconceptions regarding the thermal performance of mass timber, we seek to promote broader acceptance and integration into building codes. The findings support the development of building standards that recognize the distinctive advantages of mass timber, ultimately leading to more comfortable living environments. As industry progresses, ongoing research and collaboration will be crucial in enhancing mass timber's role in the future of construction, ensuring it meets the challenges of diverse climatic conditions while providing optimal comfort and cost-effectiveness for occupants.

ACKNOWLEDGMENTS

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Enhancing Life Cycle Assessments: The Role of Itemized Materials in Tally

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ABSTRACT

The construction industry accounts for a substantial share of energy and natural resource consumption both in the U.S. and globally. Consequently, it offers a prime opportunity to mitigate environmental impacts with new approaches. Building design has evolved significantly to identify the optimal combination of materials and equipment that not only meets schedule and cost requirements but also minimizes the environmental footprint of construction projects. With various tools available, this study focuses on Building Information Model (BIM) and Tally integration in conducting successful Life Cycle Assessments (LCA) in the construction industry. Tally, a BIM-integrated tool, facilitates detailed environmental impact assessments by analyzing building materials' embodied energy, carbon footprint, and other sustainability metrics. This study explores the significance of itemizing materials in Tally through residence hall case studies to demonstrate the benefits of granular data input in achieving accurate environmental assessments. Results will show the key patterns and discrepancies in LCA outcomes based on the level of material details provided in Tally for residential building design. This process will contribute to the advancement of sustainable decision-making and BIM methodologies by highlighting the critical role of itemized materials in an LCA framework.

Keywords: Life Cycle Assessments (LCA), Building Information Model (BIM), Tally, Itemized Materials.

INTRODUCTION AND BACKGROUND

The energy and natural resource consumption of the construction industry has been well known for decades. The global construction industry accounts for 30-40% of energy consumption (Liu, Zhou, Tian, He, and Jin, 2019). A recent and detailed analysis showed that the residential and commercial sectors consume around 27.6% of total U.S. energy in 2023, and specifically, the residential construction sector has grown significantly in the past decades and has consumed more than 11% of energy in the U.S. (Bawaneh, Das, and Rasheduzzaman, 2024). Consequently, this energy consumption results in a variety of environmental impacts that need to be mitigated

effectively. One of the main examples of environmental impacts is greenhouse gas (GHG) emissions, where the building sector contributes to 40% of emissions globally (Liu, Zhou, Tian, He, and Jin, 2019). As another example, the sector produces about 40% of solid waste (Li, Wang, Kassem, Wu, and Wei, 2022). Addressing these impacts is crucial to mitigating the negative implications of the construction industry on the environment. Life Cycle Assessments (LCA) work as an efficient tool to assess the environmental impact of buildings and the construction industry (Pomponi and Moncaster, 2018).

LCA is defined as a standardized methodology to evaluate and calculate the potential environmental impacts of a product, process, or system across its entire life cycle (ISO, 2006). It covers every phase of a building's lifespan, from the production of construction materials and the building process to its use, demolition, and eventual deconstruction (Chau, Leung, and Ng, 2015). According to ISO 14040 and 14044 standards, LCA consists of four key phases: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation (Finnveden, et al., 2009). As an accepted methodology to assess the environmental performance of buildings, construction practitioners need reliable LCA software applications and tools to perform this complicated process. LCA tools provide quantitative information about the environmental impacts occurring during the building's life phases, which enables users to analyze the implications of building design and materials selected for a project.

One of the commonly used and effective LCA tools in the construction industry is Tally (Tally, 2023). Tally can be described as a BIM-integrated LCA tool, as it needs a BIM model from Autodesk Revit to be able to perform its analysis. The integration of BIM and LCA has been utilized in the literature recently. It has been observed that BIM–LCA integration can improve efficiency, accuracy, and accessibility of environmental assessments during the design phase, as BIM allows linking design data and information with environmental databases (Soust-Verdaguer, Llatas, and García-Martínez, 2017). A recent study compared the LCA outcomes of traditional LCA methods vs BIM-integrated LCA tools (Bueno and Fabricio, 2018). They specifically used Tally as the LCA software and utilized a real-case residential building project to evaluate the accuracy and limitations of BIM-based LCA tools. Their results showed that the BIM-LCA integration outcomes align with traditional LCA environmental impacts, especially in identifying major environmental hotspots. Yet, the time spent on data collection and analysis was significantly reduced with the BIM-LCA combination. They highlighted the ease of automating material quantity take-offs in the BIM software to help LCA calculations with Tally.

Tally works within Revit to analyze the environmental impacts of an entire building by using its model properties. These properties include design elements as well as the materials created in Revit. Therefore, precision in data inputs to the Revit model will allow Tally to generate more accurate assessments of embodied energy, carbon footprint, and other environmental metrics. This can be achieved by using a comprehensive Revit model and itemizing materials in Tally. This study aims to explore how the LCA results will benefit from the impact of itemizing materials in Tally in several environmental impact categories, such as global warming,

acidification, eutrophication, and smog formation potentials. A case study approach will be utilized by selecting residence hall projects to demonstrate the use of itemized materials in Tally.

METHODOLOGY

The framework of this study is composed of three main phases: (1) Case Study Data Collection, (2) BIM Model Creation, and (3) LCA Analysis (Figure 1). Prior to initiating data collection, it was important to note the required properties of case studies for BIM-LCA integration. In this sense, the design and building structures, as well as Tally's capabilities, were considered. As the itemized materials entries are targeted in Tally, it was also important to have more specific data inputs regarding Tally's life cycle stages.

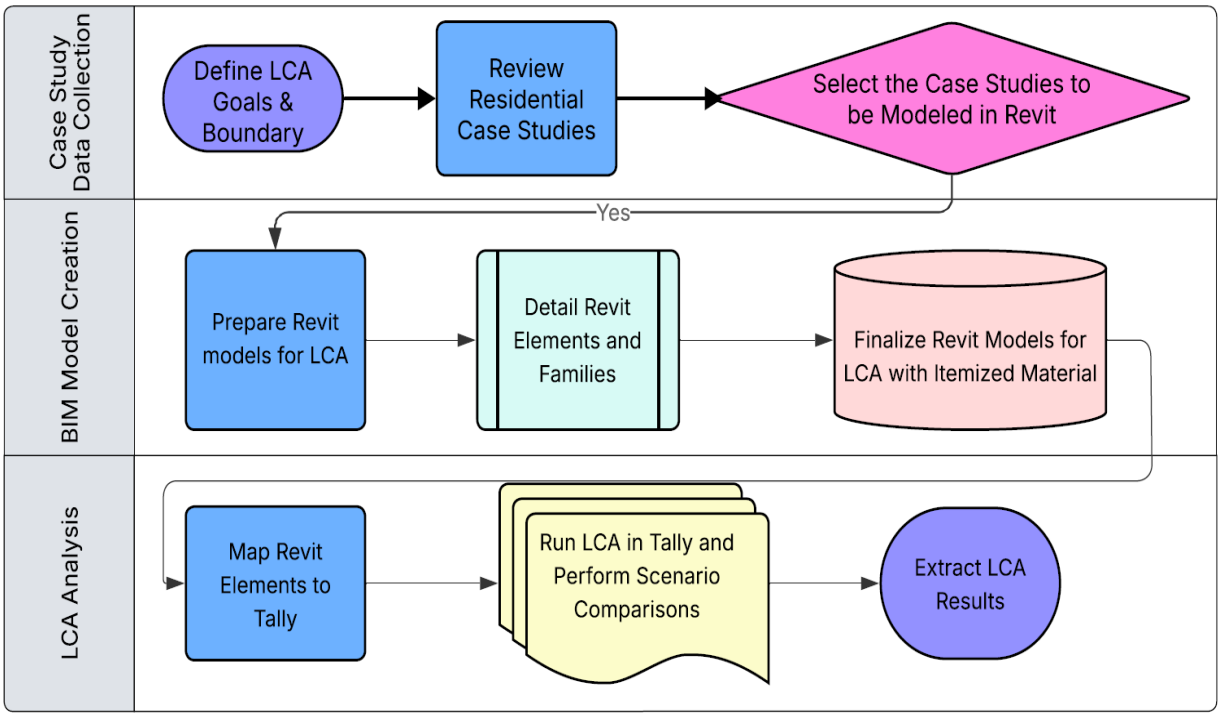

Figure 1. BIM-LCA Integration Framework.

The life cycle of Tally includes five main stages:

(1) The Product Stage [A1-A3] corresponds to the full manufacturing stage, including raw material extraction and processing, intermediate transportation, and final manufacturing and assembly.

(2) Transportation/Construction Stage [A4] includes transportation from the manufacturer to the building site and the anticipated or measured energy and water consumed on-site during the construction installation process.

(3) Maintenance and Replacement [B2-B5] encompasses the replacement of materials in accordance with their expected service life.

(4) End of Life [C2-C4] includes the relevant material collection rates for recycling, processing requirements for recycled materials, incineration rates, and landfilling rates.

(5) Module D [D] accounts for reuse potentials that fall beyond the system boundary, such as energy recovery and recycling of materials (Tally, 2023). The material inventory created in Revit assemblies will target mainly the product, transportation/construction stages, as these stages will be able to give the designer the best options with the short-term outputs in mind. Maintenance and end-of-life results will still be evaluated, yet the major contributions will be limited to the first two stages in Tally.

Case Study Data Collection

Three residential hall case studies were selected to conduct the BIM-LCA integration in this study. The selection of case studies was based on many parameters, such as: the same project types—all projects were residence halls in university campuses, similar means and methods – similar structural properties yet some alterations were intended in the materials used, certain gross square feet (SF) area requirements–all projects were selected to be smaller than 30,000 SF, and various locations–projects were selected in different locations to allow the variety in design and material selection. Below is a summary of the projects selected:

• Project 1 is a fraternity building in Lincoln, NE, with an area of around 9,000 SF. The building has 3 stories and a basement. It has a wood-framed structure with steel columns for support. The basement is essentially made up of reinforced concrete. The exterior uses a combination of brick veneer and composite wood. Interior finishes include gypsum board, paint, Vinyl Composition Tile (VCT), carpet tile, and polished concrete, with plastic laminate casework/countertops. Stairs are both concrete and wood-framed, depending on location.

• Project 2 is a dormitory building in Clemson, SC, with an area of around 13,000 SF. It is a 3-story building with the entrance level covering half of the building's footprint. Concrete, and specifically precast concrete, is utilized in this building with steel framing. Additional precast items cover steel lintels. Unique design properties include architecturally exposed structural steel in large meeting areas. Elastomeric coating is used in the roof areas. Exterior finishes include Locally Sourced Clemson Brick and stucco, while interior finishes have gypsum wallboard, carpet tiles, as well as regionally sourced wood, stone, and low-VOC paints and adhesives.

• Project 3 is a dormitory building in Wilmington, DE, with an area of around 23,000 SF. It is a 5-story building. The means and methods include the use of precast concrete for the girder-slab construction with steel framing. Its exterior is designed with high-pressure laminate (HPL) cladding for a better thermal performance. Exterior finishes include a face brick wall, while interior finishes include paint, regular and luxury tiles, carpet tiles, and ceramic tiles.

BIM Model Creation

The plans and specs of each case study were collected and reviewed in preparation for the development of the Revit digital model. Revit models were developed for each project by working on the architectural, structural, mechanical, electrical, and plumbing (MEP) components. The architectural 3D model was created to capture every detail of the building's geometry, including its critical building elements and components. BIM model creation included two rounds of revisions for each building. The first round included the creation of elements, and the second round was to improve the elements' information as the material database. This enabled users to detail materials as needed to be itemized in Tally. A sample Revit model from Project 3 is given on Figure 2 to show how the materials affecting Tally and LCA results are created in Revit.

Figure 2. Project 3 Revit model.

LCA Analysis with Tally

In this step, the building model created in Revit, including its walls, floors, ceilings, and other systems, was used to assign materials in Tally. Each element was itemized into its constituent materials. For example, a wall element or assembly consists of several layers and materials. A wall could be broken down into gypsum board, insulation, metal or wood studs, and paint or other finish material. Tally provided a catalog of material definitions based on the GaBi LCA database, which were mapped to each component. In this manner, Tally utilized environmental data from the GaBi database to calculate the environmental impact of building materials within each Revit model. Once each element was itemized, Tally quantified the embodied energy, carbon footprint, and other sustainability metrics for each case study.

An itemized material example from Project 2 will be detailed as one of the unique approaches of this research. Project 2 has a façade including a curtain wall system covering a considerable part of its exterior and brick finishes completing the curtain wall system. This exterior wall system was itemized in four groups:

- **Aluminum Curtain Wall System**

The aluminum curtain wall system was created as a rectangular mullion family in Revit and described as an average aluminum curtain wall system by YKK AP America, including enerGfacade (YCW, YHC, and YUW) and ProTek products. Entry included curtain wall mullion product, finish, and necessary fasteners, weather stripping, sealant, etc. Glazing is excluded and added separately as another itemized group. Environmental Product Declarations (EPD) were used as a representative of conditions in the U.S. market. The transportation distance was assumed as 663km according to the nearest available vendor's location. As the LCA included end-of-life scope in Tally, aluminum scrap was assumed to have a 95% recycling rate, and the other 5% and other materials were assumed to be landfilled in their end of life (EoL).

- **Aluminum Extrusion**

The aluminum extrusion represented by Exterior - Brick wall 1' 11" Terracotta finish family in Revit and described as an extruded aluminum part with industry-wide EPD from the Aluminum Extruders Council. The transportation distance and end-of-life scope were assumed to be the same as the aluminum curtain wall system. Additionally, the product was assumed to have a 36.4% scrap input, while the remainder was processed and credited as avoided burden for Module D.

- **Aluminum Storefront System**

The aluminum storefront system was created as Curtain Wall Panel Door and Curtain Wall storefront families in Revit. This itemized entry was made as an aluminum mullion system to Tally. The transportation distance and end-of-life scope were assumed to be the same as the aluminum curtain wall system. For Module D, credit was given for the avoided burden associated with recovered material, including the burden for processing.

- **Aluminum, Formed**
  The formed aluminum was created as façade louvers in Revit and described as a formed aluminum member based on data by the industry-wide EPD for cold-rolled aluminum from the Aluminum Association. The transportation distance and end-of-life scope were assumed to be the same as the items before. For Module D, the product was assumed to have a 65% scrap input, while the remainder was processed and credited as avoided burden.

It should be noted that the material selection in Revit and Tally differs slightly in that materials in Revit are primarily visual and specification-driven. They are defined by layers of assemblies, thickness, appearance, and texture of materials. The data required for LCA, such as environmental properties of materials and EPDs, must be specified for each element used in a project. On the other hand, Tally has materials created with an LCA mindset so that each material is tied to the GaBi database to gather embodied energy, carbon, and other impact factors. The remaining required data, such as thickness, density, and other quantities, need to be obtained through a platform like Revit.

The material categories in Tally are gathered from the Revit model data. Tally calculates the percentage of components in material assemblies using predefined EPDs and industry-average datasets from sources such as GaBi. For example, each material in Tally has a specific composition breakdown. When 4000 psi concrete is selected, Tally automatically assigns the concrete assembly with its materials, including cement, aggregate, water, and reinforcement. The information from Revit is combined with Tally's background data to achieve percentage calculations.

RESULTS AND DISCUSSIONS

The results from Tally included detailed quantitative data as well as graphics showing the percentage contribution of each itemized material to environmental impacts, such as GWP, acidification, eutrophication, smog formation potential, and non-renewable energy consumption. Tally provided results as itemized by Tally vs as itemized by the material categories entered by the user. Due to the page limits of this conference, Project 1 is used as a showcase to compare results by Tally vs by itemizing material entries. Figure 3 shows results by Tally's default entries for Project 1, and the results per itemized material categories for Project 1 are shown in Figure 4. Each color in these figures corresponds to a specific material category. Yellow represents concrete, green represents steel, orange represents wood, pink represents thermal and moisture protection, and purple represents finishes.

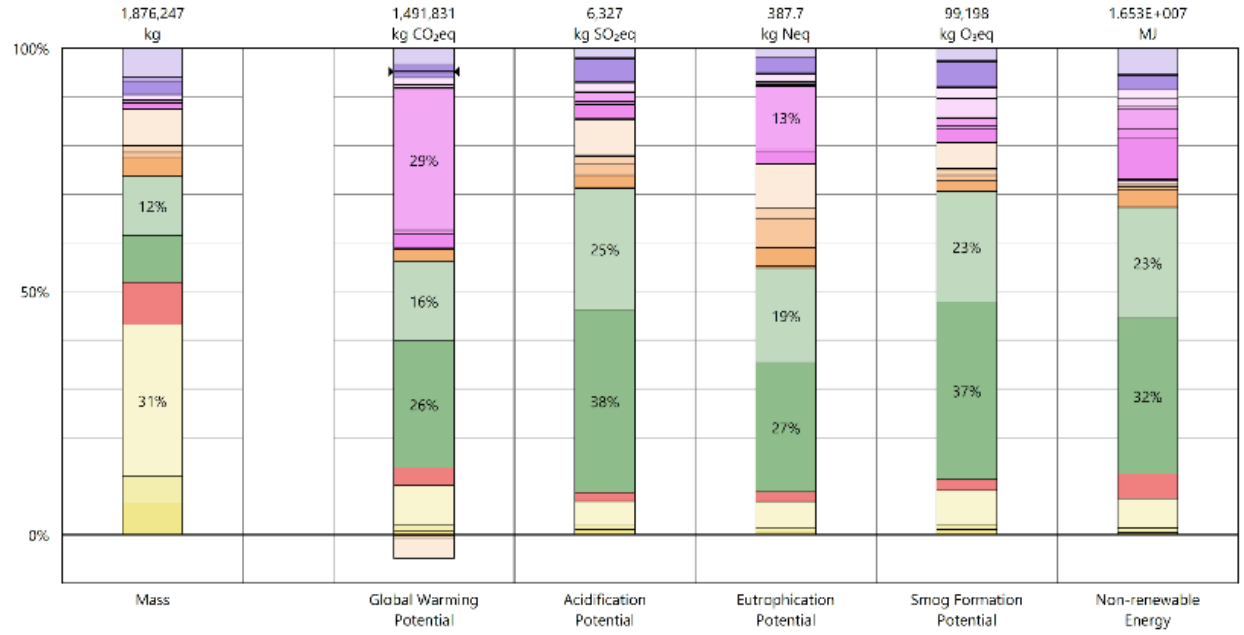

Figure 3. Project 1 Itemized Tally LCA Results.

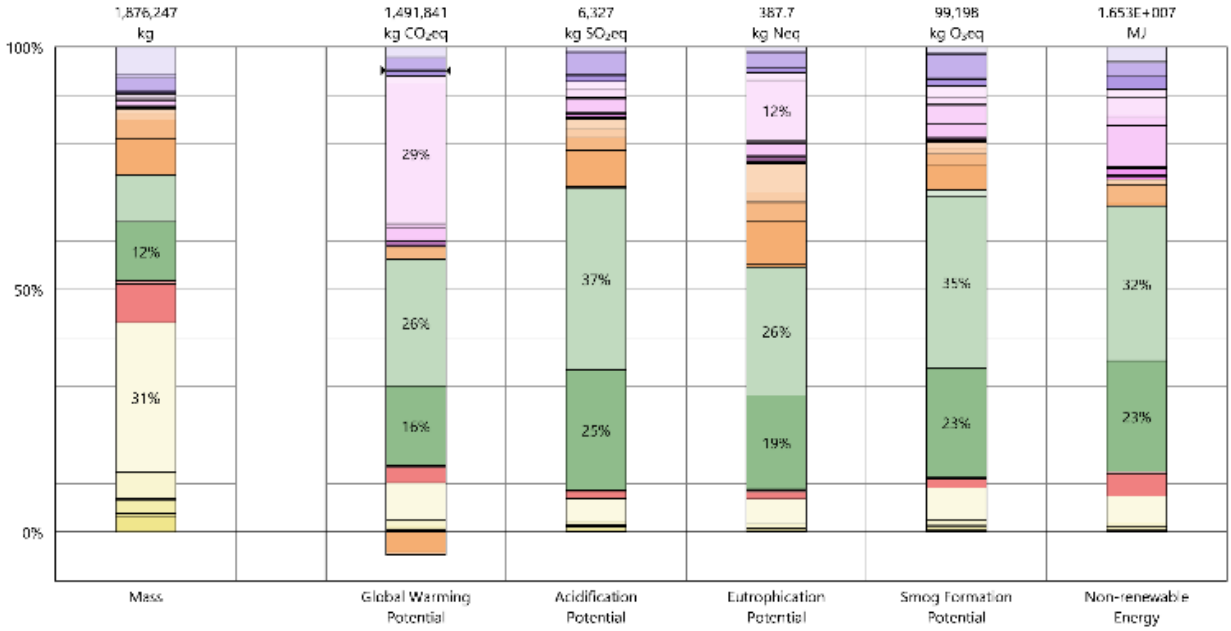

Figure 4. Project 1 Itemized Material LCA Results.

As can be observed from both figures, the results are color-coded by divisions. Yellow represents concrete, red represents masonry, green represents metals, orange is for wood/plastics/composites, pink is for thermal and moisture protection, and purple is for finishes. Different shades of these colors are used to define the level of entries as well as the level of detail for material categories. As an example, there were only 3 concrete (yellow) entries for Project 1 by Tally, while the itemized entries had 6 types of itemized materials. As a project located in Lincoln, NE, with a cold climate, the means and methods include larger amounts and various types of thermal and moisture protection (purple). The entries for thermal and moisture protection, itemized by Tally vs material details, are shown in Figure 5.

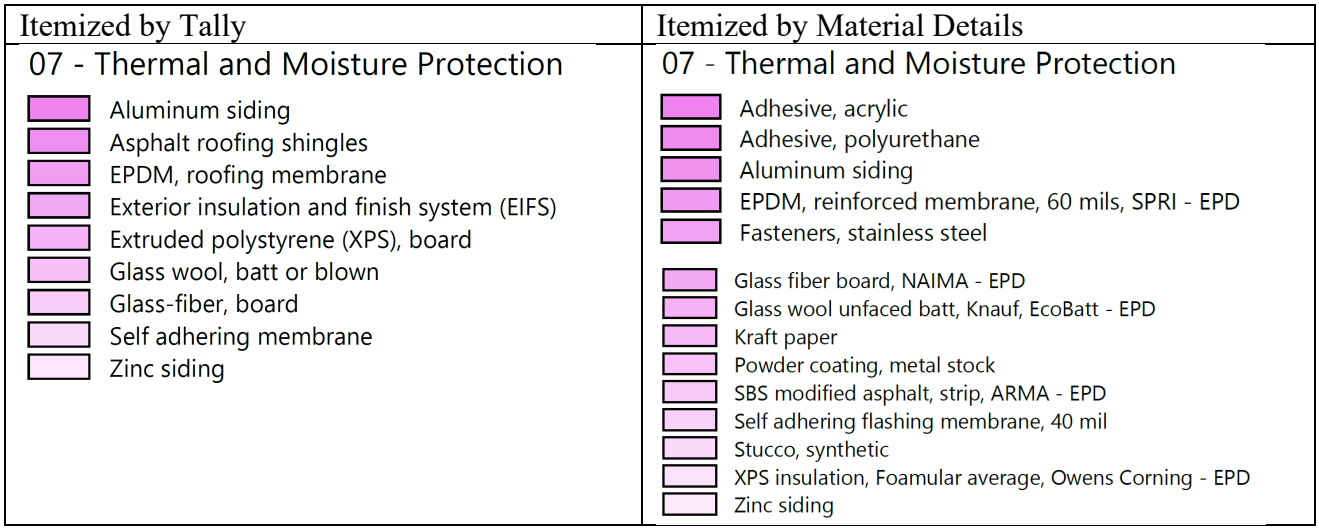

Figure 5. Entries Itemized by Tally vs Material Details.

By itemizing materials, more specific product data was input to Tally. This precision in data allowed Tally to enhance its calculations and perform a more granular analysis of each material's impact. Although the totals were the same in environmental impacts, this approach allowed for the identification of materials that contribute most to the overall environmental footprint. In this way, practitioners and designers can work on targeted improvements and more informed decision-making for sustainable construction. As an example, the material details provided for Project 1 state EPDs within the itemized material inputs. Detailed material data can be utilized for meeting compliance requirements for certifications like Leadership in Energy and Environmental Design (LEED), which require comprehensive LCA documentation to earn points under the Materials and Resources category.

Another way to benefit from the itemized material approach would be to prioritize environmental impacts. For a certain project with a goal of a net-zero energy building, the non-renewable energy category will have more importance than others. In this case, the designers can focus on the largest category, which is metals (green) for Project 1. Per Tally entries, steel decking had a

32% impact on non-renewable energy. When the itemized materials approach was used, it was seen that galvanized steel decking with insulation on metal deck-EPDM was used in the project. The default roof decking was galvanized to G90 standards and coated on both sides of a 20-gauge steel deck, roll-formed and precut. When the specific steel decking material was separated from the assembly group, the designers could focus on steel with higher recycled content and from a supplier with EPDs. The design can also be improved for deconstruction and recycling by aiming at sorting and achieving a certain percentage of recycling targets. When this approach is practiced in all material categories, itemizing materials in Tally will lead to more reliable results by supporting better sustainability practices in both design and construction.

CONCLUSIONS

This study explored how the granular data input via itemized materials in Tally provides an important new perspective on the LCA process. The detailed framework provided in this paper offers a comprehensive approach to how the BIM-LCA combination can be improved to better analyze the environmental impacts at each stage of a building's life cycle by linking design data from material information in Revit. The first stage of the framework focused on collecting data related to the three residential case studies. The second stage covered building and enhancing the Revit models with itemized materials to improve the LCA input in Tally. The third stage included performing the analysis with Tally and obtaining LCA results. LCA results with itemized Tally input vs itemized material input by the user were compared. It was observed that itemized material details provide more specific data to Tally, which enhances the LCA calculations.

The outcomes of this study provide valuable insights to construction practitioners and designers to understand the primary factors contributing to environmental impacts. With Tally's capabilities to provide percentage contributions of each material input, users will be able to prioritize the environmental impact of their choice and focus on the primary material contributor for further evaluation. This approach not only benefits the material selection process but also contributes to compliance with green rating systems, such as LEED. Suggestions for a more streamlined material selection process include creating a shared Revit material library that aligns with Tally. When the shared library utilizes quantities from Revit and environmental data from Tally early in the project, this process enables the early integration of systems, allowing users to leverage Revit schedules for automatic mapping with Tally. When material data is updated, it can be synced with Tally to prevent multiple manual entries during material selection.

Considering such benefits, the BIM-LCA combination with itemized materials offers a more sustainable decision-making practice within the built environment. One of the limitations of this approach should be highlighted as the capability of the Revit model. The BIM-LCA combination with itemized materials will only work its best with a detailed Revit model. It should also be noted that the proposed framework has only been tested on residential buildings so far. Future studies are planned on commercial and larger-scale buildings to observe patterns of the impact of granular input in Tally.

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Exploratory Study on the Applicability of Digital Twins for Housebuilding Standards

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ABSTRACT

Nigeria faces a significant housing deficit and quality concerns in housing construction. Building Information Modeling (BIM) and Digital Twins are proposed in this research to offer solutions in terms of efficiency, waste reduction, collaboration enhancement, cost control, quality assurance, sustainability, and long-term maintenance of housing projects in the country. This is on the premise that DTs are innovative technologies that can replicate physical assets and processes. This paper presents the conceptual aspect and theoretical framework of the ongoing research that aims to develop a model that combines BIM and DT functionalities to implement housebuilding standards. The overarching objective is to enhance construction quality, affordability, and regulatory compliance. The methodology includes literature reviews to gather expert insights on the technologies used in the model, as well as content analysis of case study material to provide the basis for developing the model. The model is expected to be a tool for optimising construction processes, monitoring, and management to address affordability, quality, and performance issues. The model will enable data integration, stakeholder engagement, standardisation, and be receptive to continuous improvement. Stakeholders can leverage its capabilities for the effective implementation of housebuilding standards. The adoption promises improved quality, affordability, and regulatory compliance in housing projects, potentially boosting consumer confidence, project quality, cost-effectiveness, and job opportunities. Ultimately, the research outcome will catalyse positive change in the housing development sector.

Keywords: Digital Twins, Housebuilding Standards, Nigeria, Quality, Regulatory Compliance.

INTRODUCTION

The Nigerian housing market faces challenges, including inadequate finance, limited affordable housing options, subpar quality standards, and a lack of standardised operating procedures. The House Building Standards (HBS) project, funded by the World Bank's International Development Association (IDA), aims to address these challenges in the areas of Affordability, Management, Quality, and Inspection. This research investigates the usability of Digital Twins (DTs) for implementing these standards by focusing on affordability, management, quality, and performance. DTs offer real-time monitoring, analysis, and management capabilities, and when combined with Building Information Modeling (BIM), they can enhance quality assurance and

regulatory compliance in housing construction. This study highlights the potential of DTs, BIM, and HBS to improve construction practices and address housing challenges in Nigeria, serving as a valuable reference for stakeholders in the housing sector, including developers, regulatory bodies, and professionals.

THEORETICAL FRAMEWORK

This theoretical framework provides the foundation for assessing technologies for implementing housebuilding standards in Nigeria, with a focus on the potential of Digital Twins supported with Building Information Modelling (BIM) (Bi, 2022) and powered by the Internet of Things (IoT). Digital twins are virtual replicas of physical objects created through real-world data and AI-driven software analysis. Successful digital twin implementations in construction projects like the Shanghai Tower, Hong Kong-Zhuhai-Macao Bridge, and Beijing Daxing International Airport are references because they offer encouraging advantages such as efficient data management, anomaly detection, access control, and long-term ROI (Bi, 2022). More insights are provided by Sacks et al. (2020), who propose integrating digital twin technology with data-centric construction and lean principles, introducing a Digital Twin Construction (DTC) information system to optimise design, planning, and production processes in construction. Under the GEM project funded by the World Bank, the Housebuilding Standards Manual (HBS) plays a pivotal role in setting minimum quality standards for housing projects overseen by the Nigeria Mortgage Refinance Company (NMRC). These standards align with the National Building Code of 2007, emphasising structural adequacy, safety, health, sustainability, and amenity in housing projects to address Nigeria's housing deficit and enhance client satisfaction with developer-built houses (Bi, 2022).

LITERATURE REVIEW

This literature review delves into the growing significance of digital twins in housebuilding standards and their potential to improve efficiency, quality, and compliance in residential construction. It covers consumer demand, regulatory challenges, compliance models, artisan competence, standards certification, and loan guarantee schemes, all emphasising the importance of ensuring housing quality for occupants' safety and well-being. The review uncovers the body of knowledge on digital twins. Bi (2022) presents three case studies showcasing successful digital twin implementations in construction projects like the Shanghai Tower, Hong Kong-Zhuhai-Macao Bridge, and Beijing Daxing International Airport. However, digital twin adoption in construction seems to be influenced by the specific goals of individual studies rather than being universally applicable. Opoku et al. (2022) acknowledge that digital twin adoption in the construction industry is often driven by researchers' expectations rather than practical evidence. Nevertheless, some studies emphasise the advantages of using digital twins to meet various standards such as energy efficiency, accessibility, or seismic safety. The ongoing research discussed in this paper aims to demonstrate the practical utility of digital twins in ensuring compliance with specific standards, potentially surpassing regulatory requirements. Sacks et al. (2020) discuss the integration of digital twin technology with data-centric construction and lean principles to create closed-loop control systems in construction. This integration is believed to

enhance production planning and control when combined with lean construction principles and data from digital twins.

Digital Twins in Construction and the Role of Building Information Modelling

The concept of Digital Twin has revolutionised construction by creating virtual replicas of physical assets and enabling real-time monitoring with IoT, CPS, AI, and sensors (Ammar et al., 2022). These replicas enhance smart construction through AI and data analytics for monitoring assets throughout their lifecycle (Blackridge publication, 2022). A three-layered integration model aids project management (Čustović et al., 2023), offering benefits in asset management, predictive maintenance, and cost-efficient construction. Building Information Modeling (BIM) is a digital representation of building characteristics, streamlining collaboration, reducing errors, and improving decision-making (Eastman et al., 2011; Thiong'o, 2019). BIM's benefits include integration of project data and cost savings (Eastman et al., 2011; Thiong'o, 2019). However, challenges in BIM adoption exist (Hussain et al., 2015), and research suggests various strategies to address these challenges (Olugboyega and Windapo, 2019; Tan et al., 2022). BIM and Digital Twins are complementary in construction, with BIM serving as the foundation for virtual building representations. Digital Twins evolve with physical construction, aiding decision-making and reducing waste (Sacks, et al., 2020). Integrating BIM and Digital Twins enhances data accuracy and transparency throughout the project lifecycle (Visartsakul and Damrianant, 2023). Overall, Digital Twins offer predictive capabilities and real-time monitoring, addressing BIM limitations and improving construction progress tracking, facility management, and environmental monitoring (Coupry et al., 2021). The synergy between BIM and Digital Twins has the potential to transform the construction industry.

Premises for Effective Use of Digital Twins to Implement Housebuilding Standards

The implementation of housebuilding standards through digital twins involves collaboration between researchers and industry professionals, considering integration, benefits, and challenges (Sacks et al., 2020). Digital twins offer advantages like real-time data collection and decision support in construction, promoting collaboration, transparency, energy efficiency, and cost-effective resource management (Ammar et al., 2022; Haghighat Khajavi et al., 2019; Hu et al., 2022). Challenges include the need for skilled personnel, funding, data issues, scalability, and privacy (Feng et al., 2021; Omrany, 2023; Coupry et al., 2021), which digital twins address through AI and computer vision (Greeshma and Edayadiyil, 2021). Implementing digital twins requires overcoming technical, legal, and cultural barriers (Arup, 2019) and emphasises data integration, stakeholder engagement, standardisation, real-time monitoring, and predictive maintenance. However, challenges like capital investment, data security, and specialised skills persist.

METHODS AND DISCUSSIONS OF DESIRED OUTCOMES

Methods

Researchers propose a three-tiered model for integrating Digital Twins (DTs) in housebuilding and optimising project objectives (Tuhaise et al., 2023). Key technologies include Building Information Modeling (BIM), the Internet of Things (IoT), and data processing (Tuhaise, V.V. et

al., 2023; Ali, 2022). IoT devices like laser scanners, drones, sensors, and cameras collect real-world data for DTs (Ali, 2022). BIM enhances interoperability and practical use of integrated DTs (Garagnani, 2013). Combining DTs and BIM improves monitoring and planning (ERP, 2023), fostering collaboration, efficiency, and reducing errors (Oluseye, 2016). This model enhances housing delivery comparability and facilitates stakeholder input (Tuhaise, et al., 2023).

Development of Digital Twin for Housebuilding Standards Compliance

Creating Digital Twins for housebuilding standards involves interdisciplinary collaboration among architects, engineers, data scientists, and software developers. Success depends on understanding construction processes and technology. It requires building a virtual representation of a structure to ensure compliance with requirements (Table 1).

Table 1. Proposed Steps for Creating and Maintaining a Digital Twin for Housebuilding Standards Compliance.

Steps	Description
Identify Applicable Housebuilding Standards	Determine the specific standards that are relevant to the project. This could include standards related to structural integrity, fire safety, accessibility, energy efficiency, and more.
Gather Building Data	Collect detailed data about the building's design, layout, materials, systems, and components. This information will serve as the foundation for creating the Digital Twin.
Choose a Digital Twin Platform	Select a suitable digital platform that supports the creation of 3D models, simulation capabilities, and data integration. Building Information Modeling (BIM) software is a common choice for developing Digital Twins for compliance.
Build the Virtual Model	Create a 3D digital representation of the building using the chosen platform. Include all relevant architectural, structural, and systems details. This model should accurately reflect the physical attributes of the building.
Integrate Building Specifications base on Building Code Rules	Incorporate the designers' specifications and specific rules and regulations from the building codes into the Digital Twin. This may involve encoding logic that checks for compliance with different aspects of the codes.
Simulation and Analysis	Develop simulation modules that allow the testing of Digital Twin against different scenarios. Simulate how the building responds to fire, structural loads, energy consumption, and other relevant factors.
Real-Time Monitoring	Integrate IoT sensors into the Digital Twin to monitor the building's real-time conditions. These sensors can provide data on temperature, occupancy, lighting, and other parameters that impact compliance.
Compliance Checks	Set up automated checks that compare the data from the real building (captured by sensors) with the virtual model. Identify any deviations from building code requirements and generate alerts or reports.
Visualization and Reporting	Develop a user interface that enables stakeholders to visualize the building's compliance status. Generate reports that highlight areas of non-compliance and suggest corrective actions.
Testing and Validation	Thoroughly test the Digital Twin by running simulations and monitoring real-time data. Validate its accuracy in identifying compliance issues and its ability to provide actionable insights.
Collaboration and Decision Support	Create features that allow different stakeholders, such as architects, engineers, contractors, and code officials, to collaborate within the Digital Twin platform. This facilitates communication and informed decision-making.

Steps	Description
Data Security and Privacy	Implement strong security measures to protect sensitive data, especially if real-time monitoring involves capturing occupants' information. Ensure compliance with privacy regulations.
Continuous Updates and Maintenance	Regularly update the Digital Twin to reflect any changes made to the physical building. This is crucial to maintain the accuracy of compliance assessments.
Training and Support	Provide training to users who will interact with the Digital Twin platform. Offer ongoing support to address any technical issues or questions.
Continuous Improvement	Seek feedback from users and stakeholders to identify areas for improvement. Incorporate new features, technologies, and code updates to enhance the Digital Twin's effectiveness.

PROPOSED CONCEPTUAL MODEL AND DESIRED OUTCOMES

Building the Digital Twin with BIM Software, IoTs, and Python Scripts

BIM and Digital Twins powered by IoTs are to ensure housebuilding standards compliance through 3D-5D models and data analysis, streamlined in a Common Data Environment (CDE). Integration of BIM and IoT improves safety, resource management, and productivity via real-time monitoring. Research focuses on Python-driven Digital Twins for standards enforcement, data integration, and predictive maintenance. Digital building twins, virtual replicas, enable real-time optimization but require ongoing hardware, software, and expertise investment (Altexsoft, 2021). Yoon (2023) proposed a construction-focused framework for twinning, leveraging cloud, IoT, AR/VR, 3D, and simulations (LTIMindtree). Maurya (2023) emphasized data collection, integration, modeling, and simulation. The Digital Government Authority (2021) outlined processes for building digital twins.

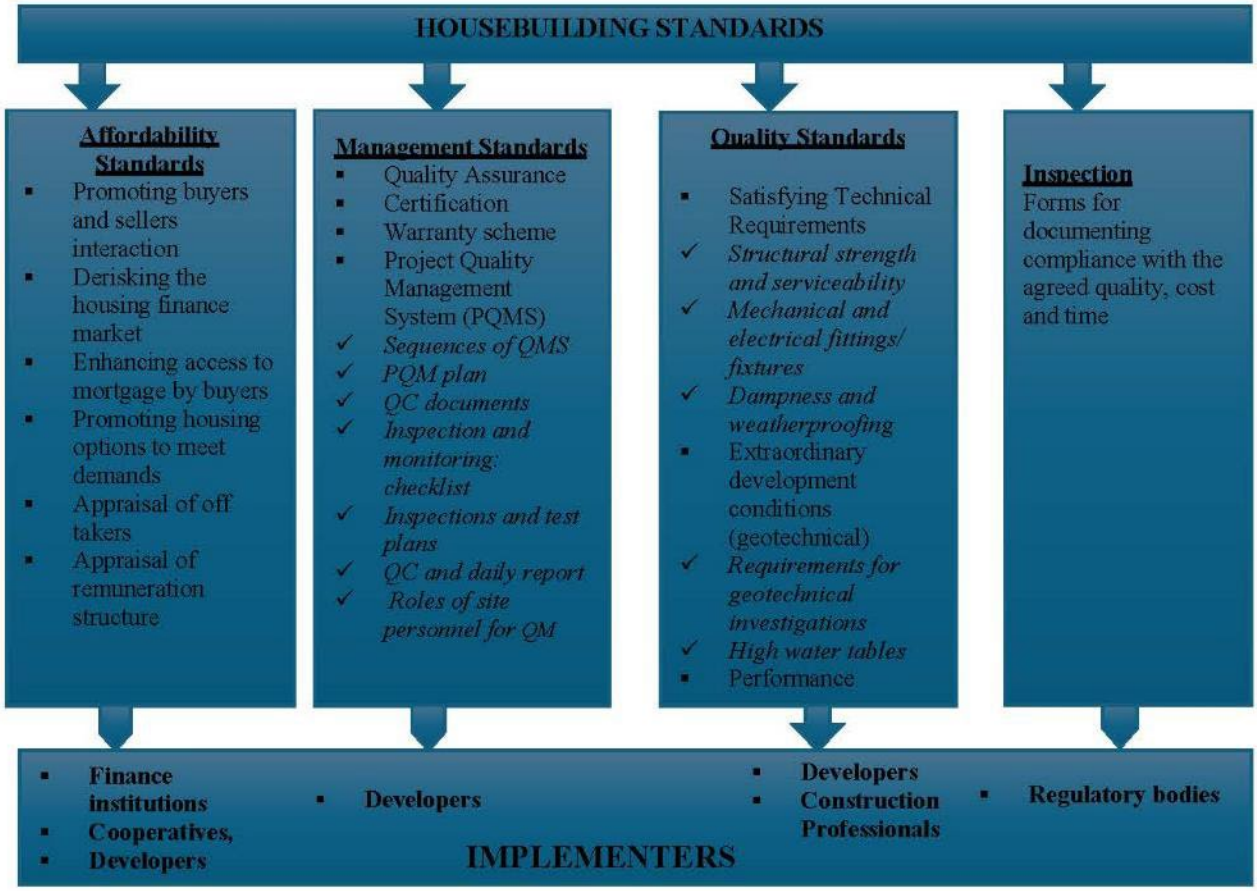
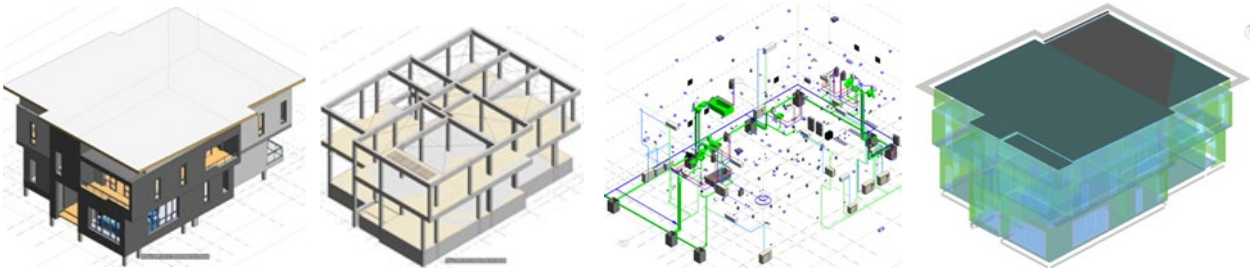


Figure 1. Housebuilding standards matrix
Source: Kuroshi, P.A. (2018) Curated from HBS (2017).

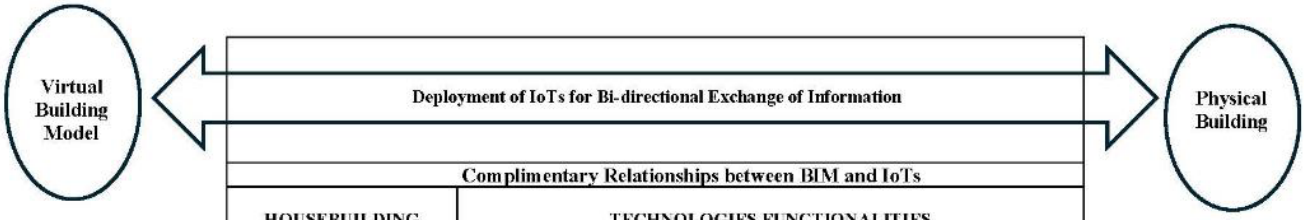
The standards highlighted in Figure 1 are intended to guide private agreements in the construction and financing of housing projects, with the overarching goals of ensuring affordability, quality, sustainability, and alignment with government objectives for the housing sector's growth and development.



Architectural Model Structural Model MEP Model Energy Model

Figure 2. Our proposed model portraying the desired synergy of BIM and IoT in the Digital Twinning of housebuilding.

Table 2. Digital Twinning and Python Scripting.



Complimentary Relationships between BIM and IoTs	
HOUSEBUILDING STANDARDS OBJECTIVES	**TECHNOLOGIES FUNCTIONALITIES**
Real-time Monitoring and Control	• IoT sensors monitor construction site parameters • BIM provides a digital twin of the site • Integration of IoT data into BIM for real-time monitoring and control
Resource Management	• IoT sensors monitor material and equipment usage • BIM provides a view of the building design and construction schedule • Integration of IoT and BIM data for efficient resource allocation
Quality Assurance	• IoT sensors monitor construction quality and processes • BIM serves as a reference for quality standards • Integration of IoT and BIM data for continuous quality checks
Progress Tracking	• IoT sensors provide real-time data on construction progress • BIM serves as a baseline for tracking milestones • Integration of IoT data into BIM for progress tracking
Energy Efficiency and Sustainability	• IoT sensors monitor energy consumption and systems • BIM simulates and optimizes energy-efficient designs • Integration of IoT and BIM data for informed decisions
Predictive Maintenance	• IoT sensors monitor machinery condition • BIM predicts maintenance requirements • Integration of IoT and BIM data for predictive maintenance

Figure 2 encapsulates the synergic deployment of BIM and IoTs for the digital twining required to implement the housebuilding standards. The integration of Building Information Modeling (BIM) and the Internet of Things (IoT) enhances construction processes, ensuring better safety, efficiency, and quality outcomes. This integration offers benefits such as improved monitoring, control, safety, resource management, quality assurance, progress tracking, energy efficiency, sustainability, and predictive maintenance, resulting in on-time and on-budget construction projects. BIM provides a Common Data Environment, while IoT tools optimise housing

standards implementation, improving quality control, project tracking, collaboration, and remote monitoring, ultimately boosting efficiency and profitability in housing projects. The DT development involves stages like sensor integration, real-time integration, data processing, analytics, and visualisation, leading to actionable insights. Core components include Sensors, Data, Integration, Analytics, and Actuators. BIM simulates real-world conditions, IoT accesses scenarios, and Python codes power operations and visualisation. The operational procedure includes X-ray scanning, time-lapse videos, digital markups, and 24/7 remote site views to compare BIM models with on-site progress.

CONCLUSIONS

This study underscores the pressing challenges facing Nigeria's construction industry, particularly in terms of housing quality and regulatory standards. It points to DTs as a promising solution to enhance quality assurance, improve collaboration, and streamline construction processes. The need to implement housebuilding standards to serve as a robust quality assurance framework is emphasised. The study envisions a future where DTs become more widespread and integrated with BIM, offering holistic digital replicas of structures. While challenges are obvious, technological solutions are expected to expedite the adoption of DTs in housebuilding for improved project outcomes, greater efficiency, and enhanced satisfaction for both stakeholders and consumers in Nigeria's housing sector.

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Method to Estimate EUI and PV Production Area to Meet Net-Zero Benchmark at the Beginning of a Building Project

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ABSTRACT

Many building projects today have a net-zero benchmark that is set in the project planning stage. Minimum energy targets, specified as energy use intensity (EUI), are increasingly required by local jurisdictions. Net-zero buildings need to have EUI targets lower than code minimum and recommended baselines for typical building types as well as being normalized to the climate zone. Setting EUI targets to estimate the physical area needed for power production prior to beginning design work and energy building modeling provides a means for determining how easy or difficult it will be to allocate enough area for energy production. The estimated area required for the photovoltaic (PV) array can be used as a metric in the evolving design of the building. Presented is a method to estimate power needed based on an EUI target vs. possible PV power production based on climate. The data is produced using a Passive House U.S. certified multifamily project as an example in a spreadsheet. The outcomes support that the method is a viable estimating tool for informing the development of a design.

INTRODUCTION

Acronyms Used:

> **EUI** - Energy Use Intensity. Calculated by dividing the total energy consumption of a building by its total floor area. Expressed as energy (kBtu) per square foot or square meter per year.
> Different building types use more energy than others and median/target EUI are established
> depending on use.
>
> **PV** (Photovoltaic) - electrical energy production from the sun's rays. Photovoltaic cells are wired in modules that have a particular watt rating. Modules are mounted and connected to create
> arrays.

It is common, and may be required to show code compliance, for building projects to have energy models to meet performance goals. Current codes in United States do not require net zero energy performance although there are states and jurisdictions that do. Energy modeling has a linear mathematical relationship between the building size and the envelope's

performance which produces the EUI. Minimum energy targets, specified as energy use intensity (EUI), are increasingly required by local jurisdictions (Energy Star). Objectives and phases of the building modeling are used to achieve performance optimization (Nguyen et al.). Energy modeling becomes quite complex because different building types have varying energy needs and usage times and there are climate zone impacts for the amount of heating and cooling needed to maintain building comfort. Net-zero energy buildings need to have EUI targets lower than code minimum and recommended baselines for typical building types (Carbonnier) as well as being normalized to the climate zone (New Buildings Institute).

Students often set a net-zero energy goal yet fail to achieve it because they do not know how much area will likely be needed for energy production. Having an area estimate as a guideline for the project design at the beginning of their studies of building proportion and form makes it possible to account for it as a design variable.

Design professionals working in a particular climate and building typology learn through repetition what the likely targets are that they will have to meet and integrate this into their project's designs. One example of this is from Onion Flats Architecture's Front Flats, a multi-family housing project located in Philadelphia, PA. Because the building fills the site and the proportion of the roof PV area of production to the floor area EUI could not be met, the architect knew he had to integrate modules on the facades of the building. This led to an innovative solution where the PV modules act as shading and visual blocks into units from grade level ("Front").

The hypothesis is that it is possible to determine a target EUI, look up solar production values for a specific building location, and use the area of a PV module to estimate the area needed for net-zero production. This can be done without any building modeling or design so that the information can be used as one of the items for evaluating the development of the building's form and volume.

MATERIALS, METHODS, AND RESULTS

The following resources and information were used to generate data used for the study.
The 2024 International Energy Conservation Code (IECC), in Appendix CC Zero Energy Commercial Building Provisions, Table CC103.1 Prescriptive Renewable Energy Requirement for Building Types and Climates provides a kWh/ft2/yr requirement based on building types and Climates (IECC). The data for the multifamily building is based on the Phius CORE 2021 certified building 127 Amory Street in Jamaica Plain, Massachusetts7 that has 96 units, is 6 stories high and has 101,283ft2 of interior conditioned floor area. For this study, the interior conditioned floor area was used as the GSF. The climate zone is 5A. This affordable housing building has a modeled site EUI of 17.84kBTU/ft2.yr.

EUI estimate determination and site/source base numbers are generated based on Energy Star PortfolioManager Target Finder8 and 2030's Zero Tool.9 Both tools require a zip code (location) and building use type, gross square footage (GSF) and other basic building information. For

Energy Star 80% reduction was used (default). For Zero Tool 70% reduction was used (default). For the estimates, it was assumed that 64 units were in the first 4 stories of the building (determined by dividing 96 units by 6 stories).

PV production estimates are from PVWatts10 which requires a zip code (location) and information about the PV array. For estimating purposes, 1kW DC was used for the array size and numbers were generated for 10o tilt facing both the east and west. These were averaged. For this research, Table 1 shows the climate zone (2024 IBC, combination number and letter) locations that were chosen, providing a variety of United States latitudes.

Table 1: Climate Zones and Locations Used for Study.

Climate Zone	City	State	Zip Code	North Latitude
1A	Honolulu	HI	96817	21.305
2A	Orlando	FL	32835	28.537
3B	Las Vegas	NV	89135	36.166
4A	Harrison	AR	17601	36.229
5A	Chicago	IL	60632	41.883
6B	Billings	MT	59107	45.783
7	Duluth	MN	55807	46.783

To convert kWh to kBTU, use the formula: kBTU = kWh x 3.412416331294. The steps for the process:

1. Determine range of EUI targets by looking up suggested EUI performance numbers from the IECC code, Energy Star Target Finder and Zero Tool. This will provide the annual total energy demand. See results in Table 2.

    a. Determine Table CC103.1 requirements, convert to kBTU for EUI, and multiply by building GSF for total energy use.

    b. Determine Energy Star Site EUI and multiply by building GSF for total energy use (target 80% reduction energy use).

    c. Determine Zero Tool Site EUI and multiply by building GSF for total energy use (target 70% reduction energy use).

2. Use PVWatts to generate an estimate of average production for 10o tilt 1kW array facing E/W at the project's location. Convert average kWh of production to kBTU

production for 1kW DC system. See results in Table 3. Note that PVWatts settings included selecting that modules are racked on the roof. The quality was left at Standard, even though the commercial module will be Premium, in order to have lower production averages. This was done to help mitigate "rosy glasses" of thinking the array will take up less physical space. Keeping the Standard setting lowers the production a bit, which helps to compensate for the fact that the estimate uses the area of the module, when in reality, the size of a module cannot be changed and will have to physically fit on the roof.

3. Divide the Total Energy Demand (step 1) by the average PV generation (step 2). See results in Table 3.

4. Select a PV module for STC rating and size. This study used a Deep Blue3.0 550W MBB Bifacial Mono PERC Half-cell double glass module. The STC rating is 550W or 0.55kW and the module is 7.474' x 3.72' for 27.8sf. This is a typical rating and size for commercial modules. See Tables 4, 5, and 6.

5. Divide the EUI production (step 3) by the PV module rating (be sure to use kW rating to keep units the same). This will provide the number of modules needed to produce the energy required. The number of modules should be rounded up. This spreadsheet rounded to nearest whole number, but could, for a more conservative number, be rounded up to the 10s or even 100s. Note that the area used in the formula is the area based as if the module were installed horizontally, even though the modules are modeled as being installed at 10o tilt. This "overestimate" of the area is intended, as stated in step 2, to help mitigate the discrepancy between using module area and the likelihood that the physical modules will take up more room (or conversely, the modules won't completely fill the designated area due to the proportions). See Tables 4, 5, and 6.

6. The last step is to multiply the number of modules (step 5) by the area of the module. Tables 4, 5, and 6 show the results based on each of the three EUI estimates.

Table 2: Possible EUI Targets per Code, Energy Star and Zero Tool.

Climate Zone	City	Gross Square Footage	Table CC103.1 kWh/ft2/yr	CC103.1 kBTU EUI	CC103.1 Total Energy Demand	E.Star Median Site EUI	E.Star Target Site EUI	E.Star Total Energy Demand	Zero Tool Baseline Site EUI	Zero Tool Target EUI	Zero Tool Total Energy Demand
1A	Honolulu	101,283	11	37.5	3,801,817	60.6	48.5	4,912,226	43	13	1,316,679
2A	Orlando	101,283	11	37.5	3,801,817	45.6	36.7	3,717,086	42	13	1,316,679
3B	Las Vegas	101,283	10	34.1	3,456,198	61.6	49.3	4,993,252	47	15	1,519,245
4A	Harrison	101,283	12	40.9	4,147,437	48.8	39	3,950,037	43	13	1,316,679
5A	Chicago	101,283	12	40.9	4,147,437	70.4	56.3	5,702,233	51	16	1,620,528
6B	Billings	101,283	13	44.4	4,493,057	62	49.6	5,023,637	47	14	1,417,962
7	Duluth	101,283	14	47.8	4,838,677	79.5	63.6	6,441,599	54	17	1,721,811

Table 3: PV Production and Production Needs per EUI.

Climate Zone	City	PVWatts 1kW DC E Tilt	PVWatts 1kW DC W Tilt	PVWatts 1 kW DC EW Ave	PV Ave Prductn kBTU	Net-Zero Prductn CC103.1	Net-Zero Prductn E.Star	Net-Zero Prductn Zero Tool
1A	Honolulu	1541.85	1538.47	1540.16	5255.67	723.37	934.65	250.53
2A	Orlando	1415.92	1379.03	1397.48	4768.77	797.23	779.46	276.10
3B	Las Vegas	1526.57	1508.85	1517.71	5179.06	667.34	964.12	293.34
4A	Harrison	1203.62	1207.37	1205.50	4113.65	1008.21	960.23	320.08
5A	Chicago	1131.2	1136.99	1134.10	3870.00	1071.69	1473.44	418.74
6B	Billings	1139.23	1119.15	1129.19	3853.27	1166.04	1303.73	367.99
7	Duluth	1058.75	1068.19	1063.47	3629.00	1333.34	1775.03	474.46

Table 4: Estimated Area of PV Modules ne.

Climate Zone	City	Net-Zero Prductn CC103.1	PV Module kW Rating	PV Module Area (sf)	Required Est. Number Modules	Req. Est. Number Modules Round Up	Est. Area PV Modules
1A	Honolulu	723.37	0.55	27.8	1315.23	1316	36,584.8
2A	Orlando	797.23	0.55	27.8	1449.51	1450	40,310.0
3B	Las Vegas	667.34	0.55	27.8	1213.35	1214	33,749.2
4A	Harrison	1008.21	0.55	27.8	1833.11	1834	50,985.2
5A	Chicago	1071.69	0.55	27.8	1948.52	1949	54,182.2
6B	Billings	1166.04	0.55	27.8	2120.07	2121	58,963.8
7	Duluth	1333.34	0.55	27.8	2424.25	2425	67,415.0

Table 5: Estimated Area of PV Modules Needed to Meet Total Energy Demand Based on Energy Star Target Finder.

Climate Zone	City	Net-Zero Prductn E.Star	PV Module kW Rating	PV Module Area (sf)	Required Est. Number Modules	Req. Est. Number Modules Round Up	Est. Area PV Modules
1A	Honolulu	934.65	0.55	27.8	1699.37	1700	47,260.0
2A	Orlando	779.46	0.55	27.8	1417.21	1418	39,420.4
3B	Las Vegas	964.12	0.55	27.8	1752.95	1753	48,733.4
4A	Harrison	960.23	0.55	27.8	1745.87	1746	48,538.8
5A	Chicago	1473.44	0.55	27.8	2678.99	2679	74,476.2
6B	Billings	1303.73	0.55	27.8	2370.43	2371	65,913.8
7	Duluth	1775.03	0.55	27.8	3227.33	3228	89,738.4

Table 6: Estimated Area of PV Modules Needed to Meet Total Energy Demand Based on Zero Tool

Climate Zone	City	Net-Zero Prductn Zero Tool	PV Module kW Rating	PV Module Area (sf)	Required Est. Number Modules	Req. Est. Number Modules Round Up	Est. Area PV Modules
1A	Honolulu	250.53	0.55	27.8	455.50	456	12,676.8
2A	Orlando	276.10	0.55	27.8	502.01	503	13,983.4
3B	Las Vegas	293.34	0.55	27.8	533.35	534	14,845.2
4A	Harrison	320.08	0.55	27.8	581.96	582	16,179.6
5A	Chicago	418.74	0.55	27.8	761.35	762	21,183.6
6B	Billings	367.99	0.55	27.8	669.07	670	18,626.0
7	Duluth	474.46	0.55	27.8	862.65	863	23,991.4

DISCUSSION

The findings show that it is possible to determine an estimated area of PV modules using this method. The main variables are how much energy is needed for heating and cooling (climate), how much sunlight is available to convert to energy (latitude and climate), and what the target EUI is (energy efficiency of the building). The data shows that, as one would surmise, colder climates are located at farther north latitudes, so have fewer hours of daylight annually (see Table 3) as well as having a higher energy demand to maintain comfort. The EUI of the IECC, Energy Star, and Zero Tool reflect that achieving the EUI in a higher demand climate is more costly: hence the larger EUI allowances for colder climate zones. The revisions to the 2024 IECC Table CC103.1 have made it more stringent than the Energy Star Target Finder estimate (at least as set at 80% for this study). However, currently, most jurisdictions have not yet adopted the 2024 IECC. There is clearly a direct linear relationship between the EUI and the amount of energy that is needed to reach net-zero. The lower the EUI, the less area is needed for PV modules, as seen in Tables 4, 5, and 6.

The use of the estimated area of PV modules can be used as a data point for decision making on the form and proportion of the building. For example, using the example building located in Chicago (5A climate zone) based on the IECC EUI of 40.9, the PV area is 54,182.2sf. The building's area is 101,283sf and if one were exploring height/length to site it is clear that you need to cover an area of about half the building's area to reach net-zero. Multifamily housing with double loaded corridors is often limited to a 50-70' cross section and are often 4 or more stories in height. The designer can quickly tell that they need a better (lower) EUI to fit the PV area onto the roof. Of course, depending on the site conditions, it may be possible to have site mounted PV, such as shading over parking.

The Zero Tool EUI is 16 for climate zone 5A. This is a bit more energy efficient than the final design of the example building which ended up at 17.84. The area of PV required in Chicago with an EUI of 16 is 21,183.6sf (Table 6). This is 20.9% of the GSF and fits on the roof

somewhere between a four-five story building. The example building ended up being 6 stories tall (not to mention a bit higher EUI, so would need a bigger area of PV), so some of the PV would have to be either on the site or on the façade of the building.

At six stories, the available area on the example building's roof is 16,880.5sf. Table 6, based on Zero Tool EUI, shows that in Honolulu, Orlando and Las Vegas it would be very likely that the designer could fit the array on the roof while meeting code setbacks for arrays and leaving space for mechanical equipment. Harrison, requiring 16,179.6sf of array space probably won't quite get all the array on the roof: except perhaps if the designer were to create a dramatic overall roof shading array like that of the Bulitt Center in Seattle, WA, or the Edith Green-Wendell Wyatt Federal Building in Portland, OR. This type of array would need to meet height and setback limitations for the building, so knowing that it could be a desirable solution would be helpful for initial design explorations.

The advantage of knowing a target area of PV is that the designer can consider the area needed and use the information to assist in creating an innovative net-zero design that fits on the site and takes advantage of where the sun is. For example, if the designer knows that it is unlikely the array will fit on the roof, they could consider creating a longer length of the façade to face south to get the best average sun orientation. Modules on this façade could be used as a window and/or patio shading device for the summer months, perhaps even tilted at the best average solar gain angle (latitude) to increase module production.

The largest limitation of this study is knowing how much space the designer really needs on the roof because there are so many variables impacting the actual placement of PV modules on the roof. For example, the narrower the building footprint is, the more the code setbacks for access impact the percentage of the roof that the PV can be placed on. The actual layout of the modules could vary from E-W orientation, and the physical dimensions of the modules might not fill the estimated area. There may also be shading issues on a site from the building's surroundings that impact the amount of available sunlight.

Future research could be done to further develop likely percentages of roof coverage based on case studies of typical multifamily building layouts and dimensions. For example, multifamily housing often has plan configurations that are rectangular, T or L or H, and one or more courtyards. Having an estimate of how much area would be available for the PV array on the roof would be helpful as the designer could then multiply the estimated area by how much more area would be needed based on the plan type. This would lead to possibly more accurate estimates of how much roof area is really needed to achieve net-zero. This process could be used by students to see how helpful it is to them in achieving their net-zero design goal as well as developing innovative designs.

In conclusion, this method does provide useful information to the designer at the beginning of the design process, allowing them to have an estimated PV array area to work with as a design parameter, therefore increasing the likelihood of achieving a net-zero building. The spreadsheet used is available for free download at https://dorothygerringarchitecture.com/.

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Improving Building Envelopes to Enhance Hybrid Renewable Energy Systems for Remote Communities

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ABSTRACT

Remote communities across the United States often suffer from limited access to reliable energy infrastructure. Many of these communities depend on diesel generators, which carry significant environmental and financial burdens. Furthermore, when energy infrastructure is damaged, restoration can take much longer due to the remoteness of these areas, which exacerbates instability. Hybrid Renewable Energy Systems (HRES) offer a promising solution that provides clean, resilient, and economically viable energy alternatives.

This study investigates how architectural building design can enhance the efficiency and feasibility of HRES for remote communities. Specifically, by optimizing building performance and reducing baseline energy demand, it becomes possible to design smaller, more cost-effective hybrid systems with lower Net Present Costs (NPC). Two case studies were selected: a 32-house community in Alaska, where per capita energy consumption is the highest in the U.S., and a comparable community in Hawaii, which faces the nation's highest residential electricity rates. Both communities currently rely on diesel generators and have partnered with DOE experts and national laboratories to transition toward resilient, renewable energy solutions.

Using the Urban Modeling Interface (UMI) software, we generated hourly energy demand profiles, which served as inputs for HOMER Pro simulations. Eight different scenarios were compared against a base case of diesel-only generation. Several hybrid configurations, combining wind turbines, PV arrays, diesel generators, lithium-ion batteries, and converters, demonstrated significantly lower NPC and Levelized Cost of Energy (LCOE) than the diesel-only baseline. Additionally, community design optimization further reduced energy demand and system costs.

Our findings highlight how thoughtful integration of architectural design with hybrid energy planning can make off-grid solutions scalable and economically attractive. This work offers a pathway for embedding resilient off-grid energy systems within broader real estate and community development frameworks, especially in remote and underserved regions.

Resilient by Design: Powering the Renewable Energy Future through Microgrid Housing Innovation for Prairie View and Gulf Coast Communities

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ABSTRACT

This paper will explore a new, integrated, interdisciplinary effort to advance climate-responsive with architectural building design and renewable energy innovation. This is achieved with the integration of the Solar Lab, the SMART Micro Grid Center, and the Micro Grid House 360; a high-performance, modular residential prototype at Prairie View A&M University. These initiatives represent a layered approach to resilience research and applied learning in architecture, engineering, and environmental design for the Gulf Coast region. This paper shares early findings, performance data, and design implications for net-zero energy housing; modular housing capable of generating sufficient solar energy to offset power consumption. This research will benefit vulnerable Gulf Coast communities, with broad relevance for modular residential construction and resilient design across various climate-stressed regions. The data collected and analyzed in this paper presents satisfactory performance indicative of a scalable House 360 microgrid design.

Keywords: House 360, Solar Lab, and Micro Grid Center.

INTRODUCTION

Prairie View A&M University's (PVAMU) Solar Lab, SMART Micro Grid Center, and Micro Grid House 360 educational and research facilities are highly integrated testbeds for real-world learning and performance measurement of microgrid and net-zero energy residential prototypes. The Micro Grid House 360's elevation and insulation help to reduce energy consumption through improved air flow and thermal transfer while generating energy through the solar cells mounted on the roof; net-zero energy is more easily achieved through the managed energy consumption matched with efficient solar generation. This integration will aid climate-stressed Gulf Coast communities and serve as a design platform for scalable microgrid housing opportunities for the future.

Coast communities continue to feel the impacts of weather-related stresses and infrastructure challenges, including hurricanes, power outages, and water management issues. On PVAMU's campus, the Solar Lab, SMART Micro Grid Center, and Micro Grid House 360 are being used together as open-air, interdisciplinary, prototyping, and testing platforms to provide research and real-world learning opportunities related to microgrid technologies and scalable solutions for students and affordable housing. This paper focuses on integration, implementation, and performance of Sol-Ark 15kW hybrid inverters (Sol-Ark, 2023), Storz $LiFePO_4$ 12V batteries (Storz Power, 2023), e-Gauge digital energy monitors (eGauge Systems, 2023), and additional tools for real-time, immersive visualization and control of renewable energy microgrid technologies and critical building systems. Data points and wireless IoT-connected systems are integrated into a centralized cloud platform that supports real-time performance metrics and ongoing applied learning and regional resilience planning. That performance data is then visualized through extended reality (XR) platforms to aid remote monitoring and controls.

SYSTEM INTEGRATION AND TECHNOLOGIES

PVAMU's residential microgrid system utilizes the Sol-Ark 15kW inverter for hybrid power management and load balancing of the three power sources present: solar, battery, and grid power. The Sol-Ark inverter was selected based on its capabilities for hybrid operation, fast switch over between power sources, dynamic voltage scaling support, high amp capability, and Maximum Power Point Tracking (MPPT) which allows for automated photovoltaic (PV) energy monitoring, net metering, and solar power optimization. Storz $LiFePO_4$ 12V batteries were selected for safe, long-term energy storage with greater than 6000 cycles of depth of discharge (DoD) at greater than 95% efficiency (Hofmann and J. P. Lopes, 2018). Performance monitoring is handled by e-Gauge 4215 meters that provide real-time power analytics for home power stations, and is linked to support for Message Queuing Telemetry Transport (MQTT) based, IoT dashboards for mobile device monitoring (National Academies, 2022). Additionally, virtual-reality dashboards and visual overlays using XR tools were tested for immersive student and operator visualization of energy flow through critical building systems, control logic, and dynamic performance benchmarks (Figure 1).

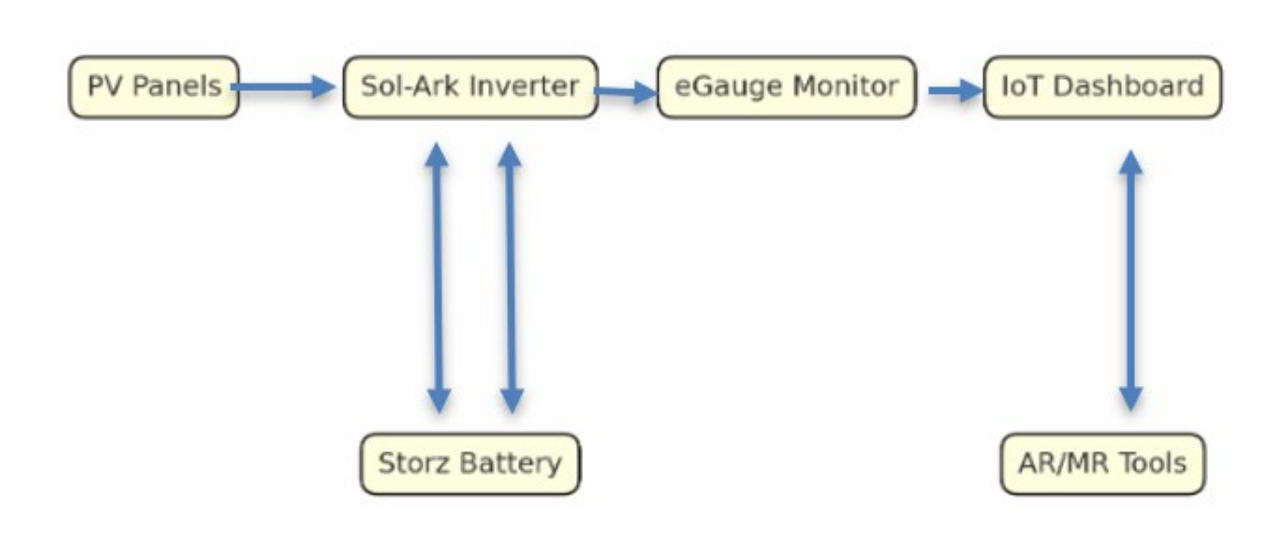

Figure 1. Integration Status of Core Microgrid Technologies by Dr. Anthony Hill. 2023.

FACILITY INTEGRATION

The system in Figure 2 is a solar platform control system, which shows an external solar photovoltaic (PV) array mounting field on the left, and an internal control room on the right. The control room is the operational heart of an off-grid solar laboratory. As visible from the picture, the control room is equipped with three Sol-Ark 15kW hybrid inverters connected in parallel, and six Storz $LiFePO_4$ batteries in "Storz Power" enclosures stacked directly underneath the three-inverters. The ensemble is an integrated energy conversion and storage system with large capacity, as well as a modular system with both AC and DC load interfaces in both single-phase and three-phase configurations.

Figure 2. The Completed Solar Lab photos by Dr. Joseph Dowell-Anthony Hill. 2025.

The Sol-Ark 15K inverters are bi-directional power electronics that can efficiently (>96%) control solar conversion, grid synchronization, and battery charging and discharging with integrated MPPT (Sol-Ark, 2024). In addition to this, they also have internal transfer switches, surge protection, and smart load prioritization control communication interfaces for remote diagnostics and backup features. Systems using these inverters are also able to have simple, seamless off-grid to grid-tied conversions, which is useful for research and experimentation where high reliability and resilience are important.

The Storz $LiFePO_4$ batteries have an estimated total storage capacity of 5.12 kWh (rounded) for a single battery, adding up to approximately 30.72 kWh of usable storage for all of them together. This type of battery is compatible with renewable energy storage and usage, they can be used for deep cycle operations, have a high energy density, and are thermally stable. These capabilities allow the batteries to be useful for providing consistent and long-lasting energy support for nighttime, low irradiance, or peak load conditions (Hill, 2023). The stack is easily extendable to more or fewer batteries, in series or parallel configurations for a variety of uses, which is a modular feature of the platform.

The PV modules in front of the control room are wired to this centralized system, providing power to the inverters for on-the-fly conversion and control. The overall layout and facility setup of the control room is ideal for a solar lab setup, with clean wiring practices, ground mounting, dust-free cabinets, and a generally good layout for safety, accessibility, and performance reliability for training and experimental usage. Altogether, this solar control system is a robust renewable energy research platform that could be used for both hands-on training or advanced energy system modeling in a variety of irradiance conditions and load profiles (Sol-Ark, 2024).

House 360 in Figure 3 is a small-scale, net-zero-capable dwelling unit. The all-electric dwelling is a highly energy-efficient home, scaled to meet the typical daily energy and living needs of a small family of two to three occupants. House 360 is designed to support a completely solar-plus-storage system, grid-tied, to meet the home's daily energy needs with an array of energy-efficient appliances, lights, electronics, and other living requirements. The house's rooftop PV system is comprised of high-efficiency monocrystalline PV panels providing electricity to both real-time loads and the battery bank. A Sol-Ark 15K hybrid inverter is the heart of the home's electrical system, coordinating solar PV DC to AC power conversion, power flows between solar PV, battery, and grid, and orchestrating seamless automatic power failovers and switchovers. The Sol-Ark hybrid inverter with integrated MPPT, grid support, load shedding, and remote monitoring and control, is well-suited for grid-interactive residential (GIR) applications (Sol-Ark, 2024).

Figure 3. House 360 photo by Dr. Joseph Dowell-Anthony Hill. 2025.

Two Storz lithium iron phosphate ($LiFePO_4$) batteries with a capacity of 5.12 kWh each, for a total energy storage of 10.24 kWh, are used to provide daily energy resilience and autonomy for House 360. The configuration is adequate to support reliable night-time energy supply or backup power during utility outages or blackouts. The selected battery type has a long cycle life, high thermal stability, and inherent safety. The batteries are commonly used in residential storage applications for consistent daily cycling with predictable degradation over time (Hill, 2023).

The interior layout and components of House 360 are designed for comfortable daily living. The kitchen is fully equipped with induction cooktop, microwave oven, refrigerator, LED lights, and other energy-efficient small appliances. The bathroom is outfitted with low-flow showerhead, faucet, and flush toilet, an on-demand electric water heater, and an energy-efficient exhaust fan. Living space is designed to provide entertainment and work functions with a television, Wi-Fi, and smart plugs to turn on and off selected loads for energy awareness and management. A small dining area is located next to the living room and has a window for natural daylight, and seating up to 4 people. The building envelope of House 360 as shown in Figure 4 was planned with a few passive design principles such as shaded porches, elevated floor levels, and energy-efficient windows to minimize the thermal load on the building envelope while maintaining indoor occupant comfort.

Figure 4. Sunset from the front porch and photo of finished Micro Grid House 360 on PVAMU Campus. 2024.

House 360 was planned and built to be a sustainable dwelling, and achieve net-zero functionality with minimal grid assistance. The renewable technologies and design planning deliver clean, reliable, affordable power in a smaller home envelope. Solar PV with battery backup can support the daily energy needs of the home and be completely off-grid for daytime energy consumption with the PV array. The dwelling unit also has the capability to export excess solar electricity back to the utility grid, thus, improving economics of operation. House 360 is an example of a real-world proof-of-concept for resilient housing, renewable energy and storage applications, and sustainable living.

Solar Lab

The Solar Lab features modular PV rack systems and working Sol-Ark systems to support net-metering and MPPT-based experimentation and scenario testing that are linked to IoT visualization dashboards and XR immersive experiences. Different values of irradiance are set on the solar cell in order to mimic the cells' efficiency (Dowell, 2025). Variations in the irradiance are made by either adjusting the brightness of the lamp or through a digital slider function. Table 1 indicates that as the irradiance increases in value, the efficiency of the inverter increases, (Dowell, 2025). It could be assumed that when the % of irradiance is high and the % of shading is low, that the cells will have a greater efficiency during inverter operation. This also suggests that when irradiance is lower, one could expect the amount of power that could be put back into the grid to also be lower, (Dowell, 2025).

Table 1. Solar Station Table Power Generated Per 100% of Solar Irradiance. 2025.

	CO5127-1S	Solar Panel Emulator	Efficiency
IRRADIANCE in %	|P_AC| in W	|P_DC| in W	η = P_AC / P_DC
5	37	71	0.52
10	110	143	0.77
20	256	288	0.89
50	686	719	0.95
100	1395	1440	0.97

The line graph in Figure 5 represents the relationship between AC power and efficiency. This line graph shows that the efficiency percentage increases with the increase in the AC power, however the graph seems to reach a plateau at 97% efficiency whenever the AC power is above 1300 W (Dowell, 2025). As the irradiance increases, the inverter losses stay almost constant.

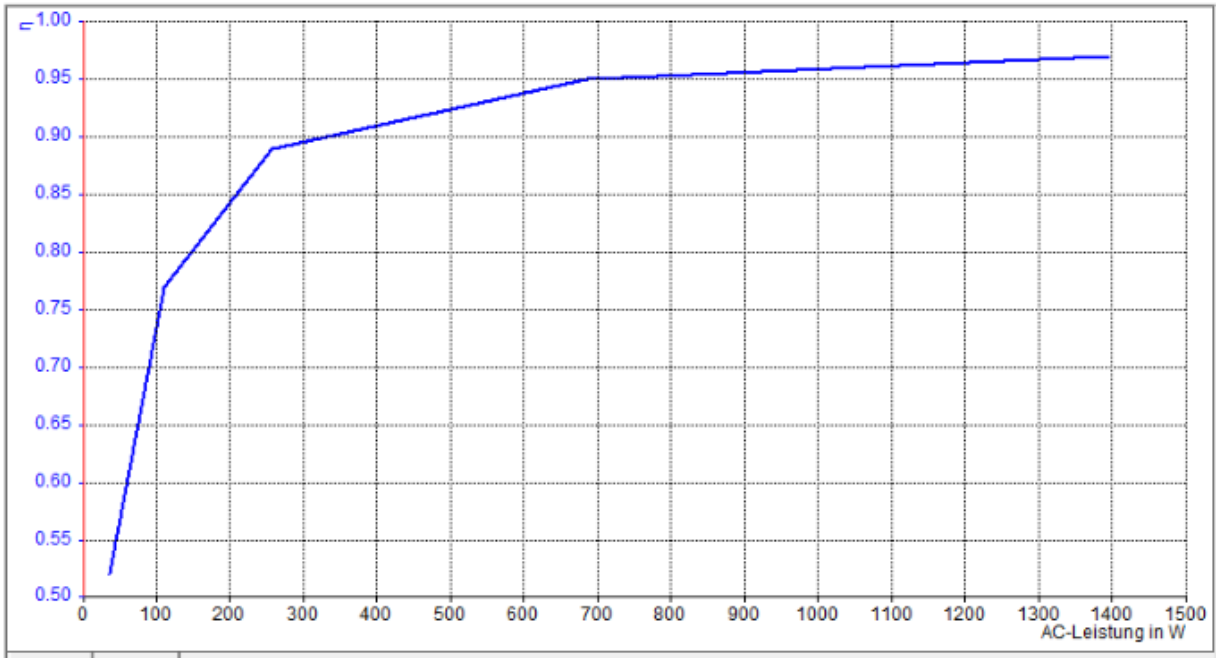

Figure 5. PV Station Inverter Chart AC Power v, Efficiency by J.M. Dowell. 2025.

SMART Micro Grid Center

SMART Micro Grid Center is used to model grid-tied and autonomous microgrid behavior and performance. PHIL models and microgrid-in-the-loop testing, fault injection routines, and demand-response protocols and configurations are being studied in the microgrid development

and planning phases with alignment to Houston's proposed Resilience Power Plan. The SMART Micro Grid Center supports research on policies regarding governance and regulatory implementation of renewable resources, micro-grids, municipal utility districts, predatory home lien-holding solar installation companies, smart grid control systems to enable hazard and risk assessments, and alleviate homeowner utility burdens throughout the Gulf Coast.

Micro Grid House 360

This DOE- and NAS-funded PVAMU modular prototype for resilient and net-zero energy housing will incorporate all of the above-mentioned systems into a net-zero capable housing testbed (IEEE Standard 1547-2018, 2018). For the first year of deployment and testing, a full year of weather-proofed performance monitoring and benchmarking will be conducted to set key parameters for energy stability, envelope performance, and environmental control for Gulf Coast microgrid housing and student housing during high-demand periods, including: extreme summer heat, grid outages, and cold snaps (US Department of Energy, 2022). Early testing has shown that a single unit could power up to two to three homes adjacent to the testbed, suggesting that a case can be made for microgrid-ready, low-income residential communities (National Academies, 2023). Figure 6 shows the interdisciplinary teaching component of engineering research assistant, Joseph Dowell, connecting to the dashboard for the first time.

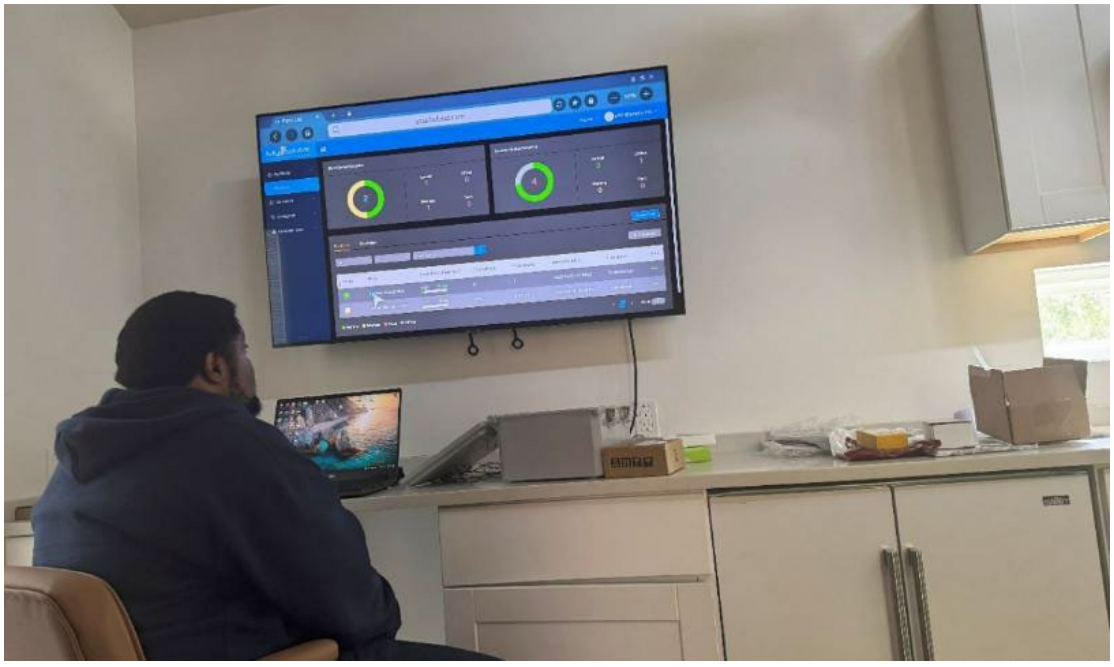

Figure 6. Research Assistant Joseph Dowell helps connect House 360 into the Micro Grid Network. 2025.

Monitoring, Visualization, and IoT Access

Systems at all facilities are currently integrated into a secure MQTT cloud environment. All e-Gauge meters send data to the secure MQTT dashboard, which is used to configure IoT dashboards and can be accessed on mobile devices for remote monitoring. Virtual dashboards and control tools for XR are being developed in Unity and Blender 3D with support for critical building systems control and virtual monitoring, including:

(1) battery state of charge (SOC),

(2) inverter performance,

(3) thermal loads, and

(4) time-of-use and real-time energy costs, among other features.

These tools will allow for both remote diagnostics education and training. Figure 7 is a view of the House 360 dashboard through the XR headset. This view displays the energy routing for the House 360, battery storage levels at that time, and usage data chart for the home. Large Spikes in the usage data chart (load current vs. the time and date) correspond to enabling multiple appliances or in-home systems at once (such as air conditioning, fans, and lighting). Due to the XR visual technique known as foveated rendering, some of the data that was not directly in the operator's focus can appear more distorted.

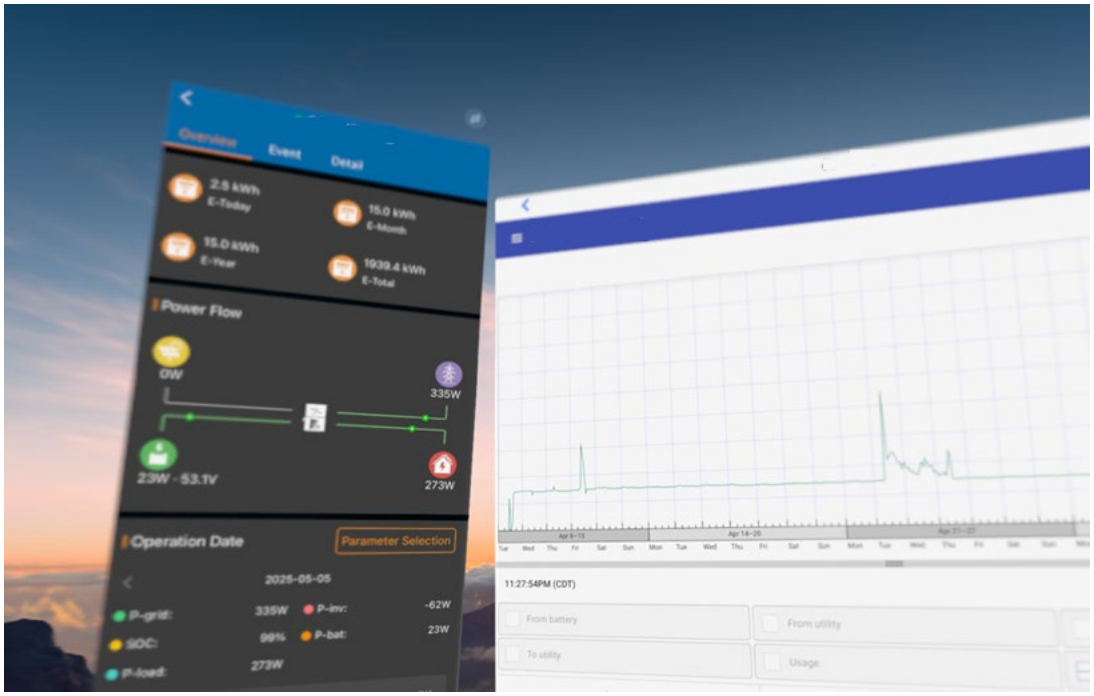

Figure 7. House 360 dashboard and meter data visualized in XR headset environment. 2025.

RESULTS, PERFORMANCE DATA, AND DISCUSSION

The PV system still requires additional sensors and hardware for a complete monitoring and control apparatus, though, preliminary data demonstrates that the House 360 can be sustainability. The Micro Grid House 360 project at PVAMU was able to generate up to 22.7 kWh/day and support solar self-consumption loads in excess of 17 kWh per day with battery round-trip efficiency greater than 94% (Dowell, 2025). Performance monitoring of simulated grid outage events lasting up to 2 to 3 days has demonstrated successful maintenance of critical loads via the inverter and battery energy storage back-up. Virtual and IoT dashboards were used to monitor user consumption and allowed for remote real-time configuration of electric loads and PV setpoints.

Table 2 displays the House 360 rooftop PV array current across a couple of days. Due to not having an irradiance monitor installed along the arrays, the current measurements outline the general performance of the arrays regarding the collection of solar radiation. The current remains around a value of .09A during overnight operation when the irradiance levels are low or insufficient for generation. This is also observed during shading and moderate cloud coverage; when there is adequate solar irradiance, that value is observed to increase. These fluctuations occur as expected during predictable sunlight patterns throughout the day, with some variance for unpredictable shading. Then Figure 8 shows an hourly view of the rooftop PV array current in mA with distinct graphical spikes during higher solar irradiation periods.

TABLE 2. The House 360 Rooftop PV Array Current Measurements for Monitoring Irradiance. 2025.

Date & Time	PV Array Current [A]
4/14/2025 0:00	0.0980
4/14/2025 1:00	0.0990
4/14/2025 2:00	0.0990
4/14/2025 3:00	0.0990
4/14/2025 4:00	0.0990
4/14/2025 5:00	0.0990
4/14/2025 6:00	0.0990
4/14/2025 7:00	0.0990
4/14/2025 8:00	0.0990
4/14/2025 9:00	0.0990
4/14/2025 10:00	0.2000
4/14/2025 11:00	0.2210
4/14/2025 12:00	0.1020
4/14/2025 13:00	0.0990
4/14/2025 14:00	0.0990
4/14/2025 15:00	0.1030

4/14/2025 16:00	0.1060
4/14/2025 17:00	0.1070
4/14/2025 18:00	0.0990
4/14/2025 19:00	0.0940
4/14/2025 20:00	0.0940
4/14/2025 21:00	0.0950
4/14/2025 22:00	0.0960
4/14/2025 23:00	0.0970
4/15/2025 0:00	0.0980
4/15/2025 1:00	0.0980
4/15/2025 2:00	0.0990
4/15/2025 3:00	0.0990
4/15/2025 4:00	0.0990
4/15/2025 5:00	0.0990
4/15/2025 6:00	0.0990
4/15/2025 7:00	0.0990
4/15/2025 8:00	0.1000
4/15/2025 9:00	0.1850
4/15/2025 10:00	0.2050
4/15/2025 11:00	0.2390
4/15/2025 12:00	0.2420
4/15/2025 13:00	0.2570
4/15/2025 14:00	0.2460
4/15/2025 15:00	0.1310
4/15/2025 16:00	0.1050
4/15/2025 17:00	0.0970
4/15/2025 18:00	0.0960
4/15/2025 19:00	0.0960
4/15/2025 20:00	0.0950
4/15/2025 21:00	0.0950
4/15/2025 22:00	0.0960
4/15/2025 23:00	0.0960

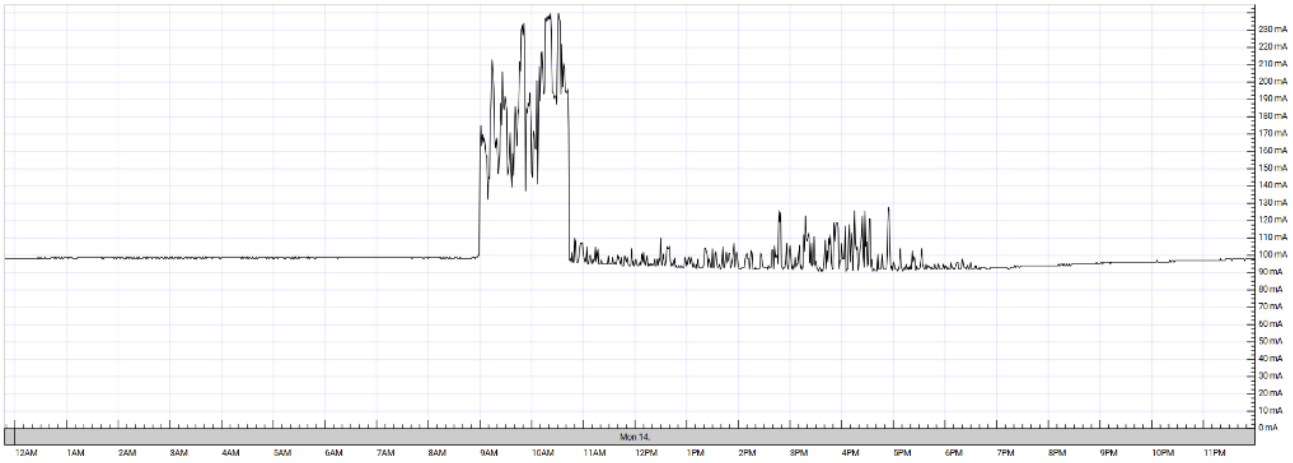

Figure 8. Daily View of the House 360 Measured PV Array Current in mA. 2025.

The image in Figure 9 shows the visualization of the House 360 dashboard through the XR headset. The headset utilizes augmented reality techniques to project data for the house on top of the real-world environment, allowing the operator to monitor and manage the house hands-free. All of the data for the house can be retrieved through the headset software, in real-time, and the operator can perform live work if necessary. Real-time data is crucial for the reliability and resilience; ensuring that power generation remains adequate to manage the power consumption through regular use of the house.

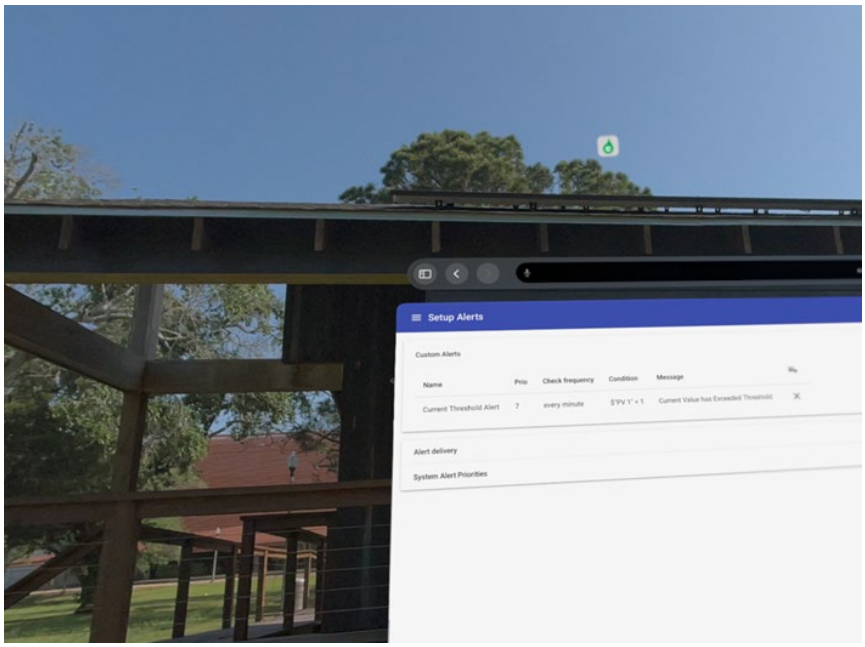

Figure 9. XR Alert Setup View for the House 360 Monitoring and Management. 2025.

Several architectural factors assist the solar system in its efficiency (Ward, 2024). The 2x6 wood frame stud construction with the use of Rockwool Comfortbatt R 23.5 (5.5”) in the walls and floor assembly. R 38 (7.25”) Rockwool Comfortbatt in between the 9” rafters along with Jeld Wen Premium Vinyl sliding and frosted casement windows (Low-E, Clear Argon, U-0.27, SHGC: 0.17), LED lights, energy star appliances, and rainscreen assembly on the walls is shown in Figure 10. Rockwool has achieved the Declare Red List approved rating. The donated Rockwool insulation is non-toxic and doesn’t irritate the skin to the touch. It also carries noteworthy fireproofing and sound silencing qualities. A preliminary thermal analysis provided during our Rockwool partnership led to our final wall and floor assembly decisions (Rockwool, 2023). The bottom sheathing layer of the raised floor assembly is not taped to allow for humidity to escape.

The house energy budget is achieving a higher energy efficiency baseline than was predicted in the early energy modeling in REVIT Insight (Figure 11), which carries a heavy implication for weatherization of homes in the Gulf Coast. Preliminary thermal transfer testing could be expanded through the introduction of sensors throughout the building envelope assemblies and additionally, further testing on battery storage is necessary.

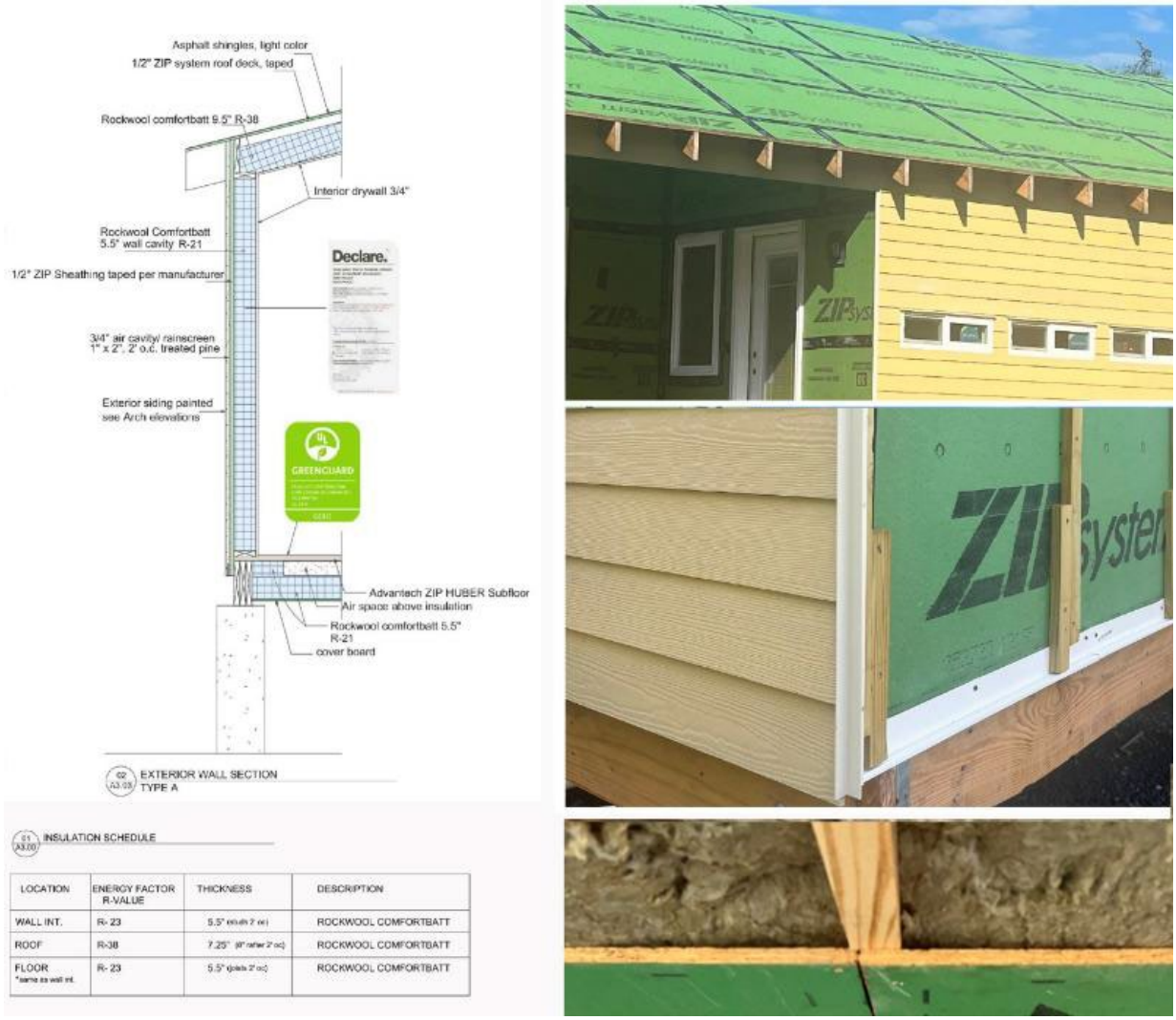

Figure 10. Construction drawings and photos with wall, roof, and floor assembly details by IDEA-CJR. 2022-2024.

Figure 11. Integrated early predictive REVIT Insight energy model and diagram by Graduate Assistant Jaylin Lee. Photos of screened porch with solar equipment. Construction drawing elevation of solar equipment porch area by IDEA-CJR. (2022-2024)

The use of the taped, fluid applied weather barrier of the HUBER ZIP System tightens the construction of the envelope, reducing labor, and eliminating the weakness of traditional house wrapping on the roof, walls and bottom of the floor assembly from getting windblown (Figure 10). Fortified roof and continuous load path details were achieved using donated Simpson Strong tie downs, the HUBER ZIP sheathing with the printed nail pattern, and tape with the rainscreen trim and vents that were provided in kind by TAMLYN. Two significant roof porch extensions further shade the east (5') and west (10') elevations of the living module with the solar ready roof area, which is free from penetration. The conduit from the panels to the inverter runs outside the roof, around the roof rafters and soffit area, only penetrating the screened porch area. It serves as an extension of the bed/bath module which provides more protection and connected space for homeowners to access the breaker box and equipment hangs on the outer wall.

The Mitsubishi Electric EZ FIT Ceiling Cassette MLZ-KP series outperformed the wall mounted unit for our climate due to several factors, including overall specifications and design. The wall mounted unit coolant line was shown to sweat during operation. This was first detected through visual wetness on the wall, then by a handheld thermal imaging camera, and later confirmed through the moisture meter readings of the studs once the wall was opened in that area. The load can be calculated to eliminate the wall hung unit for this climate zone below the hot and humid

line. The flush mounted unit's stylish aesthetic and application are more installer, and client friendly.

CONCLUSION

On May 16, 2024 a tornado that reached over 100 mph was seen crossing the Prairie View A&M University campus, downing powerlines along Owens Road (PVAMU Alert System, 2024). Hurricane Beryl, the tropical cyclone made landfall in Matagorda, Texas as a category one on July 8th, 2024. The Micro Grid House stood the test of these storms, making the coupling of integrated design features an ideal solution for policy makers.

This paper has presented a replicable and scalable model of net-zero energy, modular, climate-resilient, and microgrid-ready housing using an integrated suite of microgrid and building technologies. The House 360 is an elevated structure that is built to withstand high winds, but to also mitigate flooding. This design not only helps to protect the home and the occupants, but increases airflow and ventilation for the home to help reduce power consumption during cooling. The insulation of the building creates a more efficient thermal transfer, directly contributing to increased comfort for the occupants, reduction in energy cost, and an overall decrease in environmental impact. Combining the specialized building structure of the House 360 with the microgrid system helps to achieve the goals of resilience, reliability, and net-zero energy. As the PV rooftop arrays generate energy, it is utilized directly to power the house; therefore, the less energy the house requires for daily operations, lends way for more energy to be stored. This creates a positive correlation between generation and consumption, leading to a truly net-zero energy ecosystem, where excess solar generation could then be fed back to a utility grid.

The combination of Sol-Ark inverters, Storz battery storage, e-Gauge monitoring, and immersive XR tools strengthen the resilience of the house and provide potential for both performance and educational benefits. In performance, the house can be monitored more easily, remotely and the solar generation can be tracked. For educational purposes, it would provide engineering students an opportunity to learn more about architecture and apply smart grid principals to a real-time, modular system. Additionally, the implementation of XR introduces an approach where monitoring and management can be performed remotely and hands-free. Providing the operator with an immersive monitoring view to improve real-time work and maintenance.

Ultimately, the combination of these factors has created a novel model and a living laboratory for regional energy equity, net-zero energy, and microgrid innovation that can serve as a model for affordable student housing, for Gulf Coast communities, and other vulnerable population housing. The project will continue to improve over time with more interconnected sensors for monitoring and architectural additions to solidify the resilience and efficiency. This program will foster more interdisciplinary collaborations leading to new innovative policies and partnerships such as with the U.S. Department of Energy, Office of Electricity Community Microgrid Assistance Partnership, Bullard Center "Solar for All" program, City of Prairie View, and the City of Houston. Demonstrating proof of concept through a 2.0 prototype for student housing on campus, or the community micro grid scale for the Gulf Coast.

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A Systematic Review of Sustainable and Resilient Building Practices: New Design and Retrofitting Strategies

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ABSTRACT

The global shift towards sustainability and resilience in the built environment, driven by climate change, urbanization, and resource scarcity, has increased the need for innovative sustainable design principles and retrofit techniques to enhance the sustainability and resilience of built environments. However, the construction sector has not fully leveraged innovative design and retrofit strategies to enhance the performance of new and existing buildings. This systematic review investigates recent developments in sustainable and resilient building practices and considers papers published in Scopus and Web of Science peer-reviewed journals focusing on innovative new design principles and retrofit strategies. Based on peer-reviewed literature published between 2010 and 2025, the study aims to identify critical themes, new technologies, and performance benchmarks for the design and retrofitting of buildings. Findings revealed that by incorporating passive solar design, natural ventilation, and energy-efficient systems, sustainable buildings can reduce energy consumption and greenhouse gas emissions, contributing to a more sustainable future. Robust construction techniques, redundant systems, and adaptive design features can withstand environmental challenges and minimize the impact of disruptions on building functionality. This review contributes to the literature by demonstrating how integrated sustainable and resilient strategies are essential for shaping a future-ready built environment.

Keywords: Building Performance, Building Retrofitting, Energy-Efficient, Passive Design Techniques, Resilient construction,

INTRODUCTION

The increasing global emphasis on sustainability and resilience in the built environment has led to significant advances in building practice, particularly in design and retrofit strategies (Ejidike, Mewomo, and Olawumi 2022; Murtagh, Scott, and Fan 2020). The urgency to reduce environmental impact requires a comprehensive understanding of smart technologies, sustainable materials, and techniques that reduce carbon footprints while improving the durability of new

and existing buildings. Global cooperation is crucial in achieving sustainable development goals through green construction, highlighting the need for integrated approaches that reconcile environmental, social, and economic factors (Li and Li, 2020). Central to this discourse is integrating new design and retrofitting strategies to reduce carbon footprints and enhance building durability.

Sustainable and resilient building practices have garnered increasing attention in recent years as the construction sector seeks to address environmental degradation, resource scarcity, and climate change (Kosanović et al., 2018). Sustainable building practices refer to a comprehensive approach to building design, construction, and operation that reduces environmental impact while improving resource efficiency and occupant health and comfort (Akadiri et al., 2012). These practices emphasise integrating energy-efficient technologies, using sustainable and environmentally friendly materials, and implementing strategies to minimise waste throughout a building's life cycle. Complementary to sustainability, resilient building practises focus on improving a building's ability to withstand, adapt to, and rapidly recover to its original state from disruptive events, including natural disasters, climate change-related stresses, and operational disruptions (Al-Humaiqani and Al-Ghamdi, 2022). Resilience is characterised by adaptability, structural robustness, and the ability to maintain or quickly restore functionality, ensuring long-term performance and continuity under adverse conditions. In this context, integrating sustainability and resilience into new and existing buildings involves adopting innovative design principles and retrofitting strategies that address the evolving challenges of climate change and rapid urbanisation in the built environment. Retrofitting is the process of improving existing infrastructure to meet modern environmental and performance criteria without requiring complete reconstruction (Ejidike et al., 2025). Innovations such as construction 4.0, 5.0, and Building Information Modelling (BIM) enable more efficient, smart, sustainable, and resilient buildings (Chen et al., 2022; Yitmen et al., 2024). These technologies emerge as a critical enabler of sustainable and resilient building practices by facilitating integrated design, simulation, and management processes that improve resource use, energy efficiency, and data-driven decision-making, all essential to a resilient built environment. At the same time, Akram et al. (2022) emphasise the importance of global regulations and advanced energy-saving technologies that support sustainable building systems, highlighting the need for a multi-layered strategy to achieve resilience and sustainability in the built environment. Liu et al. (2021) highlight the role of emerging technologies, particularly building information modelling (BIM) with integrated blockchain, in promoting resilience by enabling transparent, real-time data sharing and informed decision-making in the smart city context.

This digital synergy supports proactive risk management and adaptive strategies, strengthening resilience alongside sustainability goals. Chen et al. (2023) show that integrating BIM and IoT enables real-time monitoring and efficient management of building performance, thereby contributing to sustainability by optimising energy consumption and maintenance. In addition, Adewale et al. (2024) explore the applications of artificial intelligence throughout the building lifecycle and demonstrate its potential to improve decision-making processes for sustainable construction and retrofitting. These technological advances not only improve operational efficiency but also enable adaptive responses to environmental stresses, thus strengthening the

resilience of buildings. Therefore, integrating sustainable and resilient building practices into building retrofit projects is a crucial, rapidly evolving area for improving the performance of the built environment. Despite its growing importance, only a few systematic reviews comprehensively examine the intersection of these practices in the construction industry. Therefore, this systematic review aims to synthesise existing research on innovative sustainable design principles and retrofit strategies to identify critical themes, new technologies, and performance benchmarks for the design and retrofitting of buildings to achieve sustainability and resilience of the built environment.

RESEARCH METHODOLOGY

Researchers use systematic literature reviews (SLRs) to produce thorough summaries and evaluations of research findings in specific areas, providing a basis for subsequent investigations. This study conducted a SLR to analyse the literature on sustainable and resilient building practices: new design and retrofitting strategies. SLR synthesise scientific information to address research questions, using a transparent and reproducible approach that encompasses all relevant findings while rigorously assessing their quality. This SLR applied strict inclusion and exclusion criteria to ensure only high-quality, relevant studies were selected (Ejidike and Mewomo, 2023; Lame, 2019). In this study, the PRISMA technique, "Preferred Reporting Items for systematic reviews and meta-analyses, " was used to select and analyse the studies. The PRISMA technique is a comprehensive checklist of the essential elements of research reports and includes a flowchart that visualises the research process (Toyin et al., 2024; Moher et al., 2009). Figure 1. Shows the flowchart for the SLR study. In this review, a comprehensive literature search was conducted. The first step was to carefully select a suitable database, and Web of Science and Scopus were chosen. The Web of Science and Scopus databases were selected for article searches, as they provide comprehensive coverage of peer-reviewed publications across various disciplines, ensuring access to high-quality, reliable research (Singh et al., 2021; Pranckutė, 2021). The rigorous indexing criteria, citation metrics, and intuitive search options make the database ideal for locating important studies and conducting comprehensive literature reviews. Table 1 presents the search keywords for the Web of Science and Scopus from 2010 to 2025.

Table 1: The Search Keywords.

Web of Science	"Resilient buildings" OR "sustainable design" AND "retrofitting" AND "building refurbishment" AND "climate adaptation" AND "energy efficiency"	182 articles
Scopus	"Resilient buildings" OR "sustainable design" OR "retrofitting" AND "building refurbishment" AND "climate adaptation" OR "energy efficiency"	46 articles

The “title/abstract/keyword” and “all fields” features of Scopus and Web of Science were employed to search for relevant articles. Based on the search, 228 articles were initially retrieved; inclusion and exclusion criteria were then applied to the identified articles based on the

subject areas: Energy, Engineering, Civil Engineering, and Construction Building Technology. Article types: Journal papers, review articles, and articles in the English language. Finally, 48 publications were selected for review on sustainable and resilient building practices, including new design and retrofitting strategies.

FINDINGS

This section presents and explains the results of the included studies. The first section provides an overview of the selected publications and a detailed explanation of sustainable and resilient building practices: the authors' new design and retrofitting strategies.

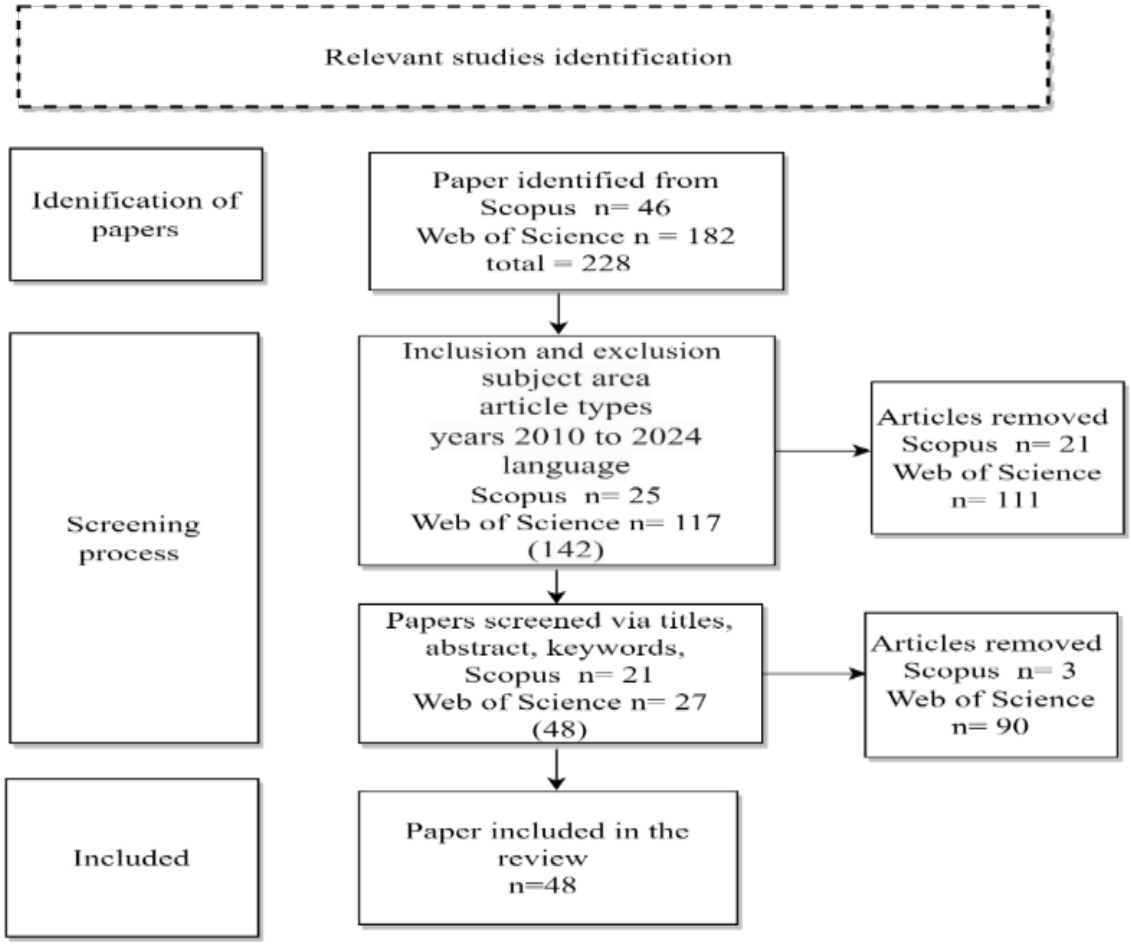

Figure 1: Research method flowchart (Source: Author 2025).

CHARACTERISTICS OF SELECTED STUDIES

The bibliometric result of the research shows that the selected full-text works reviewed for the qualitative synthesis date from 2010 to 2025. This result indicates that research on sustainable and resilient building practices: new design and retrofitting strategies was conducted during this period and spanned over a decade. However, the interest in sustainable building retrofitting strategies was surfaced in the study by Gohardani and Björk (2012), which emphasised that retrofitting offers significant economic, social, and environmental benefits compared to demolition. Since then, various multivariate design frameworks and multi-criteria decision-making tools have been developed to support building retrofitting. Figure 2 analyses the publication trends for the selected research articles. It shows that only eight publications appeared between 2010 and 2016. This observation suggests that academic interest in sustainable and resilient building practices encompassing new design and retrofit strategies was still nascent during this period. A notable upswing in research began in 2022, and the following years reflect increased scientific engagement in this area. The peak was reached in 2023, when the highest number of publications (10) was recorded, marking an important milestone in the field's development. This surge in academic output can be attributed to the growing global emphasis on integrating sustainability and resilience throughout the life cycle of buildings, a trend reinforced by numerous international initiatives and research-driven projects.

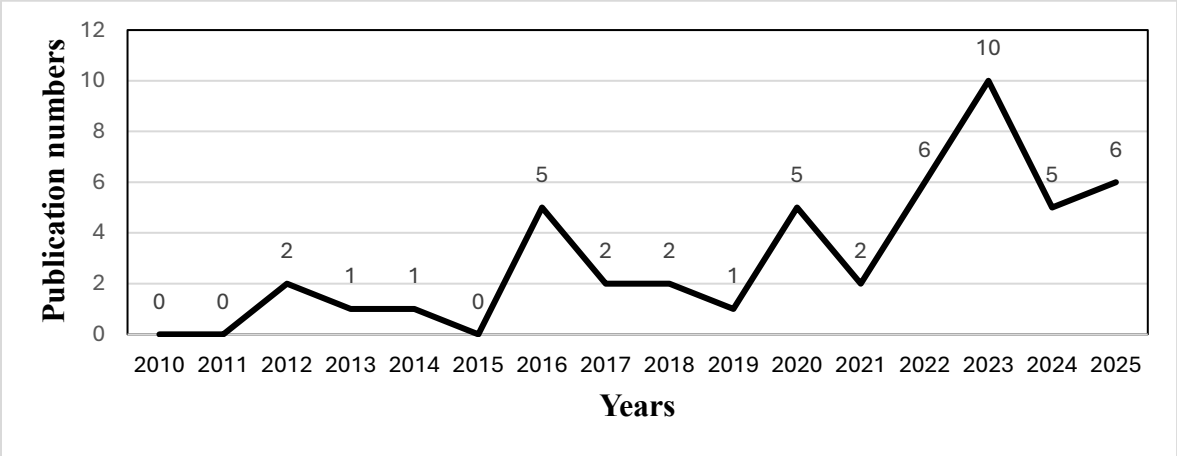

Figure 2 Annual publication trend 2010-2025 (Source: Author 2025).

Overview of Sustainable and Resilient Building Practices: New Design and Retrofitting Strategies

As global concern over climate change mitigation increases, the construction and building industry is under significant pressure to reduce carbon emissions (Schandl et al., 2016). The integration of sustainable and resilient building practises is increasingly supported by the convergence of advanced materials, digital technologies, and performance optimisation methods (Argyroudis et al., 2022). This multidisciplinary synergy enhances the design of new buildings

and the retrofitting of existing structures. At the centre of this approach is the principle of sustainability, which holistically addresses environmental integrity, economic viability, and social equity dimensions explicitly articulated in the United Nations Sustainable Development Goals (SDGs) (Argyroudis et al., 2022).

Innovative and Sustainable Materials for Resilient Building and Retrofitting

Integrating advanced materials in building design and retrofitting is critical in enhancing durability and sustainability within resilient construction practices. Using sustainable materials in building practices is essential to advancing environmental stewardship and resilience in the construction sector. Material selection and construction techniques are fundamental components in resilient building design and retrofitting of resilient buildings. They have a direct impact on mitigating climate change, promoting economic sustainability, and improving social inclusion in construction, while emphasising the need for global initiatives to facilitate the transition to an eco-friendly and resilient built environment (Soliman et al., 2022; Yahia and Shahjalal, 2024). Innovative materials are traditional materials reimagined through a design strategy prioritizing specific performance outcomes (Soliman et al., 2022). This intended performance is oriented towards high energy efficiency, sustainable construction, and durable infrastructure in line with global requirements. Therefore, using locally sourced, renewable, and high-performance materials can significantly improve a building's capacity to resist degradation from environmental stressors while maintaining ecological balance, corroborated by Adeyemi et al. (2024), who advocate for material strategies that prioritize affordability and accessibility without compromising resilience. According to Mogaji et al. (2024), some of these innovative and sustainable materials include bamboo-reinforced concrete, bio-receptive concrete, bricks derived from pollutants, 3D-printed sandstone, woven microbial cellulose, and husk-crete, developed from rice chaff and modified cement mortars. These materials collectively promote retrofitting as a cost-effective, resource-efficient approach to embed resilience in new and existing buildings, offering excellent thermal performance and aligning sustainability goals with resilience imperatives. In recent years, innovations in building materials technology have shown significant potential for sustainability and resilience in the built environment. These technologies include nanotechnology, carbonate curing, aerogel, mycelium, and 3D printing (Soliman et al., 2022). Together, these contributions highlight that material innovation must be integral to resilient design, ensuring buildings are both environmentally sustainable and capable of enduring diverse climatic challenges.

Retrofitting Strategies for Energy Efficiency, Conservation

Energy efficiency and conservation measures are pivotal to pursuing sustainable, resilient building practices and to shaping new design and retrofitting strategies. Energy performance enhancement has emerged as a critical strategy to improve the sustainability and resilience of existing buildings, addressing environmental and operational challenges. Early decision-making plays a crucial role in optimising energy performance outcomes, as Nielsen et al. (2016) highlighted, emphasising the importance of integrating energy considerations at the initial planning stages of building renovation. The study further notes that early-stage decision-support tools facilitate the identification of energy-saving opportunities and cost-effective interventions,

thereby reducing the environmental footprint of buildings while enhancing occupant comfort. Similarly, Mikaelsson and Larsson (2017) discuss how integrated planning incorporating energy efficiency objectives over extended project timelines leads to the evolution of sustainable building production processes, reinforcing the criticality of holistic approaches that align design, construction, and operational phases. Recent research underscores the importance of integrating energy-efficient technologies and resilient design principles to ensure buildings can withstand and quickly recover from disruptions. For instance, the incorporation of renewable energy systems such as solar panels and microgrids into retrofit projects has shown significant promise in enhancing energy autonomy and reducing reliance on centralized power grids, which are vulnerable to failures and extreme events (Yang et al., 2022; Masrur et al., 2022). These advancements reduce energy consumption and create more robust infrastructure to maintain essential services during crises. Incorporating Building Information Modelling (BIM) technologies has significantly advanced energy efficiency and conservation in building design and retrofitting. Fadeyi (2017) demonstrates that BIM is a transformative tool enabling multidisciplinary collaboration, accurate simulations, and performance analysis, collectively contributing to optimizing energy use throughout a building's lifecycle. Lim (2017) further elaborates on BIM-based sustainable design processes, illustrating how BIM facilitates informed decision-making by integrating energy modelling, daylight analysis, and thermal performance evaluations early in the design phase. Optimization techniques have been extensively applied to retrofitting strategies to balance energy performance, cost, and resilience. Hybrid and robust optimization models facilitate decision-making by considering uncertainties such as fluctuating energy demands and potential supply disruptions. For example, Lotfi et al., (2021) developed a robust optimization model that integrates sustainability and resilience by minimizing risk through conditional value at risk (CVaR) measures, which is particularly relevant for retrofitting projects aiming to mitigate the impact of extreme weather events or system failures. These capabilities allow for iterative refinements that minimize energy consumption and support the implementation of conservation measures tailored to specific building contexts.

Sustainable Retrofitting for Resilient Building Design

Integrating sustainability and resilience in building practices represents a critical advancement in architectural design and retrofitting strategies. Retrofitting existing buildings for sustainability is an essential approach to mitigating the environmental impact of the built environment, maximising economic benefits, and promoting social wellbeing (Iwuanyanwu et al., 2024). Sustainability in building design fundamentally revolves around minimizing environmental impact while maximizing resource efficiency throughout a building's lifecycle. D'Amico and Pomponi (2019) emphasize that sustainable building forms must consider compactness as a fundamental attribute, which reduces material use and energy consumption and enhances structural resilience against climatic stresses. This perspective aligns with Jensen et al. (2018), who highlight the complexities of sustainable renovation, noting that achieving resilience requires an integrated approach that balances energy efficiency, adaptability, and occupant wellbeing. These studies illustrate that compact, well-designed building forms are a pivotal starting point in merging sustainability and resilience objectives. Sustainable building design strategies have increasingly emphasized the integration of environmentally responsible materials and innovative technologies to minimize ecological footprints while enhancing occupant comfort

and resilience. Technological advancements and innovative design methodologies are central to facilitating this integration. Building Information Modeling (BIM) has emerged as a pivotal tool in advancing sustainable building design, construction, and management by enabling enhanced planning, visualization, and lifecycle analysis (Toyin and Mewomo, 2023). Zanni et al. (2017) advocate adopting Building Information Modeling (BIM) as a transformative tool that supports sustainable, resilient, and retrofit design by enabling clear roles, responsibilities, and collaborative workflows across project phases. A critical principle involves integrating building information modeling (BIM) technologies to enhance sustainable project delivery by facilitating informed decision-making and stakeholder collaboration. This BIM-enabled process enhances decision-making by integrating sustainability criteria with resilience considerations, such as lifecycle performance and adaptive capacity. Pan et al. (2017) further expand on this by demonstrating how automated and robotic construction techniques can contribute to sustainable building delivery, offering precision and efficiency that reduce waste and improve overall structural robustness. These technological interventions underscore the role of digital innovation in synchronizing sustainability with resilience and integrating building information modeling (BIM) technologies to enhance sustainable project delivery by facilitating informed decision-making and stakeholder collaboration (Khaddaj and Srour, 2016).. BIM-based tools (e.g., Bentley AECOsim Building Designer, Tekla Structures, Autodesk Revit Architecture, Structure, MEP, and Navisworks) can manage various data inputs (e.g., 3D designs, energy models, schedules, cost estimates) and provide comprehensive simulation and visualisation capabilities in an integrated format, allowing engineers and contractors to efficiently monitor and manage their projects (Khaddaj and Srour, 2016).

Implications for Research, Practice, and Policy

The implementation of smart retrofits must be tailored to the local building context, material availability, and socio-economic dynamics. Practitioners must take an interdisciplinary approach and use digital tools such as BIM and AI for real-time energy management, risk mitigation, and life cycle cost optimisation. Policy must support the standardisation of sustainable and resilient building codes, incentivise green retrofit initiatives, and promote capacity building through knowledge-sharing platforms and cross-sector collaboration. Legislation should also require performance-based retrofit audits as part of building fulfillment. Future research should prioritise the development of integrated performance assessment frameworks that combine resilience metrics with environmental and economic indicators. Long-term case studies and simulation-based research can provide insights into the long-term viability of new materials and technologies under different climatic and operational stresses.

CONCLUSION

This systematic review analysed the development and integration of sustainable and resilient building practices. It emphasised innovative design principles and retrofitting strategies that align with the global imperatives of climate adaptation, carbon reduction, and structural resilience. The research highlights the increasing role of advanced technologies such as Building Information Modelling (BIM), artificial intelligence, and optimisation tools that enable the seamless integration of sustainability and resilience across the building lifecycle. Key trends such as bio-

based and performance-oriented materials, compact and thermally efficient architectural forms, and digital energy modelling and risk analysis innovations have proven crucial for sustainable construction. The findings confirm that sustainable and resilient design is no longer a theoretical ideal, but a practical necessity to mitigate environmental impact, improve occupant wellbeing, and ensure the long-term functionality of buildings in times of increasing climate variability. Guided by robust performance criteria, smart technologies and policy alignment, retrofits represent an economically viable and environmentally sustainable way to transform existing structures into adaptable, low-carbon, high-performance facilities. This report argues for a paradigm shift that treats sustainability and resilience as interdependent pillars of building performance essential to achieving climate goals and protecting urban infrastructure. The future of construction lies in adaptive, intelligent, and regenerative design, where buildings are built to last and thrive.

ACKNOWLEDGEMENTS

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Techno-Economic Analysis of Off-Grid Hybrid Renewable Energy Systems for Remote Sub-Communities in Alaska and Hawaii: Impact of Building Envelope Upgrades

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ABSTRACT

This study investigates the techno-economic feasibility of Hybrid Renewable Energy Systems (HRES) for sub-communities in Alaska and Hawaii. The analysis identifies the most cost-effective configurations for each location by using Energy Plus to generate hourly energy demand profiles and HOMER Pro for optimizing hybrid systems. For Alaska, the optimal system integrates wind, photovoltaics (PV), and a diesel generator, achieving a Levelized Cost of Energy (LCOE) of $0.327/kWh. This is 27.2% lower than a diesel-only system and 56.9% lower than a 100% renewable configuration. In Hawaii, the most cost-effective system relies on a larger PV array with smaller diesel backup, returning a LCOE of $0.355/kWh, which is 12.3% below the local utility rate.

Upgrading the building envelope from its current condition (modeled based on the median age of construction) to the 2025 IECC standard reduced annual energy demand by 17.9% in Alaska and 4.3% in Hawaii and lowered the Net Present Cost (NPC) of the optimal systems by approximately 18% and 5%, respectively. This demonstrates the significant value of building efficiency in high-load, severe climates.

INTRODUCTION

As the global energy landscape shifts towards resilience, the energy needs of remote and isolated communities remain a critical and overlooked challenge. These regions vary widely in geography and climate but often share common challenges: limited energy infrastructure, high costs for imported fuels, and increased vulnerability to natural disasters (National Laboratory of the Rockies 2023). Many of these communities rely heavily on diesel generators for electricity, which poses environmental challenges (Rahman et al. 2016), and increases economic strain due to volatile and expensive fuel supply chains (Mohammed et al. 2014; Mokhtara et al. 2020). Moreover, diesel generators are becoming a less attractive option due to the rapid depletion of fossil fuel resources worldwide and the logistical challenges of transporting fuel to remote areas (Li et al. 2022). Where extending the electric grid is impractical due to high capital and infrastructure costs, such as in the vast and harsh landscapes of Alaskan villages, off-grid energy strategies become a necessary alternative. When off-grid strategies rely on renewable energy

systems like wind and solar, they offer localized and sustainable power solutions. Generating energy near the point of use reduces the need for extensive transmission infrastructure and minimizes losses along the way.

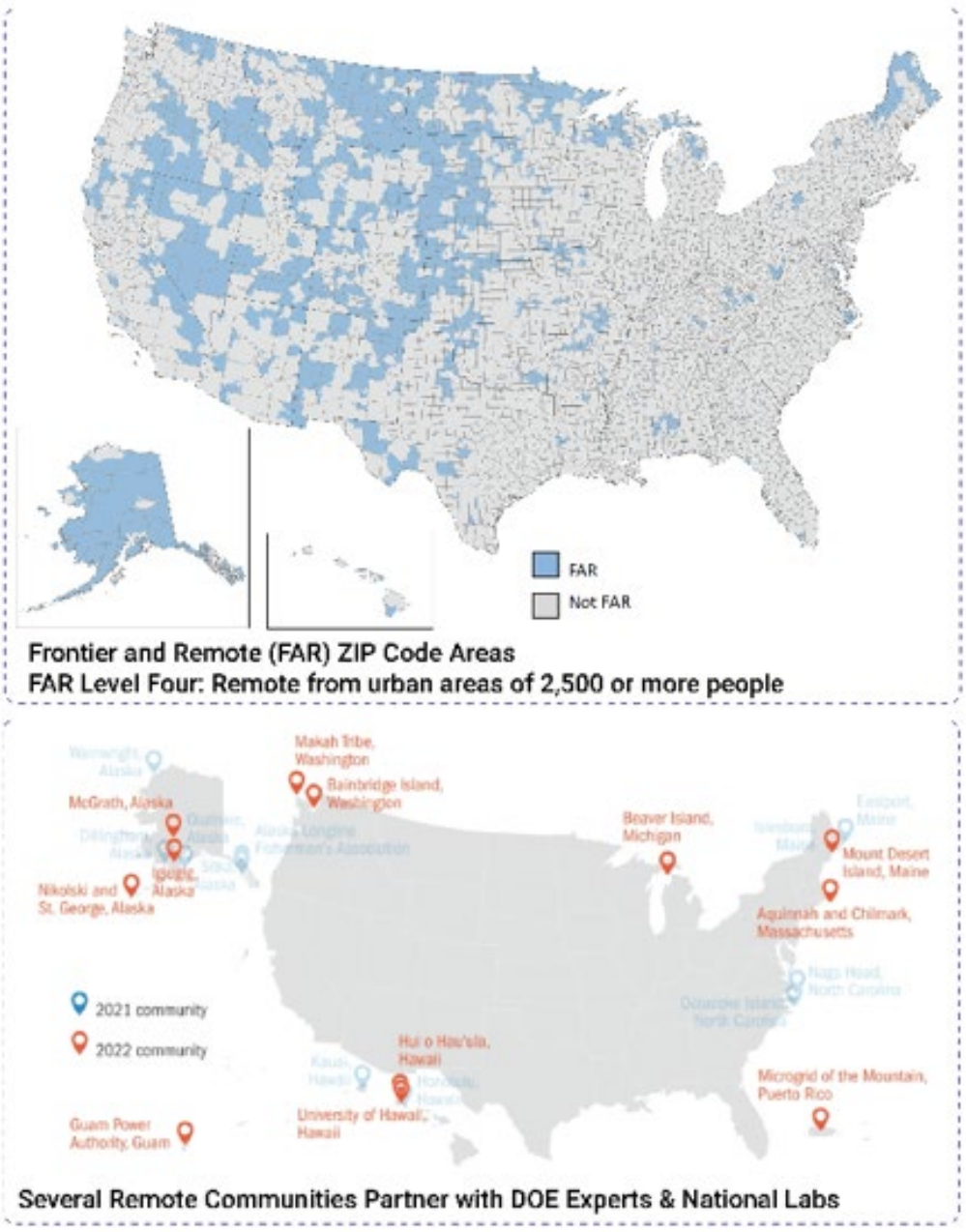

Figure 1 Selection of remote communities. Map sources: U.S. DOE ETIPP (National Laboratory of the Rockies 2023), USDA ERS (U.S. Department of Agriculture, Economic Research Service 2000).

By adopting decentralized systems, communities can lower monthly energy costs, build resilience against long-term outages, and reduce dependence on fragile or unavailable traditional infrastructure (Emiralioglu et al. 2024; Ahmed et al. 2024). However, maintaining year-round reliability, resilience, and thermal comfort can be challenging for households relying on a single technology in off-grid settings, especially in regions with high heating demands (Hu and Augenbroe 2012). Furthermore, dependence on a sole energy solution often results in system over-sizing, which increases upfront investment costs and leads to long payback periods, making such systems economically impractical (Sen and Bhattacharyya 2014; Ren et al. 2019). This highlights the importance of Hybrid Renewable Energy Systems (HRES), which employ a blend of energy sources and technologies to ensure reliable, secure, and high-quality power generation, cost reduction, and minimized inconvenience (Goel and Sharma 2017).

Addressing these challenges, this study aims to design and evaluate off-grid hybrid renewable energy systems tailored for remote communities in the U.S. facing high energy burdens and infrastructure limitations. It focuses on identifying optimal combinations of renewable technologies that balance energy reliability, cost-effectiveness, and environmental performance. Moreover, the analysis evaluates how upgrading existing building envelopes of homes in these communities to the 2025 IECC standard affects energy demand, system costs, and component sizing.

METHODOLOGY

Study Regions: To ground this analysis in real-world relevance, the focus is placed on two remote states, Alaska and Hawaii (Figure. 1), where such systems are both urgently needed and federally prioritized. The selection of these states was guided by three key criteria: 1) Geographic Remoteness, determined using the U.S. Department of Agriculture's Economic Research Service (ERS) Frontier and Remote (FAR) Level Four classification, which identifies areas located far from urban centers with populations of 2,500 or more (U.S. Department of Agriculture, Economic Research Service 2000); 2) Federal Prioritization, as both Alaska and Hawaii were included in the U.S. Department of Energy's 2023 Energy Transitions Initiative Partnership Project (ETIPP) (National Laboratory of the Rockies 2023), which supports remote and island communities in building resilient energy systems; and 3) Energy Burden, with Alaska ranking first nationally in per capita energy expenditures and consumption (U.S. Energy Information Administration 2025a), and Hawaii facing the nation's highest residential electricity rates (U.S. Energy Information Administration 2025b) (Table 1). The distinct climate conditions, energy demands, and policy support of the two selected study regions make them ideal testbeds for assessing the feasibility and performance of community-scale hybrid systems.

Table 1. Annual Energy Demand (kWh) for Each Site.

State	Consumption per Capita (Rank)	Expenditure per Capita (Rank)	Electricity Residential Rate (cents/kWh)
Alaska	1	1	24.74
Hawaii	48	9	40.51

Selected Sub-Communities: Within these two states, Wainwright, Alaska, and Kalawao County, Hawaii (Kalaupapa) were selected as representative case studies (Figure 2). Both communities face similar challenges of isolation, high energy costs, and dependence on imported diesel fuel. According to the 2023 American Community Survey, the total number of housing units in Wainwright, Alaska is 186 (U.S. Census Bureau 2025), while Kalawao County, Hawaii, with Kalaupapa as its only settlement, has 95 housing units (U.S. Census Bureau 2023); nearly all of which are 1-unit detached homes in both communities.

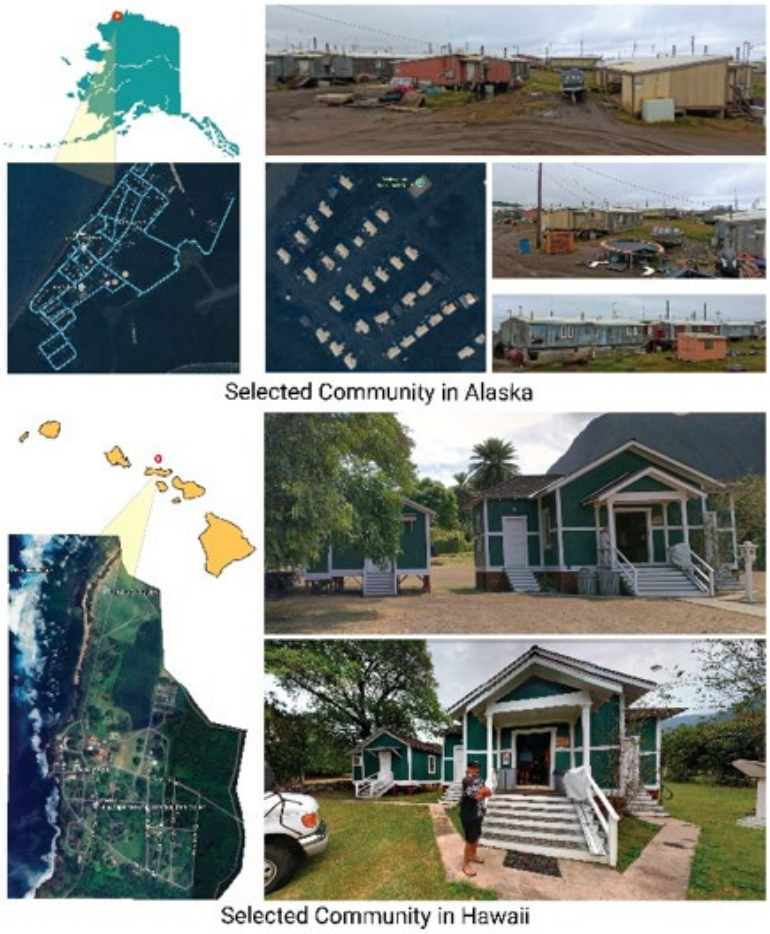

Figure 2. Selected Sub-Communities in Alaska and Hawaii.

The median year of construction is 1978 in Wainwright (U.S. Census Bureau 2025) and 1939 in Kalawao County, which shows the historic and preserved nature of Kalaupapa (U.S. Census Bureau 2023). Wainwright, with no electric utility grid, relies heavily on diesel oil for heating (North Slope Borough 2014). Kalaupapa's aging 1969 electrical system frequently fails due to deteriorated transformers, frayed lines, and damaged poles (U.S. Department of the Interior 2025). Therefore, about 85% of Kalaupapa's electricity is generated by diesel-powered systems, with the remaining 15% supplied by solar energy (U.S. Department of the Interior 2024).

Estimation and Validation of Hourly Energy Demand: Hourly energy demand for a sub-community of homes in the selected villages of Alaska and Hawaii was estimated using EnergyPlus. Based on the Thermal Characteristics of Homes document (National Association of Home Builders Research Foundation 1977) and building configurations representative of the median construction age in each region (1978 for Alaska and 1939 for Hawaii), the following assumptions were made for existing building envelopes, as presented in Table 2. Because both sites are remote and located in low-income areas, premium insulation materials and advanced construction methods were not considered.

In all the models, the following are assumed:

- Attic space and garage zones are not considered in energy calculations.
- All homes within a community have the same equipment and schedules.

Table 2. Estimated Thermal Properties of Existing Homes in Wainwright, Alaska, and Kalaupapa, Hawaii.

Building Component	Wainwright, Alaska	Kalaupapa, Hawaii
Exterior Wall	R-14	R-3
Roof/Ceiling	R-18	R-2
Floor	R-9	R-5
Window	Single glaze, U-value 1.1	Single glaze, U-value 1.1
Window Material	wood	wood
Door Material	wood	Aluminum
Insulation	None	None

Other key inputs included diesel fuel for heating, occupancy schedules, and heating and cooling setpoint temperatures, based on regional household practices. To evaluate the impact of improved building efficiency on hybrid system sizing and costs, simulations were run comparing the existing community conditions (modeled on median construction year) against an upgrade to the 2025 IECC envelope standard.

Table 3 presents the annual energy demand (kWh) for each site, calculated for building assemblies reflecting the median construction year, and assemblies designed to meet 2025 IECC prescriptive requirements. Adopting 2025 IECC building envelope requirements reduced annual energy demand by 17.9% in Alaska (from 92,858 kWh to 76,225 kWh) and by 4.3% in Hawaii (from 19,145 kWh to 18,320 kWh) compared to the median construction-year baseline.

Table 3. Annual Energy Demand (kWh) for Each Site.

Site	Alaska 1978	Alaska 2025	Hawaii 1939	Hawaii 2025
Total Energy [kWh]	92,858	76,225	19,145	18,320

Figure 3 shows the baseline monthly energy demand for the existing sub-communities in Alaska (1978) and Hawaii (1939).

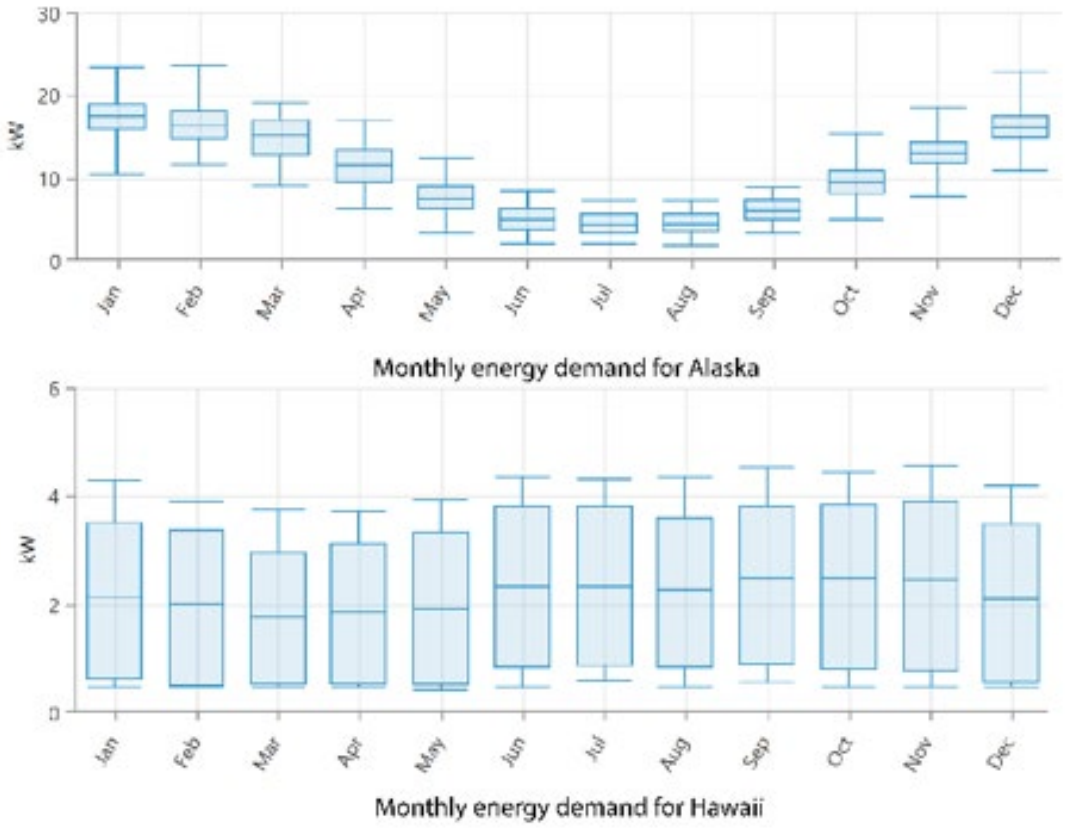

Figure 3. Simulated Monthly energy demand for Alaska (1978) and Hawaii (1939) from Energy Plus.

Simulating Hybrid Systems: To design hybrid systems, we used the Hybrid Optimization of Multiple Energy Resources (HOMER® Pro) software (UL Solutions, n.d.). HOMER Pro is an optimization and simulation software that determines the most cost-effective system configuration by minimizing the Levelized Cost of Energy (LCOE) and identifying the lowest total Net Present Cost (NPC) (Abdin et al. 2024). NPC represents the present value of all costs incurred over the system's lifetime, such as capital cost, replacement, operation and maintenance (O&M), fuel, emissions penalties, and grid purchases, minus any revenue, including salvage value and grid sales. It is calculated using equation 1 (Dawoud et al. 2018).

$$NPC = (C_{ann,tot})/(CRF(i,R_{proj})) \quad \text{(Equation 1)}$$

where NPC is total net present cost in $, $C_{ann,tot}$ is total annualized cost in $/year, CRF is capital recovery factor, *i* is the interest rate in % and R_{proj} is project lifetime in years. In HOMER Pro, capital cost (or initial capital cost) is defined as the total installed cost of a component, including purchasing, shipping, and installation, occurring at the beginning of a project.

LCOE represents the average cost per kilowatt-hour (kWh) of useful electrical energy produced by the system. It is calculated by dividing the system's annualized cost by the total useful electric energy generated, as shown in equation (2) (Amutha and Rajini 2016).

$$COE = (C_{ann,tot})/(Eprimary + E\ deferrable + E\ grid,sales) \quad \text{(Equation 2)}$$

where COE is cost of energy, $C_{ann,tot}$ is total annualized cost in $/y, $E_{primary}$ is primary load served (AC and DC) in kWh/y, $E_{deferrable}$ is deferrable load served in kWh/year, E_{grid}, sales is total grid sales (Amutha and Rajini 2016). The components used for the design of the system in HOMER Pro, along with their associated cost specifications, are summarized in Table 4. The components include Photovoltaic (PV) panels, wind turbines (Generic 10 kW), diesel generator, Lithium-Ion (Li-ion/LI) batteries (1kWh and 100 kWh) and converter.

Table 4. Summary of System Components and Their Cost Specifications Used in HOMER Pro.

Components	Capital Cost ($)/kW	Replacement ($)/kW	O&M Cost kW/year	Reference
Photovoltaic (PV)	1,492	1,119	21	(National Laboratory of the Rockies 2024)
Wind Turbine (Generic 10 kW)	50,000	50,000	500	(U.S. Department of Energy, n.d.)
Battery (Li-ion)	300	300	38	(Cole 2023)
Converter	300	300	10	(Abdin et al. 2024)
Diesel Generator	500	500	0.03 /op. h	HOMER

Maximum annual capacity shortage (%), unmet demand, is considered 0 for all scenarios. Table 5 presents the component lifetimes and system sizing for the sub-communities in Alaska and Hawaii.

Table 5. Component Lifetimes and System Sizing for Alaska and Hawaii.

Components	Sizing for Alaska	Sizing for Hawaii	Lifetime
Photovoltaic (PV) (kW)	0, 5, 10, 15, 20, 25	0, 5, 25, 50, 100, 150, 200	25 years
Wind Turbine (Generic 10 kW)	Homer Optimizer	Homer Optimizer	20 years
Battery (Li-ion) (kWh)	Homer Optimizer	Homer Optimizer	15 years
Converter/Inverter	Homer Optimizer	Homer Optimizer	15 years
Diesel Generator (kW)	0, 150, 200, 250, 300, 350, 400, 500	0, 50, 100, 150, 200	15,000 h

Seven design scenarios were simulated by varying the combination of system components (Figure 4).

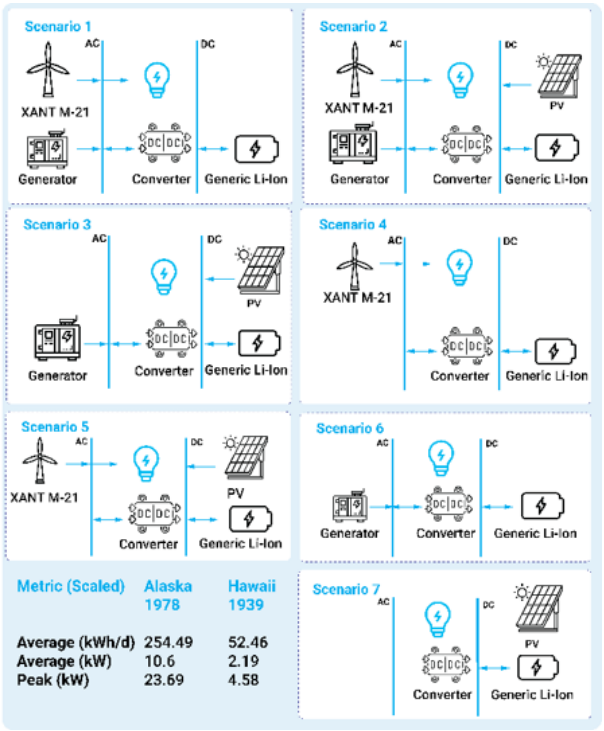

Figure 4. Various system architecture scenarios considered in the analysis, (Icons: Flaticon).

RESULTS AND DISCUSSION

Table 6 details the optimal (most economically viable) system design and component sizes for each scenario. A Design ID uniquely identifies each building scenario by combining three elements: the State Acronym, the median construction year (or "2025" for the latest code), and a distinct letter.

Table 6. Summary of System Component Sizing for Each Scenario.

Sub-Community	Scenario	Design ID	PV (kW)	Wind G10	Diesel (kW)	1kWh LI	100LI (kWh)	Converter (kW)
Alaska 1978	2	**AK78-A**	5	2	25		1	15.6
	1	**AK78-B**		2	25	26		15.3
	3	**AK78-C**	25		25		1	15.4
	6	**AK78-D**			25	20		14.3
	5	**AK78-E**	5	8			7	41.0
	4	**AK78-F**		8		649		51.9
Alaska 2025	2	**AK25-A**	5	2	25		1	14.62
	1	**AK25-B**		2	25		1	15.17
	3	**AK25-C**	25		25		1	14.72
	6	**AK25-D**			25	21		14.35
	5	**AK25-E**	5	6			6	35.13
	4	**AK25-F**		7			6	26.50
Hawaii 1939	3	**HI39-A**	25		5	37		4.88
	2	**HI39-B**	5	1	5	9		4.27
	1	**HI39-C**		1	10	18		4.13
	6	**HI39-D**			5	1		0.27
	7	**HI39-E**	50				1	4.49
	5	**HI39-F**	25	1		56		4.74
	4	**HI39-G**		1		2		4.25
Hawaii 2025	3	**HI25-A**	25		5	30		4.90
	2	**HI25-B**	5	1	5	9		4.38
	1	**HI25-C**		1	5	12		3.92
	6	**HI25-D**			5	2		1.09
	7	**HI25-E**	50				1	4.51
	5	**HI25-F**	25	1		43		4.68
	4	**HI25-G**		1			2	4.15

Comparative Energy Production by System Component: Figure 5 provides a comparison of energy production by diesel generators, PVs and wind turbines for each scenario in Alaska and Hawaii. Systems configuration and energy production can be different for the same input energy demand, especially when relying 100% on clean technologies (e.g., AK78-E or HI25-F). This is

mainly because systems are designed oversized to ensure reliability throughout the year. Furthermore, diesel generators' production plays a larger role in the overall energy production for the sub community in Alaska than in Hawaii, due to its harsher climatic conditions. Similarly, wind turbine production is more dominant than PV production in Alaska, whereas the opposite applies to Hawaii due to their different solar and wind patterns.

For the sub-community in Hawaii, 100% reliance on solar energy (e.g., HI39-F) can be feasible, while a 100% reliance on wind energy is possible for both Alaska (e.g., AK25-F) and Hawaii (e.g., HI39-G).

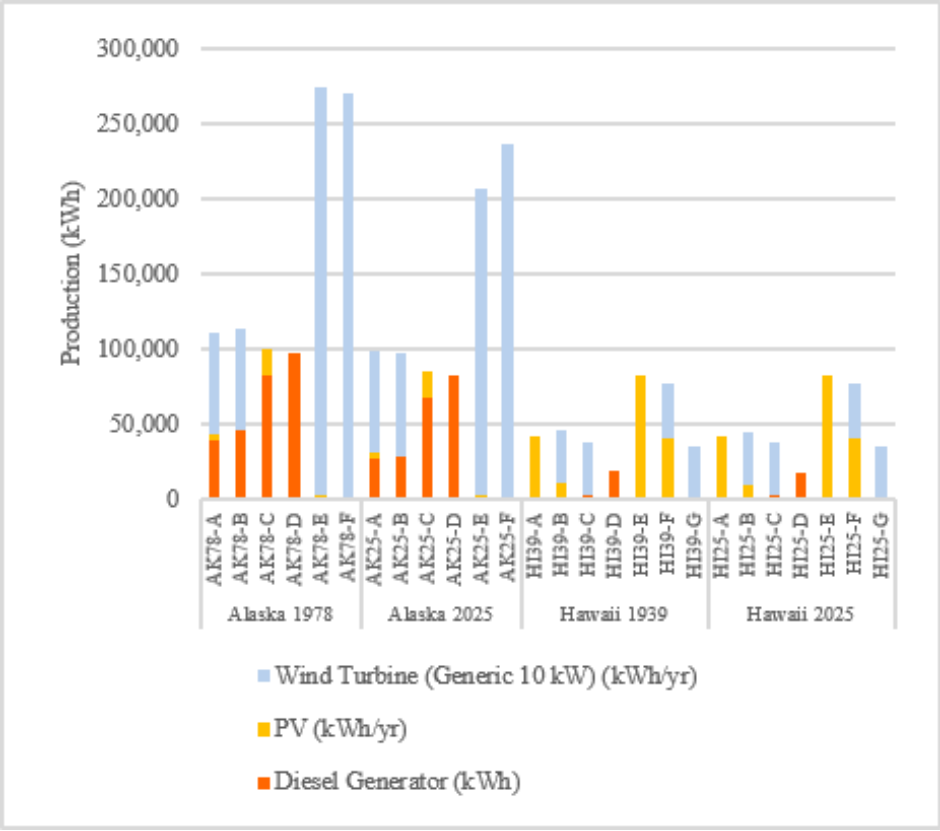

Figure 5. Comparative Energy Production by System Component.

Optimal Hybrid Configurations: Economic performance of the systems for both sub communities are presented in order of increasing NPC in Table 7. For the Alaskan community, the most economically feasible configuration is AK78-A, which includes wind turbines, PV panels, diesel generators, batteries, and a converter, with an NPC of approximately $393,000. Upgrading the building envelope to meet the 2025 IECC standard reduced the NPC for the same energy system scenario to $334,340, a reduction of 15% from the baseline. The most cost-effective option for

Hawaii is HI39-A, consisting of a larger photovoltaic (PV) array, supported by a smaller diesel generator, batteries, and a converter, with NPC of approximately $87,700. In the Hawaiian scenario, the building envelope upgrade reduced the NPC to $80,829, a reduction of 8% from the baseline cost of $87,781. The most economically optimal configuration for Alaska shows the importance of including a proportion of diesel generation (i.e., 35%) to enhance system stability and reduce NPC.

On average across all scenarios, upgrading to the 2025 IECC building envelope standard reduces the system's NPC by approximately 18% for the Alaskan sub-community and about 5% for the Hawaiian sub-community (Figure 6). This shows that the financial benefit of improved building efficiency is substantially greater in harsh, high-load climates. Since these results are derived from a small-scale community, the total savings in energy demand and system cost would be considerably larger if the 2025 IECC building envelope standards were adopted across a full community.

Table 7. Economic performance of system configurations for Alaska and Hawaii.

Sub-Community	Design ID	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)
Alaska 1978	AK78-A	392,682	0.33	18,413	154,654
	AK78-B	406,332	0.34	21,772	124,879
	AK78-C	513,003	0.43	33,154	84,411
	AK78-D	539,536	0.45	39,972	22,801
	AK78-E	910,822	0.76	21,742	629,749
	AK78-F	1,115,565	0.93	39,088	610,259
Alaska 2025	AK25-A	334,340	0.34	13,923	154,347
	AK25-B	334,868	0.34	14,528	147,052
	AK25-C	443,638	0.45	27,803	84,217
	AK25-D	470,074	0.48	34,575	23,105
	AK25-E	727,611	0.74	17,762	497,998
	AK25-F	777,622	0.79	18,540	537,951
Hawaii 1939	HI39-A	87,781	0.35	2,740	52,364
	HI39-B	100,036	0.40	2,792	63,940
	HI39-C	108,075	0.44	3,592	61,639
	HI39-D	119,001	0.48	8,982	2,881
	HI39-E	143,245	0.58	2,885	105,947
	HI39-F	159,516	0.64	4,177	105,522
	HI39-G	171,656	0.69	4,671	111,275
Hawaii 2025	HI25-A	80,829	0.34	2,364	50,271
	HI25-B	96,417	0.41	2,510	63,973
	HI25-C	97,991	0.41	3,150	57,276
	HI25-D	111,652	0.47	8,372	3,428
	HI25-E	143,255	0.60	2,885	105,955
	HI25-F	147,863	0.62	3,578	101,605
	HI25-G	171,613	0.72	4,670	111,244

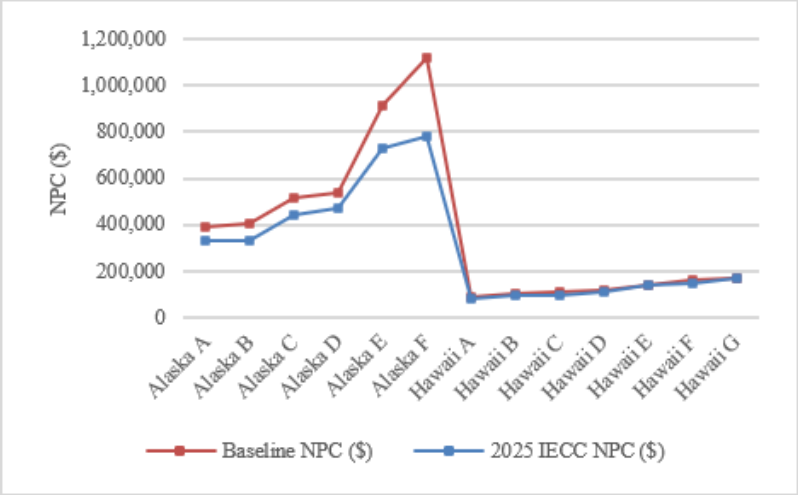

Figure 6. Effect of upgrading to the 2025 IECC building envelope standard to lower NPC.

LCOE Comparison of Hybrid, Renewable, and Diesel Systems: For the sub-community in Alaska, LCOE of the most optimal configuration is $0.327/kWh, 27.2% lower than the diesel-only configuration ($0.449/kWh) and 56.9% lower than the 100% renewable system ($0.759/kWh), though it remains 32.4% higher than the local utility rate of $0.247/kWh (Figure 7 & Table 7). Furthermore, the most optimal hybrid system is significantly lower than the typical expense for diesel-generated power in remote Alaska, which, according to a U.S. Department of Energy (2019) report, ranges from $0.50 to over $1.00 per kWh (U.S. Department of Energy 2019).

The most-cost system designed for the Hawaiian sub-community achieves an LCOE of $0.355/kWh. The cost of this optimized setting undercuts the local utility rate of $0.405/kWh by 12.3%. Attained LCOE is 26.2% cheaper than operating a diesel-only setup and represents a 38.7% cost saving over a 100% renewable system.

Across both communities, the 100% Renewable configuration results in the highest LCOE, followed by the Diesel-Only systems. The LCOE for both strategies exceeds the local retail electricity rate. This shows that neither a purely fossil-fuel-based nor a purely renewable system is the most economically viable solution for these remote communities.

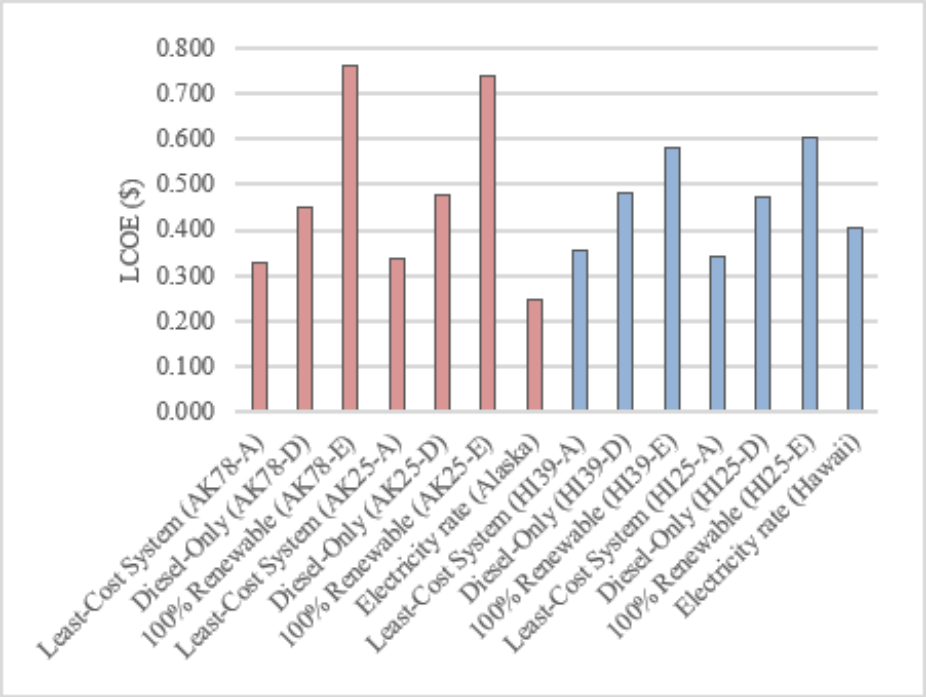

Figure 7. Renewable fraction and annual CO_2 emissions (kg/yr) for each scenario.

Economic and Environmental Impacts of Full Renewable Integration: The data (Figure 8) shows a strong, non-linear inverse relationship where CO_2 emissions approach zero only as the renewable fraction nears 100%. The results suggest a clear, three-way relationship between cost, carbon emissions, and renewable energy penetration. For a system to achieve 100% renewable operation and zero annual CO_2 emissions, a significant cost premium is required, as shown by the high NPC of the AK78-E/F and HI39-E/F/G scenarios. Conversely, the most economically optimal designs for each community (e.g., AK78-A and HI39-A) achieve a lower NPC but at the expense of higher emissions, with renewable fractions between 50-96% (Table 7). This demonstrates a direct trade-off: reducing emissions towards zero exponentially increases system cost, while minimizing cost necessitates accepting a substantial carbon footprint.

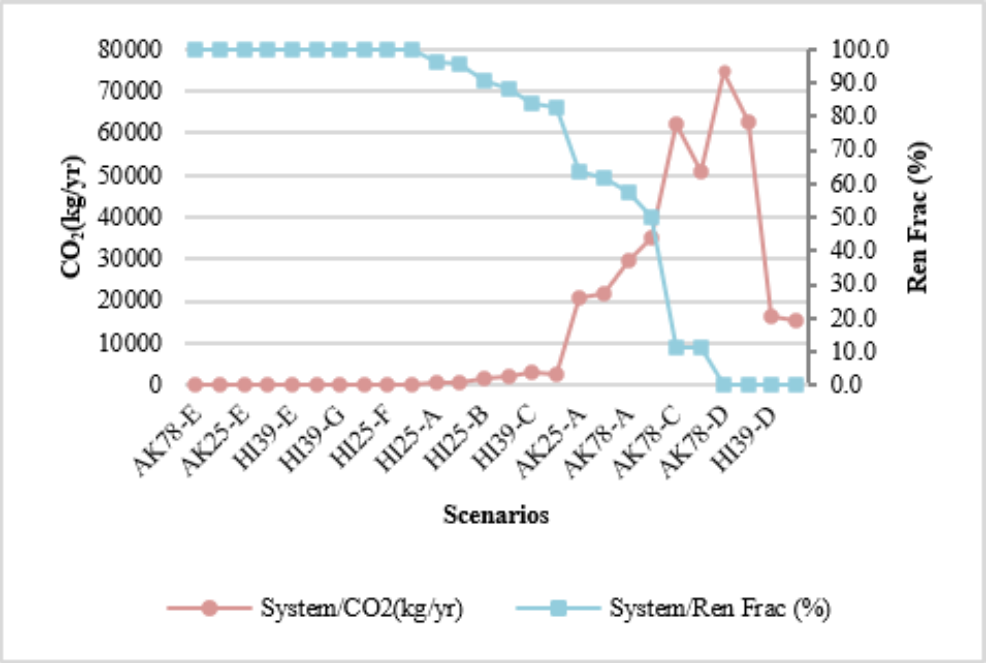

Figure 8. Renewable fraction and annual CO_2 emissions (kg/yr) for each scenario.

The data confirms that optimizing for only one objective leads to suboptimal outcomes in the other two. Therefore, effective energy policy for off-grid settings should aim for a balanced system design that intentionally weighs and combines economic viability, energy reliability, and environmental sustainability. In developed regions like Australia, Canada, and the United States, studies have explored trade-offs between cost and emissions. In Canada, increasing the share of renewables reduced emissions but raised costs, up to $1.48/kWh in fully renewable setups, while diesel-heavy systems remained cheaper but environmentally detrimental (Rahman et al. 2016).

CONCLUSION

This study demonstrates the potential of hybrid renewable energy systems as an economically and environmentally viable alternative to conventional diesel power for remote U.S. communities. The analysis identifies specific optimal configurations for each context: for the Alaskan community, system AK78-A (wind, PV, diesel, batteries) achieves the lowest NPC (~$393,000), showing the value of retaining a portion (35%) of diesel generation for stability and cost-effectiveness. For Hawaii, system HI39-A (a larger PV array with smaller diesel support) is most cost-effective, with an NPC of ~$87,700.

LCOE further reveals the advantage of hybrid energy systems. Alaska's optimal system achieves an LCOE of $0.327/kWh, significantly lower than diesel-only or 100% renewable options, though still above the current local utility rate. In contrast, Hawaii's optimal system achieves an LCOE of $0.355/kWh, which is 12.3% lower than the local utility rate and cheaper than both

diesel-only and 100% renewable setups. Notably, purely fossil-based or purely renewable systems resulted in the highest costs in these off-grid settings, confirming the economic superiority of a hybrid approach.

Upgrading existing building envelopes to meet the 2025 IECC standard reduces annual energy demand by 17.9% in Alaska and 4.3% in Hawaii. This reduction directly lowers system costs, cutting NPC by approximately 18% and 5% for the Alaskan and Hawaiian sub-communities, respectively. The savings are particularly impactful in harsh climates and would likely be substantially greater when scaled from our modeled sub-community to an entire settlement. These findings highlight that effective energy policy cannot optimize for a single goal. A practical, resilient strategy requires balanced trade-offs among affordability (NPC), reliability (firm capacity), and decarbonization (CO_2 reduction) to design socially acceptable systems. Future work should focus on two key areas: first, evaluating demand-side management strategies like peak load moderation and behavioral load shifting to lower system sizing and costs. Second, research should explore the potential of emerging technologies, including hydrogen storage systems, to enhance renewable integration and grid reliability, with particular attention to reducing their NPC and LCOE over time.

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Visualizing the Invisible: Virtual Reality Aids for Residential Energy Understanding

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ABSTRACT

Since energy is invisible to the human eye, misconceptions about its utilization can quickly go unnoticed, leading to misevaluations. There is an opportunity to reimagine how energy data is displayed to residents using virtual reality. Energy data can be embedded within visual aids in the virtual environment to showcase energy consumption throughout household appliances. This study aims to determine how participants interact with energy data embedded within visual aids in the virtual environment. Research has shown that our brain immediately processes color, shape, size, and orientation when viewing a visualization, which informed the design of the three visual aids used in this study: (1) color coding, (2) electricity flow, and (3) power meter. 32 participants answered interview questions regarding reading and arguing with energy data of household appliances. The interview results showcased that residents' ability to read and argue differed between the visual aids and appliance types they encountered. For reading, participants understood the color coding and power meter visual aids but had trouble understanding the electricity flow aid due to the wagon wheel effect. And for arguing, participants found the power meter most effective when creating a narrative for evidence, due to their ability to quantify the insights. While participants ability to use the color coding and electricity flow were subjective to the participants' understanding. This study emphasizes exploratory finding to understand what virtual visual aids are effective for visualizing residential energy data.

INTRODUCTION

Visual aids enhance digital twins and extended reality representations, revealing different interpretations of energy invisible characteristics impacting residents' energy awareness. Residential energy data is commonly communicated to residents on utility bills utilizing a line, bar, or pie chart, with energy consumption quantified using the frequently misunderstood metric of kilowatt-hour. Even at the magnitude of one thousand, the naked eye cannot see watts flowing through the copper wiring of a home. Furthermore, the Kilowatt hour is plagued by the complexity of power (watt) being first averaged, then multiplied by a period time (hour). Time is

another invisible yet quantifiable metric philosophers, and scientists have argued about well before America's relatively recent late 1800s integration of electricity into homes. Power utilities need the support of researchers to overcome the challenge of communicating a billing cycle of energy use, with varying amounts of time, into an understandable justification of energy charges to consumers.

Implementing digital twin technology and other data visualization theories provide a practical path toward increasing societal energy awareness and potentially influencing energy behavior change. A person's energy awareness ability is a result of there energy, graphical and data literacy levels. In addition, understanding kilowatt-hours is still a misconception that impacts residents' home energy performance (Anderson and White 2009; Costanza et al., 2012). To combat the misconceptions of energy terms and insights, digital twins' technologies have the power to inform residents of the effects of their energy consumption behaviors. A digital twin of a home provides a realistic representation of energy consumption insights of time-enhancing communication of energy data by increasing legibility. There is an opportunity to utilize digital twin technologies to present energy insights to residents, impacting their awareness levels. With digital twin technology, energy can be visualized to showcase energy consumption amount of household appliances. This study aims to determine how individuals read and argue appliance energy consumption data embedded within three visual aids. The three visual aids include color coding, electricity flow, and the power meter.

This study's results are critical to understanding the complex social learning process. As expected, communication effectiveness is very contextual depending on the appliance energy use pattern and visual aid capability. The power meter visual aid was the most understood due to the participants' ability to quantify energy consumption outcomes in the number of blocks. Participants had trouble quantifying the electricity consumption rates when viewing the dynamic animation representing "electricity flow" due to the speed of motion. The participants needed clarification when answering questions using the color gradient to show static lighting energy data. However, participants were spot on when answering questions using dynamic cooking and heating energy data using the electricity flow and power meter. This paper's results and discussion sections discuss other takeaways from the experiment. This research attempts to showcase the power of visual aids in virtual reality, creating a new perspective that cannot be displayed feasibly in reality.

Research Questions:

> How can displaying energy data using visual aids in a digital twin environment impact a resident's ability to read and argue energy consumption data?
>
> Read: How are participants extracting energy information from the visual aids?
>
> Argue: How are the participants utilizing virtual visual aids to argue or justify a statement?

BACKGROUND

Presenting energy data to residents in general schematic limits their understanding of energy consumption throughout their homes. Utility companies have standardized how energy consumption data is shared with residents. Standardization prevents residents from fully comprehending the energy data displayed on the utility bills because residents' interpretation differs based on literacy levels. Energy, graphical, and data literacy contribute to a person's understanding of energy insights from data visualizations. These are the main branches of literacy that enable a person to read, work with, analyze, and argue energy data embedded within data visualizations. This research study will explore two of the four categories, observing how residents read and argue energy consumption data within visual aids. Below, the two main categories are operationalized:

> To operationalize the read action: Reading involves extracting a single data point or element that is an obvious answer from the data visualization.
>
> To operationalize the argue action: Arguing involves creating a narrative from the data visualization components to provide evidence to support.

Many individuals lack the technical expertise to read and argue energy data charts (Mataloto et al. 2021). Besides using 2D visualization chart types, virtual reality (VR) creates a new perspective, allowing residents to perceive energy spatially which enhances their cognitive understanding in the learning experience. VR bridges the gap between theoretical and practical applications by providing users with dynamic 3D representations of a object, in this case energy which is difficult to display in reality (Kavanagh et al., 2017). The energy data was displayed using three visual aids in the digital twin environment, centered around our understanding and processing of object proprieties. Our brain immediately processes color, size, and orientation when viewing a visualization (Cleveland and McGill 1986; Ware 2004; Archambault et al. 2015). For the research study, the three visual aids included color coding, electricity flow, and power meter to display and compare the energy consumption data of 3 pairs of appliances.

Color

Color is a channel used to convey information. "Color is described as the single most valuable characteristic in appreciating and responding to the visual world around U.S. (Adkins and Pease 1991)". Every time a color changes, the user is informed that significant changes have occurred (Wong 2010). Utilizing color in the energy domain can provide the same alert effect that individuals experience in the real world. In the energy domain, color has been used to capture the residents' attention and impacts understanding for comparing energy consumption of the appliances (Bonino, Corno, and De Russis, 2012). In this research study to convey energy insights to residents, color coding was utilized. Color coding is defined as using color to represent a specific unit or ranges of metrics (Skulmowski, 2022). Besides color, size and orientation are two other elements that our brain processes immediately when viewing a visualization.

Size

Depending on the size of an object, conclusions can be made without the need for metrics. Embedding metric within the size of an object allows for quick observations to be made. To convey energy data insights to residents in this research study, I utilized a power energy meter in the virtual environment. A power energy meter represents an animated bar chart in the virtual reality environment. The height of the power energy meter corresponds to the amount of energy consumed in a given moment by the appliance, which resembles a bar chart. And lastly, orientation is the last element our brain immediately processes when looking at a visualization.

Orientation and Movement

Circuits in our home provide a pathway for energy to move throughout a home, providing appliances with electricity. The movement of electricity is invisible to the human eye. With virtual reality, that pathway can be revealed, exposing electricity flows to residents. The electricity-flowing visual aid was utilized in the virtual environment to visualize the movement of energy consumption insights. The electricity flow visual aid mirrors the energy flow through a wire. The electricity flow visual aid is speed-dependent; the slow, medium, and fast pace will respond to low, medium, and high energy consumption levels. With virtual reality, energy insights can be observed by the human eye, creating awareness for residents to understand how energy is consumed throughout household appliances.

Conceptual Framework

The digital twin environment can aid or hinder residents' understanding of household appliances energy consumption insights utilizing the three visual aids. A resident's ability to read and argue energy data embedded within the visual aids is a result of their literacy levels and life experiences with digital twin technologies.

Residents' familiarity with digital twin technologies contributes to their ability to understand the visual aids. Residents' ability to read and argue the (1) effects of color change, (2) movement as electricity flow through a wire, and (3) changes in the size of the power meter contributes to their ability in understanding the amount of energy consumed.

METHODS

Research Approach

- First, participants were randomly assigned an appliance category: lighting, cooking, or heating. The author switched participants to another appliance pair if they had no knowledge of the assigned to appliance pair. Thirty-two participants participated in the research study, 11 for lighting, 11 for cooking, and the remaining 10 were assigned the heating category.

- Next participants encountered the three visual aids in the virtual environment one at a time and answered interview questions retaining to reading and arguing the energy data embedded within. The author read the interview questions while the participants

answered the questions while interacting with the virtual environment. The participant responses were recorded using a desktop microphone.

- After participants finished with one virtual aid, the Oculus Quest headset was removed, and the author loaded the next virtual aid, until participants experienced all three visual aids.

Participants

Due to time constraints, 32 graduate students from Virginia Tech in a variety of departments served as participants for this study. The authors acknowledge that using graduate students could introduce potential bias. However, participants without prior knowledge of virtual environments and knowledge of energy consumption behavior of appliances did not have an advantage that would influence the results of the research study.

RESEARCH MATERIAL

Virtual Environment

The virtual environment was created in Unity, a game engine platform. The virtual model includes a fully furnished home with three pairs of appliances, shown in Figure 1. The Three appliance pairs included lighting (LED vs incandescent bulb), cooking (air fryer vs stove), and heating (space heater vs heat pump). Energy consumption data was visualized using three visual aids: (1) color coding, (2) electricity flowing, and (3) power meter.

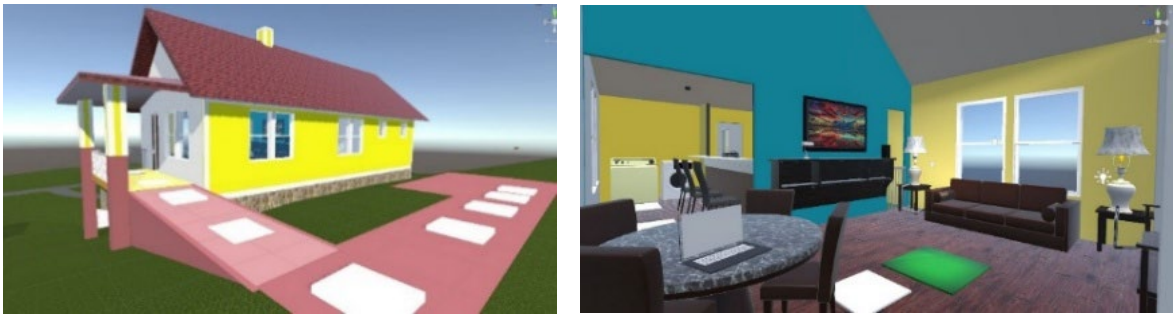


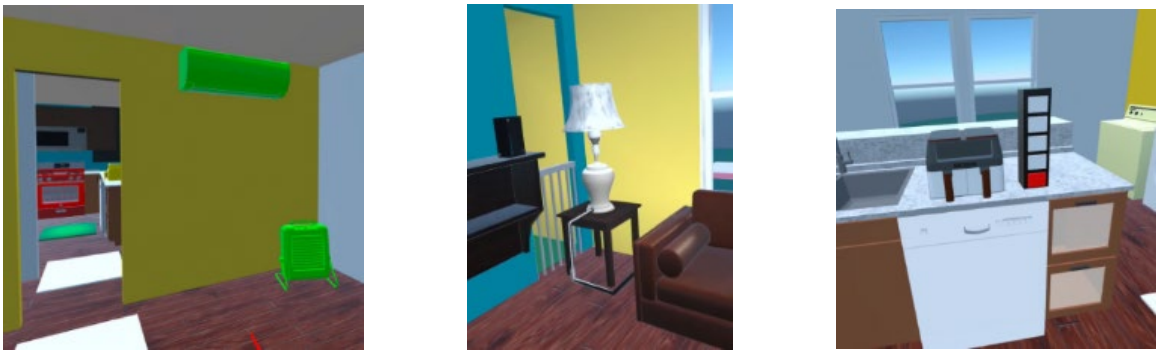
Figure 1. Outside and inside of the home in the unity game engine platform.

Color-Coding

For the color-coding visual aid, appliances change from green, displaying low, yellow, displaying medium, and red, displaying high energy consumption levels (Mataloto et al., 2021). Since appliances consumed energy differently specific intervals had to be assigned in relation to the color coding, shown in Figure 2.

Electricity Flow
For the electricity flow visual aid, the speed of the flow responds to the amount of energy consumed, shown in Figure 2. The electricity flow is made up of a 2D image displaying an arrow. The 2D image is wrapped onto the material of the wire in the virtual environment. Then the 2D image is animated to create movement, portraying energy flowing through a wire.

Power Meter
For the power meter, the number of blocks lit up responds the amount of energy consumed, shown in Figure 2. The power meter was constructed using five identical blocks stacked on top of each other to form a bar.



A. **B.** **C.**

Figure 2. A. Displays the color-coding visual aid on the heating appliances, the heat pump on the wall green in color and the space heater on the floor red in color. B. Displays the incandescent bulb with the electricity flow visual aid shown in the wire going from the wall outlet to the lamp. C. Displays the power meter visual aid next to the air fryer on the countertop.

DATA COLLECTION

Semi-Structured Interviews
Semi-structured interviews were conducted to capture the residents' experience with the visual aids in the virtual environment. The goal of using semi-structured interviews is to discover critical experiences from the residents' interactions with the data visualization format.

Semi-Structured Questions:
Color Coding
Read: What colors are shown on the appliance 1, then appliance 2?

Argue: How would you provide evidence to argue or justify the following statement: Johnny believes that the Appliance 1 consumes more energy than the Appliance 2. [The same question for argue was asked for the other visual types]

Electricity Flow
Read: How is the electricity flowing through the wire to the appliance 1, then appliance 2?

Power Meter
Read: How many blocks are used in the power meter for the Appliance 1, then how many have used in the Appliance 2?

DATA ANALYSIS

First Cycle Coding Method - Descriptive Coding
Descriptive coding was performed to searched and analyzed the transcript to reveal how residents were able to read and argue the energy data embedded within the visual aids.

Descriptive Coding Summarizes Participants Responses into Short Phrases
Most often as a noun (Saldaña, 2018). Descriptive coding is the groundwork needed to be performed from a researcher proceeds to the second round. Description is the foundation for qualitative coding analysis, its purpose is to assist the reader to see what you saw and to hear what you heard (Wolcott, 1994). After the initial descriptive codes have been collected, the second coding method pattern coding was utilized to create themes.

Second cycle Coding Method - Pattern Coding
Themes are needed to convey important insights for participants reading, working with, analyzing, and arguing the energy data, which was done using pattern coding for the second cycle coding method. Pattern coding the second cycle coding method produces themes of the important insights around reading and arguing to be convey to others. Pattern coding summaries into a smaller number of sets, themes, or constructions (Miles and Huberman, 1994). Pattern codes pull together material into a smaller number of more meaningful units (McLeod, 2024). "Pattern coding has four important functions: (1) it condenses large amounts of data into a smaller number of analytic units, (2) it gets the researcher into analysis during the data collection stage, (3) it helps the researcher elaborate a cognitive network, and (4) it lays the groundwork for cross-case analysis surfacing common themes and directional processes" (Miles, Huberman, and Saldaña, 2020).

Intercoder Reliability
Intercoder reliability was performed to validate the first and second cycle coding methods. The first author Dr. James was responsible for developing the codebook to evaluate the short phrases in the first round and to identify themes in the second coding round. Dr. Paige the second author reviewed the initial codebook to check the relation of the phrases and themes with the raw data. Involving another researcher in the coding process will ensure the validity of this research study.

RESULTS

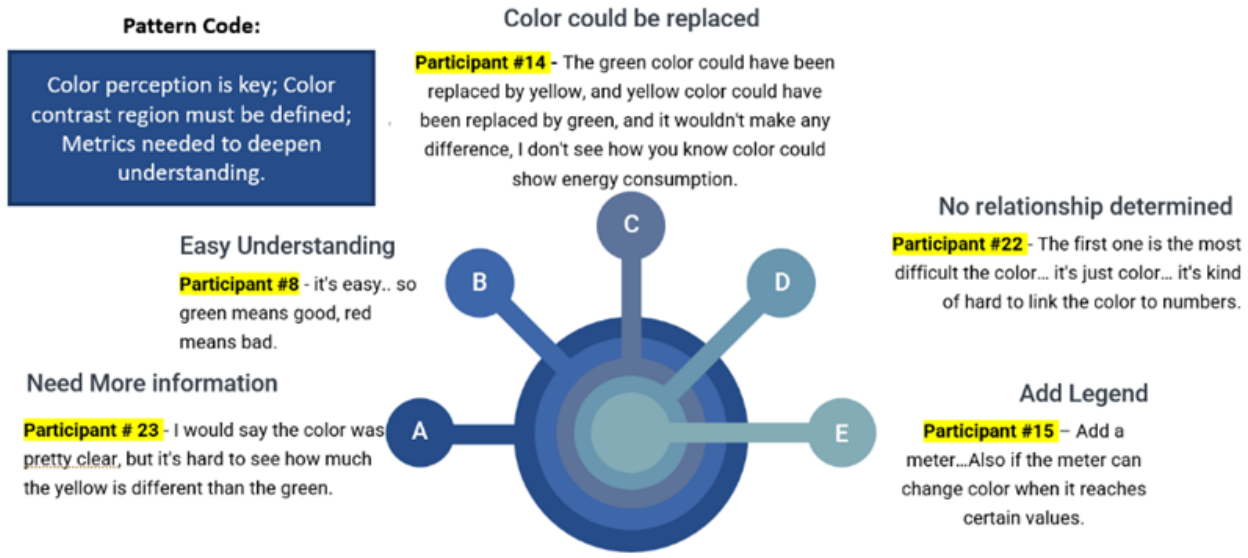


Figure 3: Displays the raw data gathered from multiple participant interviews, with the descriptive codes above, and the pattern code generated from the analysis.

DISCUSSION

The discussion section reveals how participants could read and argue the energy data embedded with the visual aids. Reading involves extracting a single data point or element that is an obvious answer from the visualization. Arguing consists of creating a narrative from the visualization components providing evidence to justify or go against that claim. The discussion will further explore the experiment process, explaining how participants responded to each utilizing the three visual aids: color coding, electricity flow, and the power meter.

Read

Participants read all the colors displayed on the appliances, providing color can utilized to show distinct changes in energy consumption. There were a few chases when participants had trouble reading the color on appliances, which was when the entire appliance was not color coded. Noting that when using color coding as a visual aid the entire appliance should be colored to reduce distractions.

When viewing the electricity flow visual aid mixed views were received from participants reading how electricity was flow through the wire to the appliance. Once the speed of the electricity flow reaches a certain level the wagon wheel effect came into play, causing participants to see the flow moving in two different directions. Some participants saw the energy flowing "from the outlet to the appliance," and others saw the flow going in the opposite

direction. In addition, other participants classified the electricity flow as burst of lights, energy packets, among other things.

Participant #28
Well, it's interesting because it like, it almost seems like it's moving in the other direction. So, where it starts at the wall, it goes to the heat pump… It's almost starting at the space heater and then going to the wall, the direction of the gray lines.

When reading the power meter participants were asked to determine how many blocks were used to display energy insights. Three opinions merge from the analysis either, participants counted the total number of blocks lit up at a moment in time, counted the number of white and red blocks, or mentioned the lit-up block sequence. Participants responses were related to the appliance type they were assigned, due to the use of static and dynamic data produced by the appliances. Next the discussion section will discuss how participants were able to use or not used the visual aids to in justifying and arguing against statements.

Argue
Participants were able to argue by providing evidence using the visual aids to as justify for comparing the energy consumption of two appliances. Color coding was successful when participants associated green, yellow, and red with corresponding low, medium, and high energy consumption levels, respectively, shown in Figure 3. However, if participants did not have a preconceived notion of the green, yellow, and red representing low, medium, and high. Participants could not use the color-coding visual aid as evidence to compare energy consumption differences.

Participant #17
The stove has a red color, so it shows that the stove has more energy consumption compared to air fryer

For using the electricity flow visual aid, participants could not always tell which appliance was consuming the most energy because the electricity flow speed looked the same in serval instances. Once the electricity flow speed reached a certain threshold, the human eye could not see the difference in speed, due to the wagon wheel effect. Therefore, participants compared the time interval in which the flow was moving versus not moving for evidence. In addition, if the flow never stopped (like the lighting appliances because the energy consumption is constant), participants could not create a stance to argue or justify because the flows look identical.

And lastly, participants using the power meter, participants compared the peak or average number of boxes for each appliance to provide evidence. The power meter was the most apparent visual aid when arguing because participants could quantitatively compare the number of boxes used as evidence. Unlike the color-coding visual aid, where participants already had to have a pre-established relationship to understand the implications of color. Of the three visual aids explored in this research study the power meter has been proven the most effective to showcase energy data insights.

CONCLUSION

Implementing residential energy data within visual aids in the digital twin has pros and cons for reading and arguing about energy insights from household appliances. Participants were asked to read the visual aids to identify the features within the visual aids. The power meter provided the best evidence because participants could quantify their response by comparing or averaging the number of blocks utilized. The electricity flow and the color-coding visual aids were challenging when using as evidence because they were subjective to the participants' understanding. The findings suggest that utilizing visual aids to display energy insights is effective when aligned with user preferences. Aligning visual aids with a person's understanding increases energy awareness and lessens confusion. This paper emphasizes exploratory findings informing residents of appliances' energy consumption insights without displaying raw energy data consumption metrics. Embedding energy metrics within tailored visual aids enables residents to comprehend energy insights, positively impact their energy awareness levels. The study's findings give new insights into the domain of energy data visualization capabilities by utilizing three visual aids color coding, electricity flow, and power meter in digital twin space.

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