



2022 RESIDENTIAL BUILDING DESIGN & CONSTRUCTION CONFERENCE PROCEEDINGS

MAY 11-12, 2022

UNIVERSITY PARK, PENNSYLVANIA, USA

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Edited by Dr. Ali M. Memari Sarah Klinetob Lowe

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



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PREFACE

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

It is with great pleasure that we share the proceedings of the 2022 Residential Building Design and Construction Conference, which was held virtually on May 11–12, 2022. As in the past five RBDC Conferences, this sixth conference provided an opportunity for researchers, design professionals, manufacturers, builders, and code officials to exchange the latest advancements in research and practice and to discuss and share their own findings, innovations, and projects related to residential buildings.

The 2022 RBDC Conference hosted 85 attendees and included 61 papers, 60 presentations, and 10 posters on various issues related to residential buildings, which encompass single- and multi-family dwellings, mid-rise and high-rise structures, factory-built housing, dormitories, and hotels/motels. Papers and presentations related to the following areas and topics were invited in the conference call:

- Aging-in-Place and Senior Living Housing
- Alternative Renewable Energy Generating Systems
- Building Information Modeling (BIM) Application in Residential Construction
- Building Integrated Photovoltaic Systems
- Building Performance Assessment/Metrics/Verification Methods and Occupant Behavior
- Building Science and Building Enclosures
- Education of Residential Design & Construction
- Energy Efficient Building Components
- Fire Damage and Protection
- High-Performance Residential Buildings
- Indoor Air Quality
- Innovations in Green Roofs and Façade/Envelope Systems
- Innovations in Residential Architecture and Design
- Innovations in Modular and Manufactured Housing
- Innovative and Emerging Housing Construction Methods/Systems
- Innovative Wall, Floor, Roof, Window, and Siding Systems
- · Learning from the Performance of Residential Buildings under Natural Disasters
- · Low-Income and Affordable Housing
- Net Zero Energy Homes
- Panelized Building Components
- Passive House Design Approach
- Resilient New Design and Retrofit of Existing Buildings under Natural Disasters
- Retrofit of Existing Buildings for Energy Efficiency
- Rural Housing Materials and Construction
- · Serviceability and Life Safety Damage Aspects
- · Smart Home Technologies, Design, and Construction
- Sustainable Housing Construction Materials and Methods
- Temporary Housing for Disaster Situations
- Whole Building Design Approach

As the Table of Contents of these proceedings show, many of the above areas were among the papers and presentations at the conference. There was considerable interest in topics including building envelope, building in Alaska, building science education, disaster resilience, hemp, high-performance housing, innovative and affordable housing, mass timber and CLT, mechanical and lighting systems, occupant behavior, retrofits, and tools for homebuilders.

Two keynote speakers were invited for the conference: Wil V. Srubar III, Ph.D., associate professor at the University of Colorado Boulder and founder and managing director of Aureus Earth, Inc. and Rusty Smith, associate director of the Rural Studio at Auburn University's School of Architecture, Planning, & Landscape Architecture. Srubar discussed his presentation titled "Transforming Buildings into Carbon Sinks." Smith shared his presentation titled "Rural Studio: What Does Affordable, High-Performance Housing Truly Afford?" The conference also hosted a closing plenary session by Jack Hébert, founder of the Cold Climate Housing Research Center and senior research advisor at the National Renewable Energy Laboratory, entitled "Indigenous Wisdom and 21st Century Technologies: An Arctic Approach to Building Science."

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

Proceedings Editors: *Ali M. Memari and Sarah Klinetob Lowe* May 2022







CONFERENCE SCHEDULE

w	WEDNESDAY, MAY 11					
Keynote: Dr. Wil V. Srubar, III Associate Professor, University of Colorado Boulder 8:15am ET - 9:30am ET Title: Transforming Buildings Into Carbon Sinks Opening Remarks by Dr. Ali Memari & Sarah Klinetob Lowe						
9:45	am ET - 10:15am ET	Virtual Networking Session				
10:	30am ET - 12:00pm ET	Conference Sessions A				
	Innovative & Affordable Housing	Building Envelope		Building Science Education		
10:30-11:00	High-performing technologies for contemporary residential Rural buildings in the Pianura Padana territory Silvio Brunoro (University of Ferrara)	Multi-chamber Standardized Testing of Air- permeable Cladding Materials Oscar Lafontaine & David O. Prevatt (University of Florido)		Introductions, Overview, and Where Are We. <u>Now?</u> Georg Reichard (Virginia Tech), Pat Huelman		
11:00-11:30	Catenary domes for housing: benefits and challenges Ryan Bradley (University of Witwatersrand)	Performance of OSB and SFS Shear Walls in Residential Building Shideh Shadravan (University of Oklahoma), Behnam Shadravan (Florida A&M University), & Chris Ramseyer (University of Oklahoma)		(University of Minnesota), & Sam Taylor (Energy & Resource Efficiency)		
11:30-12:00	THE USE OF ARTIFICIAL INTELLIGENCE TECHNIQUES FOR PREDICTING COMPRESSIVE STRENCTH FOR HIGH PERFORMANCE. CONCRET: A REVIEW Refliwe Lediga & Jeffery Mahachi (University of Johannesburg)	An Innovative, High-performance Shell Structure for Residential Construction: The SPS System Rolf Jacobson; Dan Handeen; Pat Huelman; Garrett Mosiman; Tom Schirber		Beyond Boundaries: Education to Advance the Transformation of the Architecture, Engineering, Construction, and Operations Industry Jonathan Bean (University of Arizona) & Sarah Truitt (NREL)		
12:	12:00pm ET -12:30pm ET LUNCH BREAK					
12:	30pm ET - 2:00pm ET	Conference Sessions B				
	Disaster Resilient Housing	Mechanical & Lighting	Mass Timber & CLT	Building Science Education		
12:30-1:00	Observations and Analysis of wind pressures. on roof overhangs and underneath walls of a low-rise building Korim Mostofa (Florida International University), loannis Zisis (Florida International University), & Ted Stathopoulous (Concordia University)	Balance Points are Changing – and That's Just Sensible! Pat Huelman (University of Minnesota)	Parametric Evaluation of Embodied Carbon within Design for Hybrid Mass Timber Floor Systems Samantha Leonard, Ryan Solnosky, Nathan Brown, & Corey Gracie-Griffin (Penn State)	Resilience and Social Justice as a Framework for Architectural Education. Research and Practice – The Design+Build Kunga ADU Jörg Rügemer (University of Utah)		
1:00-1:30	Analysis of Complex Flow Characteristics from. Field and Simulated Hurricane Measurements Jianing Wong & Chelokara Subramanian (Florida Institute of Technology)	Development of Smart Watering Algorithm To Improve Biowall Performance William Hutzel (Purdue University)	Structural Design of a Cross-Laminated Timber. (CLT) Single-Family Home Anthony Jellen (Jellen Engineering Services) & Ali Memari (Penn State)	Facilitating Real-World Project-Based Service- Learning Opportunities by Participating in. Department of Energy Race to Zero and Solar Decathlon Competitions Jeremy Farner (Weber State University)		
1:30-2:00	CASE STUDIES OF BUILDING RESILIENCE IN <u>HURRICANES</u> Behnam Shadravan (Florida A&M University) & Shideh Shadravan (Oklahama University)	Machine learning based surrogate model for faster davlighting estimation in building design Noveen Kumon Muthumanickam (NREL). José Pinto Duarte (Penn State), & Tim Simpson (Penn State)	Moisture Vapor Buffering and Latent Heat Effects of CLT Insulated with Wood Fiber Insulation Assembly on Energy Swing Ling U (Inwersity of Maine), Jake Snow (Linwersity of Maine), Moltam Alabba (University of Maine), Samuel V Glass (Forest Service FPL), Benjamin Herrag (University of Maine), & Stephen Shaler (University of Maine)	Continued Experiences with the Solar Decathlon Design Challenge Tom Collins (Boll State University)		
2:15	5pm ET - 2:45pm ET	Poster Session **See Next Tab**				
3:0	Opm ET - 4:30pm ET	Conference Sessions C				
	Innovative & Affordable Housing	Occupant Behavior	Нетр	Building Science Education		
3:00-3:30	Frame House System: An Open-Source Housing Design and Construction System Puja Bhagat, Celina Deng, & Benay Gürsoy (Penn State)	Case Study: The Effect of Homeowner. Behavior on Energy-Efficiency in a High- Performance Home Lindsey Beates (Beates Properties) & Jason Lucas (Clemson University)	Use of Industrial Hemp and Bamboo Fiber in Construction Dan Hindman, Tom Hammett, & Jonas Hauptman (Virginia Tech)	Bicking Equation A Build's Colours		
3:30-4:00	How to Make Zero Energy Ready Pencil Out at the Production Scale Eric Werling (US DOE), Kevin Brazyna (Insight Homes), & Thereso Gilbride (PNNL)	Impact of Occupant Characteristics on the Energy Performance of Multifamily Residential Building in the United States Debrudra Mitra, Yiyi Chu, & Kristen Cetin (Michigan State University)	Critical Review of the Characterization of Environmental and Mechanical Properties of Hemp Hurd and Hempcrete Hojoe VI, Corey Gracie-Griffin, & Ali Memari (Penn State)	Education Nowcase/Nowdown Panel Education Showcase/Nowdown Panel Georg Reichard (Virginia Tech), Jonathan Bean (University) of Arizona), David Fannon (Northeastern), Walter Grondzik (Ball State University), Bruce Haglund (University of Idaho), Pat Huelman (University of Minnesota), Ulivike Passe (Iowa State University), & Brian Wolfgang (Penn State)		
4:00-4:30	Discussion of Tiny Home Inclusion as a Concentric Diversification Strategy in. Production Home Building to Address Housing Crisis Molly Smith, Wei Wu, Yupeng (Vivien) Luo, & Micheler Randel (California State University, Fresno)	Development and validation of a post- occupancy evaluation model for LEED-certified residential projects Mohsen Goodarzi (Ball State University) & George H. Berghorn (Michigan State University)	Modeling of 3D printing Concrete based on Meshfree Explicit Galerkin Analysis Method Aleksandra Radiinska, Hanbin Cheng, Feihong Liu, & Michael Hillman (Penn State)	,		

Thursday, May 12

8:1	5am ET - 9:30am ET	Keynote: Rusty Smith Associate Director, Rural Studio at Auburn University Title: <u>Rural Studio: What Does Affordable, High-Performance Housing Truly Afford?</u> Opening Remarks by Dr. All Memari & Sarah Klinetab Lowe			
9:45	5am ET - 10:15am ET	Virtual Networking Session			
10:	30am - 12:00pm ET	Conference Sessions D			
	Innovative Housing	Retrofits	Tools for Homebuilders	Disaster Resilience	
10:30-11:00	A Multi-manufacturer Platform Approach to Modular Volumetric Construction – An Experiment in Cross-polinating Design with Fabrication Carlo Carbone (Université du Québec à Montréal)	Application of refractive fluid flow imaging. techniques for visualizing building exfitration Philip Boudreaux, Emishaw iffa, & Venkat Singanallur (ORNL)	Creating a Virtual Environment Data Collection Tool for Construction Safety Daniel Hindman, Leann Rhodes, Rafael Patrick, Alicia Johnson, & Todd Ogle (Virginia Tech)		
11:00-11:30	Design Grammar of Scaffold-Free 3D Printed Shells Mohan Motamedi (ENSAPM, Laboratoire GSA), Shadi Nazarian (Penn State), Romain Mesnil (ENPC, Laboratoire NAVIER), Robin Oval (University of Cambridge), & Olivier Baverel (ENPC, Laboratoire NAVIER)	Drone-based scanning technology for characterizing the geometry and thermal conditions of building enclosure system for. fast energy audit and design of retrofitting strategies Shoyan Mirzabeigi (SUNY ESF), Parisa Eteghad (SUNY ESF), Mohamed Razkenari (SUNY ESF), Paul Crovello (SUNY ESF), & Jianshun Zhang (Syracuse University)	Likeliness to Recommend: A Mixed Methods. Analysis of Consumer Perceptions of Home. Builders Todd Usher & Jason Lucas (Clemson University)	Transdisciplinary Perspectives on Equitable, Sustainable, Resilient Housins: Panel. Discussion & Moderated O&A Stacey Connaughton (Purdue University), Mohamed Hilmi (InterAction), George Foden (Loughborough University), Steht Obonyo (Penn State)	
11:30-12:00	UTILIZING ARTIFICIAL INTELLIGENCE FOR DESIGNING CEMENT-BASED MATERIALS FOR. 3D CONCRETE PRINTING APPLICATIONS Refliwe Lediga & Jefferey Mahachi (University of Johannesburg)	Energy Modeling to Determine Optimum Order of Component Installation in Stepwise. Retrofit Towards EnerPHit Standard Sophia Welch, Esther Obonyo, & Ali Memari (Penn State)			
12: 12:	00pm ET -12:30pm ET 30pm - 2:00pm	LUNCH BREAK Conference Sessions E			
	High Performance Housing	Retrofits	Building in Alaska	Disaster Resilience	
12:30-1:00	Site Net Zero Target Contemporegional Architecture – The Barn Haus in Utah Jörg Rügemer (University of Utah)	Comparine, Affordable, Durahle and Energy, Efficient Vull Betroft Systems Chrisi Antonopoulos (PMNL), Pett Gunderson (PMNL) Tyder Plett (PMNL), Thor Sahley (PMNL), Pat Huelman (Inuversity of Minasota), Antonio Aldykiewicz (ORNL), Garett Mosiman (University of Minnescuti, Arachi Nagda (PMNL), Cherny Metzgre (PMNL), Ardre Desjardis (ORNL), & Rolf Jacobson (University of Minnescuti)	Design of homes for concrete printing in the permafrost regions of Alaska José Duarte, Goncalo Duarte, Nathan Brown, Shadi Nazarian, & Ali Memari (Penn State)	Building for Energy Efficiency and Disaster. Resistance: Complementary Goals, Most of the Time Edward Louie, Chrissi Antonopoulos, & Theresa Gibride (PNNL)	
1:00-1:30	The Intersection of Passive House and Affordability in Cold Climate Residential Construction Christopher Wingate (MSR Design) & Sean Sonnabend (AKF Group)	Hygrothermal simulation of exterior retrofits. In a cold climate Antonio Aldykiewicz (ORNL), Andre Desjarlais (ORNL), Pat Huelman (University of Minnesota), & Garrett Mosiman (University of Minnesota)	Structural Evaluation of a proposed concrete. 3D printed Habitat in remote Alaska Gonçalo Durate, Ali Memori, Natthon Brown, José Duarte, & Zhengyu Wu (Penn State)	A parametric investigation of canopy heat islands mitigation strategies: A case study of a new residential development master plan of a U.S. north-eastern city Forzad Hashemi, Lisa D. Iulo, & Ute Poerschke (Penn State)	
1:30-2:00	Reducing Interior Overheating of Residential Buildings by Passive Cooling Measures Michal Bartko, Abdelaziz Laouadi, & Michael Lacasse (National Research Council Canada)	Insitu Testing for PNNL/ORNL/UMN Deep Wall Insulation Upgrade Project Pot Huelman, Garrett Mosiman, Fotih Evren, & Rolf Jacobson (University of Minnesota)	A comparison of thermal insulation strategies for 3D printed concrete structures in cold regions Nothan Brown, Ali Memari, Ming Xiao, Zhengyu Wu, José Durce, Shodi Nazarian, & Gonçalo Duarte (Penn State)	Small-Scale Testing of Air Barrier Systems Adhered on Sheathing Panels Under In-plane, Relative Displacement Simulating Seismic, Effect Korim Abdelwohab, Carey Gracie-Griffin, Ali Memari, & Lisa D. Iulo (Penn State)	
2:1	5pm - 2:45pm ET	Roundtable Networking Session			

 Building In Alaska

 Retrofits
 Building In Alaska

 Building In Alaska
 Building In Alaska

 Building Durability In Extreme, Changing, Uparade Wall Insulation and Windows Ratherine Cort & Theresa Gilbride (PNNL)
 Building Durability In Extreme, Changing, Climates Zoe Kaufman, Robbin Gorber-Slaght, Tanushree Chara, & Conor Dennety (NREL)

 Determining Energy Savings for Various High, Som Meleia & Anthony Fontanini (NREL)
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4:00-4:30

A Zero-carbon Bio-based Wall Panel as an Energy Retrofit Solution for Buildings Shaphayegh Kurzinski, Poul Crowello, Mohamad Razkenari, & William Smith (SUNY ESF)

4:45pm ET - 6:00pm ET Closing Plenary: Jack Hébert| Founder - Cold Climate Housing Research Center (CCHRC) Title: Indigenous Wisdom and 21st Century Technologies: An Arctic Approach to Building Science Closing Remarks by Dr. Ali Memari & Sarah Klinetob Lowe

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Multiple benefits through residential building energy retrofit and thermal resilient design Shayan Mirzabeigi & Mohamad Razkenari (SUNY ESF)	Educating the Youth On Energy Literacy Through <u>Virtual Reality</u> Joseph James (Virginia Tech)	Practical Construction of 3D Printed Reinforced Concrete Members Zhengyu Wu & Ali Memari (Pen State)	Review of Mechanical and Structural Testing for 3D Printed Concrete Zhengyu Wu & Ali Memari (Penn State)
Resilience in Modular Construction Maryam Kouhirostami (University of Florida), Arezou Sadoughi (Appalachian State University), Mahtab Kouhirostami (University of Florida), & Robert Ries (University of Florida)	<u>Use of Plastic Waste in Building Construction</u> <u>Industry</u> Shahryar Habibi (University of Ferrara) & Ali Memari (Penn State)	Small-Scale Testing of Air Barrier Systems Adhered on Sheathing Panels Under In-plane Relative Displacement Simulating Seismic Effect Karim Abdelwahab, Corey Gracie-Griffin, Ali Memari and Lisa Iulo (Penn State)	Review of Structural Load Resisting Systems for Cross-Laminated Timber Multi-story Residential Buildings Nadia M. Mirzai and Ali Memari (Penn State)
<mark>Literature review on triodetic foundation system for permafrost regions</mark> Nima Aminpour and Ali Memari (Penn State)	3D Printing of Residential Houses by Adapting the Historical African Sustainable Housings Eden Binega and Ali Memari (Penn State)		

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High-performing technologies for contemporary residential Rural buildings in the Pianura Padana territory.

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ABSTRACT

The paper illustrates the potentialities of designing high – efficient rural buildings, by introducing innovative methodology and techniques. Sharing of services and efficient building technologies represents a growing strategy that can fulfill the goal of the 20-20-20 EU energy policies. Rural housing - homes and services built with agricultural and farming purposes - is an historical heritage in Italy, are mainly diffused in the Emilia Romagna Lombardia and Veneto Region (area called Pianura Padana). The rural real estate in this territory is now not efficiently valorized, as economic, functional and cultural constraints generally rules the design phase. The theme of the residence is then particularly insidious as it collides with preconceptions that are difficult to overcome, this both on the front of the client and of the construction companies. The main aim of the paper is to investigate the possibilities to introduce experimental contents - both in architectural then in technical issues - in reconstructing rural settlements, besides of the opportunity to build efficiently while respecting limited budgets and keeping references to traditional typologies together with the most up-to-date technological equipment and construction systems. In this paper, smallscale high – efficient rural projects are analyzed. Realized examples of young Architects (KM429, MIDE architects) are presented, showing several residential interventions where sustainable construction systems, thanks to their design sensitivity, are well integrated into very delicate rural contexts.

INTRODUCTION

The ancient rural buildings represent a testimony of exceptional historical and cultural value in Italy They are disseminated along the Pianura Padana, an Italian territory comprehended between the Emilia Romagna Lombardia and Veneto Region (Figure 1). Today such complexes are most of all abandonment and/or damaged, for many reasons, most of all the shift between rural and industrial economy and the progressive migration from country to town.

The seismic events of 20 and 29 May 2012 in Pianura Padana caused considerable damages to the rural settlements, both to agricultural activities than to the agricultural sector, and to the built heritage as a whole.

In this area, which includes more than 30 municipalities between the Reggio Emila and the upper Ferrara province, agriculture has always played an important role in terms of surface extension agricultural used and economic level reached. The earthquake has hit hard the activities and the scattered rural building fabric of the Emilian countryside. The greatest damage was recorded for historical rural courts: those complexes for which maintenance has not been continuous or that were even in a total state of decay. Moreover these complexes do not fulfil the recent standards in the field of energy efficiency [*Marangoni, 2013*].



Figure 1. An example of historical rural building in the Pianura Padana territory

The main purpose of the study is to investigate methods and examples to deal with rural architecture by introducing modern languages and efficient technologies for the reconstructing of rural settlements, respecting traditional typologies and at the same time using efficient sustainable technologies and construction systems.

The main objectives at the center of the work are :

- the management of the relationships between past and modern in the composition of the complexes buildings, linked to the agricultural landscape;
- the enhancement of the historical heritage language (re-interpretation of the preserved agricultural heritage) with new materials, methods and techniques;
- The control of the building quality, energy efficiency and budget limitations.

The study aims to suggest methods and best practices for the integration between landscape and modern rural architecture, pursuing a twofold objective: in the first place to interpret in a modern language the basic architectural and technical features of rural houses in the Pianura Padana landscape (from the typology to the landscape colors) then to upgrade to high – efficient energy standards. The use of a contemporary language and technologies do not distort the concept of rural house.

COURTYARDS AND RURAL COMPLEXES IN THE HISTORICAL CONTEXT

From the 1950s to today, the Pianura Padana rural landscape has undergone radical transformations. The evolution of the built complexes shows equally evident signs of change, legible in the growth and articulation of centers already present in the 1950s, and only more rarely in the creation of new functional nuclei for agricultural companies [*Baricchi*, 1990].

Building new settlements had more to do with the inclusion of incongruous functions, such as residential compartments and isolated production activities. The transformations have thus determined a gradual alteration of the structuring characteristics of the landscape, making homogenization inexorable with the margins

of urbanization and the trivialization of signs, tradition and memory linked to the agricultural world.



Figure 2. Main basic typologies of rural architecture in the Pianura Padana a.Courtyard. b,c. Rural farming complex

Rebuilding can be an unmissable opportunity to improve the rural landscape in its original tradition settlement as a whole, an at the same time to upgrade it to new efficient standard by using sustainable construction systems such as dry technologies, eternal thermal insulation, high – performing windows etc..

Historical rural settlements can be defined in their historical asset by the following macro-categories [*Gambi*, 2008]:

Courtyard (Figure 2 a)

This is the elementary rural unit consisting of two buildings, one intended for the tenant's home and the other used as services and storage. Other secondary buildings may be present and play a service role.

Rural farming complex (Figure 2 b,c)

It is the evolution of the elementary unit, with the inclusion of recent buildings, diversified activities and functions which make the composition and the functioning of the court more complexes: a cattle shed, machinery storage buildings agricultural, warehouses.

The main typological variations of these two macro categories, depending on the territory, can be listed as follows:

- *Bolognese typology (separate buildings)* It consists of two principal buildings of similar size arranged in a chessboard or on a single axis, quadrangular floor and with hipped roofs, one for family house home and one stable;
- Modenese typology (separate buildings)
 Is a variation of the Bolognese court, for smaller size companies It is a court where dwelling and secondary rural building are arranged perpendicular. Dwelling is general rectangular floor and is three floors high with slope roof. Stable has large dimensions due to the intense dairy cow breeding, with grated openings that give air to the barn;
- One-building typology

It is one of the oldest types spread everywhere in the area of Modena where house and secondary functions are settled under the same roof. Here the house is half-divided in vertical: a load bearing wall divides the house from the barn for fire – safety. The rural building consists of a high roof with pillars, forming a porch in front of the entrance of the stable .

MODERN RURAL ARCHITECTURE DESIGN PRINCIPLES AND REALIZED EXAMPLES

In this chapter, small-scale high – energy efficient rural projects are analyzed. Realized examples of two young Architects companies (KM429 architects, MIDE architects) are presented, showing how a careful design can address and solve the main abovementioned issues. four projects are presented, in different contexts, using sustainable - construction systems which, thanks to their design sensitivity, are well integrated into very delicate rural contexts.

Small rural architectures are diffused in the territory represented in Figure 3. The challenge is to approach to the architectural rural landscape using a modern language as well as, at the same time, respecting the typological characters, materials and colors of the tradition. The case studies analyzed are representative of a capillary network to rebuild the lost rural landscape. Most of the examples are built to replace existing rural houses severely compromised by the earthquake of May 2012.

Also it has to be highlighted that the new houses rises in one of the most evocative and characteristic areas of Italy, with a rare historical-landscape and naturalistic value, the result of the spontaneous fusion between nature and centuries-old human work. This landscape, consolidated over the centuries by a continuous rural use remained unchanged in forms and methods, has acquired a characteristic and unrepeatable aspect. [*Regione Emilia Romagna, 1986*]:



Figure 3. The Pianura Padana territory in which the modern rural settlements network is diffused.

Architectural principles and layout

The analyze projects, as representative of the above – mentioned re construction philosophy are: the 8-HOUSE located in Dosso di Sant'Agostino, the FLOWER HOUSE in San Posidonio (Mirandola, Modena), the HOUSE OF VALLEY in Novellara (Modena), HOUSE IN THE POPLAR in Scorzè (Venezia) (FIG 4,5). These are only a few group of amore diffused network of interventions spread all over the territory, with the same characteristics and intentions.

The first three houses are built on the ground of the old rural houses, destroyed by the earthquake of 2012. Behind the projects there is the desire to enhance the existing context, by re-interpreting the peculiarity of the rural buildings in a contemporary key. Design choices are made in order to respect the memory of the places, by assuming the peculiarities of the agricultural countryside, to conserve the typical image of the around landscape and at the same time to try to innovate the housing layout concept to modern requirements.



Figure 4. Case studies of modern rural buildings. 8 HOUSE, Flower House (KM429 Architects)



Figure 5. Case studies of modern rural buildings. House of Valley(KM429 Architects), House in the poplar (MIDE Architects).

Common principle is to valorize the rural typology by adopting an architectural language in line to the context, respecting design composition and the peculiar element of the rural architecture such as to have compact shapes with visual cones toward the countryside. The research of a visual deep continuity with internal and external spaces is very important, as represented in Figure 6,7,8. Other peculiar elements recalling shapes and suggestions of the tradition are the use of the porch, of large openings, of brick-clad basement, concrete or other materials of the tradition.



Figure 6. 8 House, Sant'Agostino –Ferrara (KM429 Architects). Floor plan and visual layout. The plan has been designed to try to recreate an intimate atmosphere of protection, and at the same time opening towards the countryside, framing it in reserved visual cones.

In the 8 HOUSE (FIG. 6), the entire architectural composition provides for an internalexternal dialectical relationship without boundaries, surrounded by a porch that regulates the solar gains and visual comfort. The main livable spaces, such as the living room and the dining kitchen, overlook the porch that encloses all the rooms; it is punctually marked by the presence of exposed masonry pillars in memory of the typical columns of the "barchesse", a rural service building, typical of the rural architecture. Next to it and in close dialectical relationship, is the service block characterized by the use of concrete and exposed bricks. The house develops around the dining room located at the center of the ground floor. It is sized to accommodate the extended family gathering on weekends.



Figure 7: The Flower house, Mirandola, Modena, (KM429 Architects). Floor plan and visual layout. The house is spread on over one compact ground-floor, typical of the places. In addition to the porch on which the living room and kitchen overlook, two loggias have been created to the east and west, marked by the presence of green flowerbeds.

The FLOWER HOUSE for a family of three, consists of a living room, kitchen-dining room with pantry, boiler room-laundry, three bedrooms, a bathroom and porch. The layout comprehends dedicated views from the internal rooms to outdoor spaces, that makes the architecture changing during seasonal changes. In addition to the porch on which the living room and kitchen overlook, two "intimate" loggias have been created to the east and west, marked by the presence of green flower beds, where the property can stay in total privacy, giving itself emotions of peace and relaxation, during family banquets (FIG.7).



Figure 8. The House of valley, Novellara, Modena (KM429 Architects). Floor and first plan, visual layout. The house has a compact form where the functional distribution element is reduced to the minimum surface. This choice is due on the one hand to the containment of economic costs and on the other hand aimed at maximizing the effects of thermal and acoustic insulation. Landscape, light, water and wood are the project materials

The compact shape and volume of the HOUSE OF VALLEY is spread over an area of approximately 9.15 meters x 8.40 meters with a maximum ridge height of 8.80 meters, taking up the characteristics of two-pitched roof rural buildings typical of these areas (FIG.8).. To confirm the typology of the previous building and of the Reggio Emilia rural settlements, it is spread over two levels and an attic. The main services are located on the ground floor, such as the kitchen, the bathroom, the boiler room and the cellar with the addition of a bedroom, while on the second floor the living area and another bedroom with bathroom and closet.

For the HOUSE IN THE POPLAR design (FIG.9)., the wide plot of land, bordered by a watercourse, allowed to design a single-floor building with a double pitch roof. To reduce the visual impact of the new building, the project include a T-shaped floor plan, allowing for a better orientation of the rooms, each with a different destination. the large stained glass windows in the living room permit to further enlarge the space, constantly mutating during the day. Designing and building a house in the countryside of Veneto means to interact with the building techniques of the traditional rural constructions,

choosing specific materials and recalling shapes and suggestions Some typical agricultural components, such as the spontaneous vegetation next to the porch and the wooden overhanging roof are used as solar protection devices.



Figure 9. House in the poplar. To reduce the visual impact of the new building, the project include a T-shaped floor plan, allowing for a better orientation of the rooms.

The house is characterized by a deep continuity between the internal and the external spaces and the generous natural lighting characterize the interior spaces.

Technologies

A great attention is given to the use of high – efficient technologies both in terms of sustainability than in cost – benefit evaluation. Moreover the projects' materials and surfaces have been chosen from a careful study of the site, merging the traditional and the contemporary construction techniques.

Residential rural houses are built mainly using wooden dry – technologies, without the use of water in the assembly process, by layering materials on a resistant internal frame. This construction method, has very ancient origins, and this is the first reason of its employment, besides of the recycling, optimization and respect of times/costs, construction site safety, speed, lightness.

A first family of houses, such as 8 House, flower and house of valley houses are built with wooden frame structure (FIG.10), with wooden fiber coating insulation, reaching energy A - class. In these case studies, the envelope is designed to fulfill low U-value standards. A typical layer composition is internal insulation is 8 cm of rock wool, density 50 Kg / mc and an 8 cm panel of wood fiber density 140 Kg / mc. The wall is then closed and braced by wooden - flake panels (Fig.11). The external insulation, cladding, in high-density wood fiber, for a total thickness of 4 cm, completes the stratigraphy. Besides of its structural and thermal properties, the wall is only 190 cm

thick: this is one of the most advantages of using dry technologies such as platform frame where, the use of a high – efficient thermal insulation allows to reach optimum results with very small thickness. All the external walls are completed by internal metal frame and double wooden slabs, to constitute a technical compartment for the incorporation of electrical and plumbing systems.



Figure 10. In the 8 House, the wooden fir lamellar wood frame is made of uprights and crosspieces with base beam 16x10 cm, upper beam 16x10 cm, uprights and crosspieces 16x6 cm.





Figure 11. Flower House. High performing wooden – stratified layer envelope is made of: 01 External thermal insulation wooden fiber cm 4 Thermal coat in wood fiber with shaving 02 XPS insulation layer 03 Waterproofing sheath 04 Concrete foundation 05 OSB multilayer panel 06 Lamellar starting crosspiece 07 L shaped metallic stirrups 08 Torx screws 09 Upright 10 Bracing 11 Double plasterboard panels 12. Internal rock wool insulation layer 13. Insulation inside the frame 8+8 cm wood fiber and rock wool.

The roof structure (Fig. 12) is primary beams and secondary joists in fir lamellar wood, laminate, sanded and finished with water varnish. Roof external thermal insulation is double layer of wooden fiber panel, medium density 160 mm and high – density 40 mm.



Figure 12. 8 House. The roof structure.

A second group of case studies is made by concrete technologies. As it can be seen from the section (FIG 13) a high – efficient envelope both in terms of thermal insulation and in thermal inertia is designed.

Designing and building a house in the countryside of Veneto means to interact with the building techniques of the traditional rural constructions, choosing specific materials and recalling shapes and suggestions.. The project's materials and surfaces have been chosen from a careful evaluation of the site. The building reminds the atmospheres of these places and the chromatism of the surrounding environment. The external concrete walls are characterized by a rough surface obtained with a special formwork that has the print of a typical cane field that can be found in the countryside of Veneto.

The roof of the living space is realized with timber beams recovered from the demolition of the decks of ancient villas.



Figure 13. House in the poplar (MIDE Architects). And construction section. The external envelope is, from internal to external, ma de of: double drywall slab 2,5 cm, thermal insulation rock wool 7,5 cm, vapor barrier, thermal insulation rock wool 15 cm, exposed concrete wall 35 cm.

Energy efficiency

All the case studies are labelled in A4 class that means the most performant energy class according to Italian energy efficiency standards. The estimated annual overall

energy consumption ranges between 23,13 (House of poplar) and 41,54 Kwh/m²/year (8 House). In wooden frame buildings (8 house, flower house, house of valley) the electricity production is made through photovoltaic installation, with a peak power of 3.00 kWp. The system is on the roof, exploiting the favorably exposed pitch, and consists of 1 photovoltaic generator and 12 polycrystalline silicon photovoltaic modules distributed over an area of 21 square meters. The production is estimated at 3300 kWh per year.

CONCLUSIONS

Designing high – efficient rural buildings, by introducing innovative methodologies and techniques, allows to introduce experimental contents - both in architectural then in technical issues - in reconstructing rural settlements.

In this paper, innovative residential architectures has been presented, showing how a modern language can be integrated into very delicate rural contexts and rural identity can be re- interpreted with sustainable -construction systems.

The research was carried out to investigate possible methods, addresses and examples for the valorization, enhancement and reconstruction of the rural landscape in the lower Pianura Padana, pursuing a twofold objective: on the one hand to orient the transformations by new languages , on the other hand promoting a "landscape vision" of the rural territory with integration between modern architecture and agricultural world.

A reconstruction cannot be limited to re-propose the pre-earthquake or historical state of affairs, but must seize the opportunity to offer to improve the rural landscape as a whole: improve the heritage from the point of view of seismic safety and energy efficiency.

Designing small rural architectures might be seen above all as a possible opportunity for the redevelopment and recreation of new rural landscape in the portion of the territory included in the network.

Starting from the concise and expeditious analysis of the characteristics of the landscape, of the heritage and of the resources that constitute the identity of the territory, the individuation of upgraded architectural and technical requirements has been the starting point of the design concept.

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A special thanks to MIDE Architects (www.midearchitetti.it) by courtesy of images and details of the case study HOUSE IN THE POPLAR that is published in this paper.

REFERENCES

Baricchi W. (1990) Insediamento storico e beni culturali, bassa pianura reggiana, Reggio Emilia

Gambi L. (2008) "La casa dei contadini", in Guermandi M., Tonet G., La cognizione del paesaggio. Scritti di Lucio Gambi sull'Emilia-Romagna, Bononia University Press, Bologna

Marangoni B., edited by (2013) PAESAGGI DA RICOSTRUIRE. Linee guida per la tutela, valorizzazione, ricostruzione del paesaggio rurale nella bassa pianura emiliana, Regione Emilia-Romagna, Bologna

Regione Emilia-Romagna (1986) Le case rurali, Bologna Zerbi M. C., edited by (2007) Guida europea all'osservazione del patrimonio rurale, Guerini scientifica, Milano

Catenary domes for housing: structural benefits R. A. Bradley

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ABSTRACT

Catenary shapes are well recognized as offering material and cost efficiency when applied to arches and vaults. These advantages may be particularly attractive to designers of low-rise structures, such as housing and recreational buildings, in which the entire envelope is formed with a shell. In this paper, the structural efficiency of catenary domes, of varying profiles, is presented by finite element (FE) analyses and closed-form membrane solutions. These analyses show that catenary domes experience only compressive hoop and meridian stresses under uniform vertical loads. Moreover, it is shown that steeper profiles are especially efficient due to the minimal impact of the base support (or boundary) on stress magnitude and distribution. The catenary, unlike more conventional semi-circular and ellipsoidal domes, engenders a form which matches the natural flow of stress. The fact that hoop stresses are purely compressive, in combination with minimal bending forces, make steeper profiles attractive for the implementation of conventional building materials which perform poorly in tension, e.g., masonry and concrete.

INTRODUCTION

The building industry is becoming more cognizant of the increasing need to design and construct buildings which encompass improved materials efficiency and sustainability. The choice of a particular building material may significantly impact embodied as well as operational energy (and carbon) associated with housing structures. However, it is not only material specification that is of importance: the structural form selected to resist the magnitude and type of stresses, imposed on the structure, also plays a significant role. The structural benefit associated with reduced bending and shear forces is well understood, and shell structures are particularly effective in this regard. The principal advantage associated with shells is that forces are largely transferred through in-plane action, with limited bending moments and shears at supports (i.e., boundary effects). Further structural efficiency is achievable through the implementation of funicular shells, which generate strength and stability through structural form. Catenary domes are found in some of the most iconic structures on earth, e.g., St. Paul's cathedral in London, St. Peter's cathedral in Rome and the Basilica of Sagrada Familia in Barcelona (Gohnert and Bradley, 2022). Possibly, the most well-known example is the Pantheon in Rome, which was built almost 2000 years ago. The walls of the Pantheon rotunda and concrete dome were constructed without any steel reinforcement, and the structure is still in excellent condition today. Amazingly, the Pantheon dome has a diameter of 43 m and the compression strength of the concrete used was only about 12 MPa (Brune et al., 2010). Goshima (2011) postulated, by inscribing a catenary shape on the cross-section of the dome and walls, that the Pantheon is in pure compression.

The pantheon is an example of a building designed without steel reinforcement, constructed at a large scale, and with relatively weak materials that has last two millennia.

THE CATENARY DOME

The catenary form is defined by the shape of a hanging chain, supported at the two ends, and allowed to drape naturally under its own self-weight (Figure 1a). The form is structurally optimal for arches and singly curved vaults under self-weight. Other funicular shapes are optimal for arches with of variable thickness and/or non-uniform loads, which can be obtained by means of numerical, graphical, or physical modelling techniques. For example, the profile shown in Figure 1b corresponds to the varying load distribution of a dome lune (Minke, 2009).



(a) Catenary (uniform) Figure 1. Hanging chain forms

The catenary profile for an arch or dome is mathematically defined by Eq. 1.

$$y = H - a \cosh\left(\frac{x}{a}\right) + a \tag{1}$$

where H is the apex height, and 'a' is constant which is dependent on the height (H) and base diameter of the shell (L). Gohnert and Bradley (2021) report that the value of "a" for a particular shell may be determined by balancing Eq. 2.

$$H = a \cosh(L/2a) - a$$

2

Equation 1 gives the curve for half the dome, and to complete the profile the coordinates are mirrored about the central vertical axis, as shown in Figure 2.

The base angle of the catenary is somewhat shallower than that for the hemispherical dome, as illustrated in Figure 2a, and in the case of smaller shells this would generate greater *dead space* toward the edge of the floor area. A route to reduce the extent of the aforesaid problem is to position the dome atop a cylinder wall. However, this would necessitate a ring-beam to counteract the lateral base thrust and may not be the optimal solution. These forces can be significant in heavy shell roofs (e.g., masonry), and the reported failure and collapse such domes is largely due to deficient or missing ring-beams (Bradley et al., 2018). Alternatively, *steeper* catenary profiles could be used to alleviate the issue of dead space, without significantly

increasing the surface area (and material) when compared to the more conventional forms, e.g., hemispherical and ellipsoidal domes. For example, the steeper catenary profile shown in Figure 2b has the same surface area as a hemisphere but lesser issue with the base slope of the catenary in Figure 2a. The added steepness of the profile may also be beneficial for houses that have two levels.



STRUCTURAL PERFORMANCE OF CATERANRY DOMES

Modeling. To highlight the structural advantage of catenary profiles over more conventional forms, e.g., circular, a stress analysis of several small concrete domes was implemented in the software package Abaqus/CAE (Dassault Systemes, 2020). Only a quarter-dome was modelled due to the geometric and load symmetry associated with the analysis. The applicable displacement and rotational restraints were imposed along the resulting boundary edges. The support at the base was either pinned or fixed, and conventional S4R shell elements were utilized in all analyses discussed herein. The material considered was concrete, and Table 1 presents the material and geometric characteristics utilised in the above-mentioned FE analysis. In the study, an elastic analysis was implemented with isotropic material characteristics applied to the small concrete domes. The assumed elastic materials characteristics fall within typical ranges for concrete materials (Beushausen et al., 2021).

A suitably refined mesh was adopted for each model dome, i.e., the mesh density was increased until convergence of the stress distribution. The adequacy of the modelling was also validated with the full closed-form solution, i.e., membrane stresses + boundary stresses, for circular domes. The theoretical stress equations for circular profiles were obtained from Gohnert (2022), and a comparison of the mid-surface stress results, obtained from both approaches, are presented for two circular profiles in Figure 3a and 3b. These plots demonstrate an excellent match, which further validates the accuracy of the FE modelling.

Thickness	Density	Base Length	Elastic Mod.	Poisson's
(mm)	(kN/m ³)	(m)	(kN/ m²)	Ratio
150	23.5	8.0	30x10 ⁶	0.15

Table 1. Material and geometric characteristics of the concrete domes



Figure 3. Mid-surface hoop and meridian stresses in circular domes (pinned base)

Structural Efficiency. Figures 4a through 4d show the hoop and meridian stress distributions, at the mid-surface/mid-plane, for the catenary and hemispherical domes. Also included in these figures are the corresponding closed-form membrane stress solutions form the literature (Gohnert and Bradley, 2021; Gohnert, 2022). By comparing the mid-plane FE stresses with the membrane solution, the magnitude and extent of the in-plane boundary forces may be inferred. Figure 4 shows that the FE and membrane solution match closely for the catenary domes considered herein. There is some localized divergence between the membrane and FE stresses at the base, which is due to the in-plane boundary forces associated with fixity and the Poisson effect (Gohnert and Bradley, 2021). Moreover, Figure 4 clearly indicates minimal in-plane boundary forces in the catenary domes (Figures 4a, 4c and 4d) when compared with the hemisphere (Figure 4b).

Figures 5a through 5d show the mid-surface, outer, and inner stress distributions for each dome. As is expected with thin-shell structures under surface loads, the inner and outer stresses coincide along most of the length of each shell (Figure 5). The divergence of the meridian stresses toward the base is expected and attributed to the localized bending moment associated with fixity, i.e., boundary effects. A fixed base was adopted in these analyses to give the largest influence of the boundary on the stress distributions, i.e., full rotational restraint. There is, however, significant disparity between the stresses toward the base of the hemisphere, as shown in Figure 5b, which is indicative of bending moment in the shell. In contrast, the inner and outer stresses match closely for the catenary domes, especially those with steeper profiles (Figure 5c and 5d). In fact, these stress plots reveal that bending is minimal in the catenary domes and at least an order of magnitude lower than that for a hemisphere. Finally, the membrane and FE solutions match very closely for the catenary domes, which highlights the structural efficiency of the catenary form.







Figure 5. Influence of base restraint (boundary effects) on the inner, outer, and midplane stress distributions (fixed base)

Figure 4b and 5b also reveal that the hemisphere experiences tensile stress in the hoop direction and, although not evident in Figure 5b, approximately 60% of the hemispherical shell in is tension in the hoop direction (See the hoop stress vectors and contour patterns, corresponding the outer stress distribution, in Figure 6 below). The extent of the hoop tension zone extends down from a point that is at angle of approximately 52° from the horizontal, and this observation is similarly reported in the literature (e.g., Arun, 2006; Wilson, 2005; Gohnert, 2022).



(a) Hoop stress vectors (b) Hoop stress contours Figure 6. Outer principal stress plot: hemispherical dome with fixed boundary support

Practical Implications. Of significance regarding the design of catenary domes is that compression exists throughout the shell in the hoop direction. This structural advantage of the catenary is also true of the paraboloid (Arun, 2006) and is particularly meaningful for the implementation of unreinforced masonry domes, in which tension may be detrimental to durability and safety, e.g., in masonry circular domes the tension zone
toward the base can cause large vertical cracks in the shell (Arun, 2006). These tension forces must be mitigated in the design of circular masonry domes, e.g., through the incorporation of continuous walls or closely spaced columns tied with small arches to change the tensile forces at the base into compression (Arun, 2006). Base thickening is also implemented in masonry and RC shells to account for the boundary effects and base thrusts (Arun, 2006; Gohnert, 2022). In small RC domes, minimum tension steel reinforcement may govern in the lower region. For the compression region in a small RC circular dome, the minimum steel requirement is lower than that for tension and governed by aspects such as maximum bar spacing or shrinkage and temperature (Wilson, 2006). However, the pure-compression benefit illustrated in Figure 5 is likely less significant for the catenary over more conventional RC dome housing because the design of these small shells is largely governed by minimum steel outlined in reinforced concrete design standards (Wilson, 2005; Gohnert, 2022). Nevertheless, pure-compression forms are well recognized as offering increased longevity/durability to building structures (Gohnert et al., 2013).

Although the catenary dome is in pure compression under self-weight, the introduction of stiffening and openings generate localized bending forces, which may engender tensile stresses in the shell. To prevent diagonal cracks around openings in masonry domes, such as in the corners of windows and doors, some limited reinforcement may be needed to prevent cracking in the adjacent masonry. Wire stitching around openings is a particularly simple and efficient solution in masonry structures (Gohnert et al., 2006). Thickening around openings is also implemented in RC domes to accommodate additional reinforcing bars on all sides of the opening (Wilson, 2005)

Imposed loads such as wind, snow, and seismic may need to be considered in the design of domes for housing. Wilson (2006) reported that the performance of small RC dome houses is excellent for snow, wind, or earthquake loads. In many regions, wind may be the dominant imposed load, and it is widely acknowledged that shell structures offer substantial benefits regarding aerodynamic efficiency and have repeatedly shown this advantage over more conventional housing structures in strong winds. For example, South (2018) described minor damage to a caterpillar shaped RC dome house situated in Florida - a small hole in the shell wall - which was caused by a wind-borne residential transformer (estimated to weigh about 500 lbs) during Hurricane Michael. The dome house was still habitable, whilst neighboring conventional housing structures were either destroyed by the strong winds or uninhabitable. Norton (1997) reported that earth masonry shell roofs in the Sahel (in Northern Africa) performed excellently in high wind areas, whereas the metal sheet roofs, popular on more conventional structures, were frequently blown off. The performance advantage of these heavy masonry shells can be attributed to several factors; the foremost being that domed or vaulted masonry roofs provide considerable mass to counteract uplift and lateral forces. Unlike the smooth aerodynamic form of a dome, box-like structures create more obstruction for the wind, as well as early flowseparation at eaves, gable ends and other sharp edges (e.g., roof ridge). The resulting wind forces, in combination with greater surface area, may result in significantly higher pressures and suctions over these more conventional buildings when compared to shells.

CONCLUSION

The catenary dome is an alternate to more conventional shells, such as the hemisphere or oblate ellipsoid. The catenary, however, has a shallower base angle, which may be problematic regarding *dead space* near the shell wall in small residential structures. Using steeper catenary domes can alleviate this issue, whilst offering a structurally superior solution. Several advantages related to the catenary dome, particularly those with steeper profiles, were reported in this paper. These are summarized below.

- Boundary effects are minimal in steeper catenary domes. Bending and in-plane boundary forces are insignificant and an order of magnitude lower than that observed in the conventional hemisphere.
- Like the catenary vault, the catenary dome is a pure compression structure under uniform vertical load. This state of compression is especially favorable when building with materials that perform poorly in tension, e.g., masonry and concrete.
- The membrane stresses for the steep catenary domes matched very closely with the corresponding FE stress distributions, which emphasizes the structural efficiency of the form. This is an important finding because the membrane solution, being an equilibrium approach, is independent of the material characteristics and boundary fixity.

The above structural attributes elucidate that the catenary dome is highly efficient structural form. The results presented merit further investigation as well as their practical application regarding the utilization of the catenary dome for housing and other buildings.

REFERENCES

Auroville Earth Institute (2016). "*Construction Projects*," <u>http://www.earth-auro-ville.com/construction_projects_en.php</u>, Visited site 27/10/2016.

- Arun, G. (2006). "Behaviour of Masonry Vaults and Domes: Geometrical Considerations," *Structural Analysis of Historical Constructions*, New Delhi, India.
- Bradley, R.A., Gohnert, M., and Fitchett, A. (2018). "Guidelines to Mitigate Cracking in Compressed Stabilized Earth Brick (CSEB) Shells," *J. Perf. of Constr. Fac.*, Vol. 32., No. 3.
- Beushausen, H., Arito, P., van Zijl, G. and Alexander, M.G. (2021) "Deformation and volume change of hardened concrete," Fulton's Concrete Technology, Tenth Edition, The Concrete Institute, pp. 211–288.
- Brune P., et al. (2010). "The Toughness of Imperial Roman Concrete," International Association of Fracture Mechanics of Concrete and Concrete Structures–

Recent Advances of Fracture Mechanics of Concrete, Korean Concrete Institute, Korea.

- Dassault Systemes. (2020). Abaqus/CAE [Software], Dassault Systemes Simulia Corp., Johnston, RI.
- Gohnert, M. (2022). Shell Structures: Theory and Application. Springer Nature, Switzerland AG.
- Gohnert, M., Mahamed, Z., and Nadasen, Y. (2006). "Wire Stitching to Strengthen and Repair Masonry Walls and Beams." *Concrete Beton*, Vol. 113., pp. 5-10.
- Gohnert, M., Fitchett, A., Bulovic, I., and Bhikhoo, N. (2013). "Structurally efficient housing incorporating natural forms." *Journal of the South African Institution of Civil Engineering*, Vol. 55. No. 3., pp. 96–102.
- Gohnert, M. and Bradley, R. (2020), "Catenary Solutions for Arches and Vaults," *Journal of Architectural Engineering*, Vol. 26, No. 2.
- Gohnert, M. and Bradley, R. (2021). "Membrane Solution for a Catenary Dome," J. Int. Assoc. Shell Spatial Struct., Vol. 62., No. 1, pp. 37-49.
- Gohnert, M. and Bradley, R. (2022). "Membrane stress equations for a catenary dome with a variation in wall thickness," *Engineering Structures*, DOI: 10.1016/j.engstruct.2021.113793.
- Goshima, R. (2011). "Investigation of the cross-section of the Pantheon dome through catenary mechanism," *J. Int. Assoc. Shell Spatial Struct.*, Vol. 52., No. 1., pp. 19-23.
- Minke, G. (2009). Building with Earth: Design and Technology of a Sustainable Architecture, 2nd edition. Birkhauser, Berlin, Germany.
- Norton, J. (1997). Woodless Construction: Unstabilised Earth Brick Vault and Dome Roofing Without Formwork. Lund University, Sweden.
- South, D. (2018). "Hurricane Michael smashes power transformer into Monolithic Dome home," <u>https://www.monolithic.org/round2it/hurricane-michael-</u> <u>smashes-power-trans-former-into-monolithic-dome-home</u>, Visited site on 2/11/2018.
- Wilson, A. (2005). Practical Design of Concrete Shells. Monolithic Dome Institute, Texas, USA.

THE USE OF ARTIFICIAL INTELLIGENCE TECHNIQUES FOR PREDICTING COMPRESSIVE STRENGTH FOR HIGH PERFORMANCE CONCRETE: A REVIEW

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ABSTRACT

High Performance Concrete (HPC) is commonly used in the construction industry, its design is often a complex process due to the materials utilized making it difficult to model its behaviour. Artificial Intelligence (AI) is a powerful tool that has the capability of making good predictions if adequate training data is available. Studies have shown that AI can be leveraged to assist in modelling complex data structures. Furthermore, AI can be used to predict concrete behaviour and its properties such as compressive strength with margin error. There is a wide range of techniques that can be used such as Artificial Neural Networks (ANN), Regression and Classification Algorithms. ANN's are a AI technique used to solve complex and commonly nonlinear task using interconnected artificial neurons to compute and model the desired outcome. Regression and Classification algorithms use supervised learning to predict numerical and categorical outcomes respectively. The aim of the paper is to investigate how AI can be used for HPC modelling and the various strategies that are used that leverage this tool. Research using ANN's will be investigated followed by a comparative study of various regression algorithms and the use of ensemble or combination models and algorithms. This study will also include the accuracy and performance of these models using statistical techniques such as Root Mean Square Error and coefficient of determination. Finally a recommendation on the most optimal approach will be provided at the end of this article.

Keywords: High Performance Concrete, Artificial Intelligence, Machine Learning

Introduction

High Performance Concrete (HPC) is widely used in the civil engineering sector for the construction of bridges, buildings, roads and other structures that are load bearing and are subjected to compressive strength. The main constituents in traditional concrete are cement, aggregate and water, HPC has additional materials such as Fly Ash and Silica Fume added to improve it properties (Bezgin, 2017). Important considerations for HPC are factors such as mix proportions, concrete age, curing etc. Predicting the compressive strength of HPC is complex as there is a non-linear relationship making it difficult to model mathematically.

Traditional techniques have their shortfalls due to the limited number of datasets that are used for modelling, the techniques are often unsuitable and inaccurate (Yeh & Lien, 2009). One of the methods that are currently used is the Abram's rule which determines compressive strength based on the water to cement ratio. Although this approach has value, it is often used without supplementary material that are used in HPC (Bhanja & Sengupta, 2003). Artificial Intelligence (AI) has become a powerful tool in finding underlying patterns from a complex data structure and modelling the data to make good predictions. AI has been used

in many sectors such as finance, media and construction to name a few. With adequate data, training, and algorithm choice, it can be a powerful prediction tool (Harfouche, 2021).

Artificial intelligence is a study and collection of technologies that make machines perform tasks that humans currently do better (Abioye et al., 2021). Therefore, these systems exhibit similar characteristics associated with the intelligence of human beings. The common branches of AI are Neural Newtorks, Machine Learning, Natural Language Processing, Expert Systems, Fuzzy Logic, Robotics and Computer Vision (Lee & Shin, 2020).

With sufficient data, AI can be used to predict the compressive strength of concrete. In 2009, Prasad et al focussed on self-compacting concrete and proposed using ANN's to predict compressive strength to leverage this technology (Prasad et al., 2009). Naderpour et al conducted research on using ANN's for recycled aggregate concrete in predicting compressive strength (Naderpour et al., 2018). There is research conducted on the use of a M5P model algorithm to predict compressive strength using ordinary concrete (Behnood et al., 2017).

The remaining paper will review the use of ANN's and the approached used in predicting the compressive strength of High Performance Concrete. This will be followed by studying commonly used algorithms and comparing their prediction performance. The use of an ensemble or combination models will be reviewed as well. Finally, a recommendation on an optimal AI approach using HPC for predicting compressive strength will be proposed.

Artificial Intelligence Algorithms And Models

Artificial Neural Networks are interconnected artificial neurons that resemble how a brain functions. The neurons interact with each other through weighted connections. Each neuron has a weight or coefficient that influence the strength and outcome of the entire network (Touretzky et al., 1993). They are usually two or more layers organized in a logical sequence and order. Architecturally, the network has an input layer and an output value that is a response to the entire network, with a hidden layer in-between (Chen et al., 2021). After the forward propagation process, the system evaluates the error based on the target output. The weights are adjusted through a process called backpropagation and the process is repeated until a desirable output is achieved (Chen et al., 2021). Therefore it is important for the neural network to be trained on reliable data and hyperparameters for accurate predictions.



Figure 1 : Architecture of an Artificial Neural Network (Chen et al., 2021)

There is a collection of regression algorithms that have been developed that have the ability to make good predictions. Amongst others, the most commonly used are Support Vector Machine (SVM), Multilayer Perceptron, Gradient Boost Machines and Extreme Gradient Boost. These algorithms can be used to model HPC concrete and predicting their compressive strength (J.-S. Chou et al., 2011).

Support Vector Machine (SVM) is one of the most commonly used supervised machine learning algorithms. It was developed in the 1990's in the bell labs primarily used due it accuracy and low computational requirements. The key concept around SVM's is that it takes the inputs and places them on a vector feature space creating hyperplanes. The objective is to find a plane that will have the maximum distance of the datapoints provided. Furthermore, this plane ensures generalization of the datapoints for making reasonable predictions based on the data provided (Agarwal, 2021).

In 1999 Friedman proposed Gradient Boost Machines which are learning models that take an approach of using "weak" learners sequentially with the objective of creating an arbitrary strong learner which are typically better than a random guess. This allows many weak learners to be introduced to overall minimize the error of the model (Friedman, 1999). They are regression trees which use Stochastic Gradient Descent (SGD) iteratively to minimize the loss.

The highly scalable extension of the GBM's are eXtreme Gradient Boosting (XGB's). XGB's are widely used and considered a state of the art approach to machine learning (Konstantinov & Utkin, 2021).



Figure 2:Graphical representation of SVM algorithm (Agarwal, 2021)

There are many more algorithms available to choose from such as ridge regression, lasso regression, decision tree regression, random forest and KNN's etc. They are very powerful tools, however they will not be covered in this research. **Performance And Accuracy Metrics**

It is important to measure accuracy of models and performance. One of most commonly used methods for numerical performance for regression algorithms is the coefficient of determination (R^2) and Root Mean Square Error (RMSE). R^2 measures the regression models proportional variance of its dependent variables, it normally ranges between 0 and 1.0 is an indication that the models is unable to model the data and 1 means that the model fits the data perfectly and highly reliable for prediction purposes. RMSE is simply how far the concentrated datapoints are from the line that best fits the dataset (Gupta, 2021). The lower the value the lower the error.

Other commonly used accuracy metrics are Mean Absolute Percentage Error (MAPE) which sums of the individual errors divided by the demand and Mean Absolute Error (MAE) which is the mean of the absolute error. These metrices are useful however it is important to understand the dataset and have the relevant domain knowledge to interpret the error's significance and impact (Nguyen et al., 2021).

The Use Of AI In Predicting Compressive Strength

Artificial Neural Networks Approach

In 1991 Ghaboussi used a Artificial Neural Network (ANN) to model the behavior of concrete that is subjected to plane stress using monotonic and uniaxial cycle loading (Ghaboussi, 1991). This early experiments demonstrated the power of neural networks using backpropagation for material modelling (Yeh, 1998). Further research was conducted using neural network trained on data such as material constituents, ratios and other environmental

information for predicting the thermal and mechanical properties of composite materials (Hajela & Berke, 1992). Kasperkiewiez in his research demonstrated that fuzzy ARTMAP neural network can be used in modelling the strength of High Performance Concrete as well as optimizing the mixes (Kasperkiewicz, 1995). Chou et al. conducted research that optimizes prediction accuracy using data-mining techniques(J.-S. Chou et al., 2011).

Yeh et al conducted research using Modified Neural Networks for predicting concrete strength for High Performance Concrete (Yeh, 1998). In the research cement, blast- furnace slag, flash ash, water, super plasticizer, coarse aggregate, fine aggregate and age of testing were used as inputs for training a neural network to predict compressive strength as shown in Table 1.



Figure 3: Schematic layout of an Artificial Neural Network predicting compressive strength (J.S. Chou et al., 2011)

Material	Unit	Minimum	Maximum	Average
Cement	kg/m ³	71	600	232.20
Fly Ash	kg/m ³	0	175	46.4
Blast Furnace	kg/m ³	0	359	79.2
Slag				
Water	kg/m ³	120	228	186.4
Superplasticer	kg/m ³	0	20.8	3.5
Coarse Aggregate	kg/m ³	730	1322	943.5
Fine Aggregate	kg/m ³	486	968	819.p

Table 1: Materials and dataset statistics

The dataset was derived from 17 sources with 1 000 samples. In the research, the following parameters of the neural network were used: Number of hidden layers = 1, Number of hidden units = 8, learning rate = 1, Momentum factor= 0.4 and learning cycle = 3 000. Figure 4 displays the results of the predicted compressive strength versus the strength observed in the lab. The model achieved a R^2 of more than 0.8. The results demonstrated that ANN's can be powerful tools in predicting Compressive strength of HPC (Yeh, 1998). The disadvantage however is that there is a need to fine tune parameters such as the number of hidden layers, number of neurons etc. Therefore this becomes a very technical process that requires a trial and error process.



Figure 4: Predicted compressive strength values with laboratory results (Yeh, 1998)

There has been further studies by (Fazel Zarandu et al. 2008), Jang 1993, lee et al 2009; Mostofi and Samaee 1995; Oh et al 1999; Seyhan et al 2005; Topcu and Sarldemi 2008;

Comparison Of Different Models

Nguyen et al conducted research that investigated various AI based models for predicting compressive strength. The research focussed on ANN's, Support Vector Machines, Gradient Boost Machines and eXtreme Boost Machines to predict the compressive strength of High Performance Concrete. A dataset with 1 133 samples was used with the statistical features and materials shown in Table 2 below (Nguyen et al., 2021).

Materials	Unit	Minimum	Maximum	Mean	Standard deviation
Cement	kg/m ³	102.00	540.00	276.50	103.47
Blast Furnace Slag	kg/m ³	0.00	359.40	74.27	84.25

Table 2: Materials and Statistics of dataset

Fly Ash	kg/m ³	0.00	260.00	62.81	71.58
Water	kg/m ³	121.75	247.00	182.98	21.71
Superplasticizer	kg/m ³	0.00	32.20	6.42	5.80
Coarse	kg/m ³	708.00	1145.00	964.83	82.79
Aggregate					
Fine Aggregate	kg/m ³	594.00	992.60	770.49	79.37
Age	day	1.00	365.00	44.06	60.44
Compressive	MPa	82.60	82.60	35.84	16.10
Strength					

The results captured in Table 3 show that Support Vector Regressor has the lowest performance of the four techniques with a RMSE of 5 and R^2 of 0.95. ANN showed the second best results, the architecture has 2 hidden layers consisting of 300 and 1 000 neurons respectively.

XGB displayed the best performance on the dataset similar to Gradient Boost Regressor with a coefficient of correlation of 0.97. The machine used for processing the algorithms was Core i5 with central processing of 2.9GHz and a 8GB RAM using python version 3.6 libraries. ANN by far required more time to process and was computationally expensive with 89 seconds. SVR and XGBooost had an almost similar processing time. The algorithm that required the least processing time was XGBoost Regressor.

METHOD	R ²	RMSE	MAE	MAPE	TIME (s)
SVR	0.95	5	3.79	12.73	28
ANN	0.96	4.34	2.94	9.83	89
GBR	0.97	3.77	2.44	8.31	29
XGBOOST	0.97	3.78	2.47	8.64	5

Table 3: Results of different used for compressive strength

There has been further studies conducted that compared XGBoost Regressor with Random Forest and Logistic Regression. XGBoost shown superior performance overall (Morde, 2019). Muliauwan et al compared the ANN, SVM and Linear Regression algorithms, in the research it was found that ANN displayed the best performance amongst the three models (Muliauwan et al., 2020).

Ensemble And Hybrid Models

Further research was conducted on using hybrid and ensemble models for predicting the compressive strength of HPC. In 2009, Yeh and Lien combined a genetic algorithm with and operational tree to predict the accuracy of predicting compressive strength for HPC. The results showed that this approach is more accurate than regression formulas but however less accurate compared to ANN models (Yeh & Lien, 2009). Furthmore, a hierachial approach combining classification and regression approach proved to improve prediction accuracy for compressive strength(J. S. Chou & Tsai, 2012). In 2013 Chou proposed combing two models and to assess the performance in comparison with single models (Chou, 2013). The sample size of the dataset were 194 samples. The supplementary materials were Blast-Furnace Slag and Superplasticizer (Luther, 2005). The algorithms chosen for the studies were

Artificial Neural Networks (ANN'S), Support Vector Machines (SVM), Chi-squared Automatic Interaction Detector (CHAID), Classification and Regression Trees (CART). The research conducted had the following combinations of models: ANN's + CHAID, ANN's + SVM's, CHAID + SVM's, ANN's + SVM's + CHAID. Table 4 and 5 show the individual results and the ensemble results respectively.

Predictive Method	R ²	RMSE	MAE	MAPE
ANN'S	0.93	6.329	4.421	15.3
CART	0.84	9.703	6.815	24.1
CHAID	0.861	8.983	6.088	20.7
SVM	0.923	6.911	4.764	17.3

Table 4: Individual results

Results showed that ANN's followed by SVM's have the best performance as compared to CART and CHAID algorithms when assessed individually. The results from Esemble models also show that combination of ANN's, CHAID and SVM yield a better performance compared any of the individual models.

Predictive	R	RMSE	MAE	MAPE	
Method					
ANN'S +	0.922	7.028	4.668	16.2	
CHAID					
ANN'S + SVM	0.939	6.174	4.236	15.2	
CHAID + SVM	0.929	6.692	4.580	16.3	
ANN'S +	0.933	6.231	4.276	15.2	
CHAID + SVM					

 Table 5: Combination/ Ensemble Models

These findings have shown that based on the structure of the dataset and the right combination of models, ensemble models can in certain instances produce better results for predicting compressive strength for High Performance Concrete than individual models.

Conclusion And Recommendations

The study reviewed the use of AI based models for predicting the compressive stress of the High Performance Concrete. The study covered one of the most widely used techniques called ANN's for compressive strength prediction and performance. A dataset with 1 000 samples was used to train an Artificial Neural Network with specific hyperparameters. When measuring the performance, the trained model achieved R^2 of more than 0.8 and a graph comparing predicted results and lab results was presented. This displayed the power of ANN's and their usefulness in making reasonable predictions.

Subsequently an investigation in comparing different algorithms was reviewed. eXtreme Gradient Boosting Machine algorithm is a state of the art technique and displayed the best

performance with the lowest computational processing time. The prospects of using esemble models was also reviewed, although single models are also powerful, the study showed that `using ANN's, CHAID and SVM as a combination can increase the performance of the model. The study has proven that there is more than one algorithmic solution in building models that perform well. However good the model is in the research presented, there are limitations if an inappropriate dataset is used. This must be followed by the assessment of various algorithms by measuring their R^2 , RMSE, MAPE and MAE. Generally, most models perform well and yield reasonable results regardless of the algorithmic strategy. More research on using algorithms such as Ridge regression, Lasso regression, Decision tree regression, Random forest and KNN's also needs to be conducted when using HPC for predicting compressive strength.

References

- Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, 44(April 2020), 103299. https://doi.org/10.1016/j.jobe.2021.103299
- Agarwal, D. (2021). Introduction to SVM(Support Vector Machine) Along with Python Code. Analyticics Vidha.
- Behnood, A., Behnood, V., Modiri Gharehveran, M., & Alyamac, K. E. (2017). Prediction of the compressive strength of normal and high-performance concretes using M5P model tree algorithm. *Construction and Building Materials*, 142, 199–207. https://doi.org/10.1016/j.conbuildmat.2017.03.061
- Bezgin, N. Ö. (2017). High performance concrete requirements for prefabricated high speed railway sleepers. *Construction and Building Materials*, *138*, 340–351. https://doi.org/10.1016/j.conbuildmat.2017.02.020
- Bhanja, S., & Sengupta, B. (2003). Modified water-cement ratio law for silica fume concretes. *Cement and Concrete Research*, 33(3), 447–450. https://doi.org/10.1016/S0008-8846(02)00977-8
- Chen, Z., Wang, M., Meng, Z., Wang, H., Liu, L., & Wang, X. (2021). Development of structure-informed artificial neural network for accurately modeling viscosity of multicomponent molten slags. *Ceramics International, June*. https://doi.org/10.1016/j.ceramint.2021.07.248
- Chou, J.-S., Chiu, C.-K., Farfoura, M., & Al-Taharwa, I. (2011). Optimizing the Prediction Accuracy of Concrete Compressive Strength Based on a Comparison of Data-Mining Techniques. *Journal of Computing in Civil Engineering*, 25(3), 242–253. https://doi.org/10.1061/(asce)cp.1943-5487.0000088
- Chou, J. S., & Pham, A. D. (2013). Enhanced artificial intelligence for ensemble approach to predicting high performance concrete compressive strength. *Construction and Building Materials*, 49, 554–563. https://doi.org/10.1016/j.conbuildmat.2013.08.078
- Chou, J. S., & Tsai, C. F. (2012). Concrete compressive strength analysis using a combined classification and regression technique. *Automation in Construction*, 24, 52–60. https://doi.org/10.1016/j.autcon.2012.02.001
- Friedman, J. H. (1999). Greedy function approximation: A gradient boosting machine. *Annals of Statistics*, 29(5), 1189–1232. https://doi.org/10.1214/aos/1013203451

- Ghaboussi. (1991). Knowledge-Based Modeling of Material Behavior with Neural Networks. *Journal of Engineering Mechanics*, 117.
- Gupta, S. (2021). RMSE: What does it mean? Medium.
- Hajela, P., & Berke, L. (1992). Neural networks in structural analysis and design: An overview. 4th Symposium on Multidisciplinary Analysis and Optimization, 1992, 3, 902–914. https://doi.org/10.2514/6.1992-4805
- Harfouche, A. (2021). Ready , Steady , Go AI : A Practical Tutorial on Explainable Artificial Intelligence and Its. *Patterns*, 2(9), 100323. https://doi.org/10.1016/j.patter.2021.100323
- Kasperkiewicz. (1995). HPC Strength Prediction Using Artificial Neural Network. *Journal* of Computing in Civil Engineering, 9.
- Konstantinov, A. V., & Utkin, L. V. (2021). Interpretable machine learning with an ensemble of gradient boosting machines. *Knowledge-Based Systems*, 222, 106993. https://doi.org/10.1016/j.knosys.2021.106993
- Lee, I., & Shin, Y. J. (2020). Machine learning for enterprises: Applications, algorithm selection, and challenges. *Business Horizons*, 63(2), 157–170. https://doi.org/10.1016/j.bushor.2019.10.005
- Luther, D. (2005). Modeling Portland Blast-Furnace Slag Cement High-Performance Concrete. Paper by Carlos Videla and Cristian Gaedicke. *Science Engineering Medicine*, 102.
- Morde, V. (2019). XGBoost Algorithm: Long May She Reign! Towards Datascience.
- Muliauwan, H. N., Prayogo, D., Gaby, G., & Harsono, K. (2020). Prediction of Concrete Compressive Strength Using Artificial Intelligence Methods. *Journal of Physics: Conference Series*, 1625(1). https://doi.org/10.1088/1742-6596/1625/1/012018
- Naderpour, H., Rafiean, A. H., & Fakharian, P. (2018). Compressive strength prediction of environmentally friendly concrete using artificial neural networks. *Journal of Building Engineering*, 16(October 2017), 213–219. https://doi.org/10.1016/j.jobe.2018.01.007
- Nguyen, H., Vu, T., Vo, T. P., & Thai, H. T. (2021). Efficient machine learning models for prediction of concrete strengths. *Construction and Building Materials*, 266, 120950. https://doi.org/10.1016/j.conbuildmat.2020.120950
- Prasad, B. K. R., Eskandari, H., & Reddy, B. V. V. (2009). Prediction of compressive strength of SCC and HPC with high volume fly ash using ANN. *Construction and Building Materials*, 23(1), 117–128. https://doi.org/10.1016/j.conbuildmat.2008.01.014
- Touretzky, D., Elman, J., Sejnowski, T., & Ahmad, S. (1993). David Touretzky, Jeffrey Elman, Terrence Sejnowski and Geoffrey Hinton, eds., 62, 117–127.
- Yeh. (1998). Modelling of strength of High-Performance Concrete Using Artificial Neural Networks. 28(12), 3–8.
- Yeh, I. C., & Lien, L. C. (2009). Knowledge discovery of concrete material using Genetic Operation Trees. *Expert Systems with Applications*, 36(3 PART 2), 5807–5812. https://doi.org/10.1016/j.eswa.2008.07.004

Performance of OSB and SFS Shear Walls in Residential Building

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ABSTRACT

Different load-bearing materials are used in residential building construction in the United States. The Oriented Strand Board (OSB) and Structural Foam Sheathing (SFS) are two of the most common types of engineered materials used for various loadbearing construction applications in the United States. According to each one of the manufacturers, their products have higher strength and stiffness than other products used in the residential building. This study focused on wood shear walls' ultimate lateral load capacity in residential buildings. A total of eight tests were conducted: four tests with OSB sheaths and four with SFS sheaths. These tests were subjected to gradually applied monotonically increasing load. The wood frame walls were constructed with OSB on one side of the wall frame using a bearing plate washer. One of the OSB walls was without straps, and three OSB walls had three different types of straps tied to the baseplates: SPIZ, HS 2.5, and LSTA9. The wood frame walls were constructed with SFS on one side and $\frac{1}{2}$ in (12.7 mm) Gypsum wallboard (GWB) on the opposite side of the wall frame, with Simpson HDO8, hold down anchors. Two different types of SFS were tested: ¹/₂ in. (12.7 mm) R-Max Thermasheath-SI and Thermo-Sheath Red Structural Sheathing. Type, size, and spacing of fasteners for sheathing and Gypsums Wallboard followed APA test details. The results for the SFS walls were compared to the published specifications by SFS manufacturers and the results from OSB tests. This study provides a better understanding of the strength, stiffness, and behavior of shear walls sheathed with OSB was compared to the SFS wall sheathing subjected to lateral loads in the residential building.

Keywords: residential building, construction, engineered materials, lateral load capacity, wood shear walls, Oriented Strand Board, Structural Foam Sheathing

INTRODUCTION

Wood framing has been used in the United States since the early 1600s. There have been enormous forest and other wood resources to provide wood materials for buildings, specifically residential buildings. The wood frame is sheathed with different types of sheathing. The most common sheathing used in the US is Oriented Strand Board (OSB) and plywood. These sheathings are engineered materials with high lateral load capacity (APA 2020). Structural Foam Sheathing (SFS) is the new material recently used as sheathing for wood frames. According to OX Engineered Product (2020), Structural Foam Sheathing has high lateral load resisting capacity, water resistance, and high R values. For these reasons, the SFS has high material performance and is considered an alternative to other sheathing materials like OSB and plywood.

Numerous studies were published on wood frame shear walls sheathed with OSB, plywood, and gypsum wallboard (GWB), subjected to static and dynamic loads (Filiatrault 1990; Oliva 1990; Polensek and Schimel 1991; Dolan and Madsen 1992; Karacabeyli and Ceccotti 1996; Karacabeyli *et al.* 1999; McMullin and Merrick 2002; Seaders *et al.* 2009; Memari and Solnosky 2014; Chen *et al.* 2016; Lafontaine *et al.* 2017, Shadravan *et al.* 2018-2019). In contrast, few research studies concerning wood frame walls sheathed with structural foam sheathing.

According to Dolen and Madison (1992), plywood improves the ultimate load capacity of wood-frame shear walls. Dinehart and Shenton III's study (1998) indicated OSB increased the wood-frame shear wall load capacity. Casagrande *et al.* (2016) showed the sensitivity of wall capacity to the shear wall length. As the length of the shear wall increases, the lateral load capacity of the walls increases. However, it is a non-linear relationship. Shadravan and Ramseyer (2018) study supported the conclusion by Casagrande et al.

Effect of GWB sheathing on one side of wood frame with OSB sheathing on the opposite side of the wood frame was studied by different researchers (Karacabeyli and Ceccotti (1996), Sinha and Gupta (2009), Zhou and He (2011). These studies showed GWB increased the ultimate wall load capacity and improved the tested walls' elastic stiffness and energy dissipated. Filiatrault *et al.* (2002) experienced a full-scale, two-story building. They focused on building behavior subjected to seismic by using two-triaxial shake tables. They found a significant improvement in response to seismic by using interior gypsum wallboard and exterior stucco.

Considering wood-frame shear walls connection failures, Rezazadeh et al. (2016) found that the leading cause of failure of wood frame buildings is the sill-plate failure during tornadoes. Shadravan and Ramseyer's study (2018) showed doubling base plate, increasing the size of washers, reducing the anchor bolt spacing, reducing the sheathing nail spacing, and using ring shank nails instead of smooth shank nails improved the shear wall strength. Other studies on wall-to-foundation connection indicate that using metal straps at the shear wall connection to the foundation improves the wall performance, which can be as effective as anchor bolts (Marshall 2003; Canfield *et al.* 1991; Vilasineekul 2014; Caprolu *et al.* 2015; Shadravan *et al.* 2019).

Shadravan and Ramseyer (2019) conducted tests using four different types of Structural Foam Sheathing. They used both static (monotonic) and cyclic testing following ASTM E564 and ASTM E2126. The test details followed the manufacturers' specifications. The results showed that the capacity of tested walls was smaller than the manufacturers' published design values. Shadravan et al. (2019) compared the lateral load capacity of wood shear wall sheathed with structural foam sheaths with the walls sheathed with OSB. Four types of Structural Foam Sheathings were compared to OSB walls without strap and OSB walls with LSTA9 strap tied to the baseplates on each

wall frame stud. The loads were monotonically applied to the wall tests in this study. The results showed that LSTA9 ties effectively improved the OSB wall capacity. The tested wall with Structural Foam Sheathing showed a reduction in strength capacity compared to the published design values.

This study conducted eight wood shear wall tests subjected to static load: four wall tests sheathed with OSB and four wall tests sheathed with SFS and GWB. The wall configurations and details followed Moore, Oklahoma Adopted New Building Code (2014) for OSB walls, and the manufacturers' wall details and ASTM E564 used for SFS walls.

TESTING PROCEDURE AND DETAILS

This study uses two types of wall sheathing: Oriented Strand Board (OSB) and Structural Foam Sheathing (SFS). The walls were subjected to static load.

• *Oriented Strand Board (OSB):* The OSB shear walls configuration followed Moore, Oklahoma Adopted New Building Code (2014). The Moore City Council adopted the New Building Codes after Moore, Oklahoma, was hit by an EF5 tornado in May 2013, causing the loss of several lives and billions of dollars in damage.

OSB Wall configuration (Table 1): The wall specimens were 12 ft (3.6 m) long and 8 ft (2.4 m) in height. The walls were constructed with single terminal stud, double top plates, and double baseplates. Studs, top, and base plates were made with 2×4 dimension grade Fir lumber (1.5×3.5 in. [38×88 mm]). 7/16 in. (11.0 mm) OSB panels were fastened to one side of the wall frame with 8d ring shank nails ($2-3/8 \times 0.113$ in. [60×2.85 mm]), and 4 in./6 in. (100 mm/150 mm. - edge/field) nail patterns. The studs were spaced 16 in. (40.5 cm) on the center (City Adopts New Building Code, 2014), Figure 1 a., b.

The OSB panels were fastened to the doubled base plates with a staggered nail pattern (Figure 1. c) and to the doubled top plates with one row of nails. The studs were end nailed to the top and bottom baseplates with (2) 16d, $(0.131 \times 3 \text{ in.}[3.3 \times 75 \text{ mm}])$, smooth shank nails. A minimum 3/4 in. (19 mm) edge distance was kept for the bottom row nails based on NDS, SDPWS (2014), Sec. 4.2.7.1.3. The doubled base plates and doubled top plates were fastened with (2 rows) 16d, $(0.131 \times 3 \text{ in.}[3.3 \times 75 \text{ mm}])$, smooth shank nails with 16 in. (40.5 cm) spacing, at the location of studs. The wall baseplates were anchored to the steel beam (W10×39) using 1/2 in. (12.5 mm) anchor bolts spaced 6 ft (1.8 m). The steel beam was bolted to the lab floor (Figure 1).

Four OSB walls were tested; one wall had no strap, and three were tied to the baseplates with three types of straps: SPIZ, HS-2.5, and LSTA9.

The straps tied the studs and baseplates with N8 and N10. Table 1 indicates the test wall configurations.

The static lateral load was applied gradually to the test walls.

• Structural Foam Sheathing (SFS): The SFS wall configurations followed the manufacturing wall details. The wall specimens were 8 ft (2.4 m) long and 8 ft (2.4 m) in height. The walls were sheathed with SFS on one side and 1/2 in. (12.5 mm) GWB on the opposite side of the wood frame. The wood wall frames were constructed with stud, double top plates, single baseplates, and double terminal studs using 2×4 dimension grade Fir lumber (1.5×3.5 in. [38×88 mm]). The studs were spaced 16 in

(40.5 cm). This study tested two types of structural foam sheathing: 0.078 in. (2 mm) ThermoPly Green and Thermo-Sheath Red Structural Sheathing. Following the manufacturer's test detail, the SFS and GWB were fastened to the stud wall frame with an edge distance of 3/8 in. (10 mm). Two similar shear walls were tested for each type of SFS wall. Table 2 indicates the test detail.

The SFS was stapled to the wall stud with 16-gage staples. Simpson HDQ8 tiedown anchors were used at each end of the wall frame to tie it to the base using 5/8 in. (16 mm) anchor bolts. The Simpson tie-downs were screwed to the terminal studs with (14) $1/4 \times 3$ in. (6.3 × 75 mm) SDS screws. Finally, the wall frames were anchored to a steel beam (W10×39) bolted to the test floor Figure 2.

The static lateral load was applied following ASTM E564 test method.

Table 1: Oriented Strand Board (OSB) wall configurations. 1ft= 0.304 m, 1 in.= 25.4 mm

	Shear Wall Configurations	Strap ((Ties)	Base Plate	(1/2 in) Anchor Bolt	
Wall No.	Wall LxH: 12 ft x 8ft	Straps Type	Fastener Type	Single/Double	Nominal Spacing	Washer Type
1	Stud Spacing: 16 in	None	None			
2	Nail Pattern: 4 in/6 in	SPIZ Tie	N8 & N10			
3	(Edge/Field)	HS-2.5 Tie	N8	Double	6 ft	3 in x 3 in
4	Sheathing Nail Type: 8d Ring Shank (R.S.) (2.5" x1/8")	LSTA9 Tie	N8			



Figure 1. OSB wall configurations: a) Wall without a strap, b) Wall with HS-2.5 strap, c) Staggered nail pattern to the doubled base plates

Wall No.	Type of structural foam Sheathing	Type of Staple/Fastener (in.)	Panel fastener spacing (in./in.)	GWB Screw Spacing edge/field (in./in.)	
5	Thermonly Green	Crown: 1	3/3	8/8	
6	Thermophy Green	Leg: 1.5	0,0	0/0	
7	Thermo-Sheath Red Structural	Crown: 1	3/3	0/0	
8	Sheathing	Leg: 1.5	3/3	ð/ð	

Table 2. Test detail-Structural Foam Sheathing (SFS)1 in.=25.4 mm





Figure 2. SFS wall: a) Thermoply Green wall, b) Wall after test, through cut GWB

TEST RESULTS

As the length of OSB wall specimens was 12 ft (3.6m) and the length of SFS wall specimens was 8 ft (2.4 m), unit shear capacity is considered for comparison in test results.

OSB Walls Test results: The OSB walls were gradually subjected to static load at the top until the wall reached its maximum load capacity. Loading gradually continued until a deflection beyond the allowable deflection (ASCE 7) in-service was achieved. The maximum applied deflection was approximately 3 in. (76 mm), at which point the wall was stopped and unloaded.

Test results for OSB wall specimens are summarized in Table 3, including the maximum load, wall deflection at maximum load, and unit shear at maximum load. Wall deflection refers to a displacement of the top of the wall specimens. Allowable drift limit is calculated (Eq. 1) based on ASCE Section 12.12:

 $\Delta_{Ultimate}$ =0.02h Eq. (1)

 $\Delta_{Ultimate} = 0.02 \text{ (8ft x 12 '')} = 1.92 \text{ in.} (48 \text{ mm})$

Table 3 shows that deflections at maximum load are less than the allowable drift [1.92 in. (48 mm)] at maximum load (Eq. 1). The OSB walls with straps showed higher load capacity than the walls with no strap. Wall with LSTA9 tie strap showed the highest load capacity for the OSB wall specimens in this study.

Table 3 also indicates that using the SPIZ tie strap (wall specimen 2) improved the wall capacity 1588 lbs (7.0 kN) in comparison to the wall without a strap (wall specimen 1), the HS-2.5 tie strap (wall specimen 3) improved the wall capacity (wall specimen 1) 1815 lbs (8 kN). The LSTA9 tie strap improved the wall capacity by 3222 lbs (14.3 kN).

Figure 3 illustrates the load-deflection behavior for the OSB walls with and without straps.

	Oriented Strand Board- Wall Specimens										
Wall No.	Strap Type	Maximum Applied Load (lb)	Increased Load Capacity (lb)	Deflection at Max. Load (in.)	Unit Shear (plf)						
1	None	5550	-	0.95	463						
2	SPIZ Tie	7138	1588	1.54	595						
3	HS-2.5 Tie	7365	1815	1.05	614						
4	LSTA9 Tie	8772	3222	1.78	731						

Table 3. Test results for OSB wall specimens 1 in.= 25.4 mm, 1 lb= 0.00445 kN, I lb/ft= 0.0146 kN/m



Figure 3. Effect of tie straps on shear wall lateral resistance capacity-walls

SFS Walls Test results: This study used two types of Structural Foam Sheathing: 0.078 in. (2 mm) Thermoply Green and Thermo-Sheath Red. Two tests were conducted for each SFS wall. The walls were subjected to static load at the top of the wall following ASTM E564. Test results for SFS wall specimens are summarized in Table 4. The table indicates the maximum load, manufacturer's published value for wall capacity, wall deflection at full load, and wall capacity unit shear.

Deflection refers to a displacement of the top of the wall specimens. The allowable drift limit is 1.92 in. (48 mm) calculated based on ASCE Section 12.12 (Eq. 1). Averages of the test results for each pair of tests were computed and compared to the manufacturer's published design values. The average static test values for a pair of tests were 27 and 38 percent below the manufacturer's published design values. Figure 4 shows Published design value vs. average test value.

Table 4. Test results for SFS wall specimens

	Structural Foam Sheating- Wall Specimens Compared to Publised Value											
Wall No.	Strap Type	Maximum Applied Load (Ibs)	Average Test Value (Ibs)	Average Test Value- Unit Shear (plf)	Published Value- Ultimate Unit shear (plf)	Variation between Avg. Test Value and Published Value (%)	Deflection at Max. Load (in.)	Average Deflection (in.)				
4	Thermoply	4781	1609	576	795	27	1.60	1 75				
5	Green	4435	4000	570	785	27	1.90	1.75				
6	Thermo-	5198	5027	679	1010	20	1.88	1 76				
7	Sheath Red	4855	5027	020	1010	30	1.64	1.70				

1 in = 25.4 mm 1 lb = 0.00445 kN I lb/ft= 0.0146 kN/m



Figure 4. Variation between the average test values and published design values

DISCUSSION

This section discusses failure modes for the two types of walls conducted with Oriented Strand Boards (OSB) and Structural Foam Sheathing (SFS).

The OSB walls failure modes were due to the failure of shear panels due to bearing of the nails through panel (Figure 5. a), bending of the baseplate (Figure 5. b, c), withdrawing strap nails (Figure 5.), disconnection of end studs and baseplate at the far end from the load caused by uplift (Figure 5).



Figure 5. OSB wall failure modes: a) Shear panel nail failure, b) wall without out strap, c) wall with SPIZ tie strap

As mentioned before, the wall with LSTA9 tie strap showed the highest load capacity, which is expected. From Simpson Strong Tie, the Allowable Tensile load for LSTA9 is between 715 and 1095 lbs per strap, and Allowable Tensile load for HS 2.5 is between 615 and 700 lbs per strap. Some of the variations in capacity might be due to the strap configuration. For example, the LSTA9 engages more of the stud and is longer, and the HS-2.5 is nonsymmetrical and prone to more rotation. Therefore, this suggests a stiffer, symmetrical connector that engages more of the stud improves the overall lateral resistance of these systems.

The SFS walls' failure modes were due to the failure of shear panels: staples bearing through the SFS (Figure 6. a and b) and screws bearing through the GWB (Figure 6. c) and combinations of these two failures. It is noticeable that none of the SFS walls failed due to the connections at the baseplates as HDQ8 hold-downs tied the wall frame to the base.

In a comparison of OSB and SFS, as only one side of the wood frame was sheathed with OSB wall samples, and there was no HDQ8, it was expected that the OSB wall with hold down, and GWB on the opposite side of the wood frame must have a higher OSB wall capacity. The hold-down and GWB improve the wall capacity (Pardoen et al. 2000, Gatto and Uang 2002, Karacabeyli and Ceccotti 1996, Filiatrault et al. 2002, Sinha and Gupta 2009, Zhou and He 2011).



Figure 6. Structural Foam Sheathing Failure mode: a) Wall during testing, b) Staple bearing through panel failure, and c) Screws bearing through the GWB failure

CONCLUSION

Overall, adding straps increased the Oriented Strand Board (OSB) wall load capacity. The test values for Structural Foam Sheathing (SFS) were 27 and 38 percent smaller than the manufacturer's published design values. One of the most important differences between the tested OSB walls and SFS walls in this study, besides the type of sheathings, was that the OSB walls had only one side of wood frame sheathed with OSB, and there was no HDQ8 anchoring the OSB wall frames to the baseplates. Previous studies showed that sheathing the other side of the wood frame with GWB increased the strength of OSB walls. Therefore, it was expected that the OSB wall with hold-down anchors and GWB on the opposite side of the wood frame would have a higher wall capacity, which opens a future research area.

REFERENCES

APA 2020: https://www.apawood.org/osb

APA OSB Product Report, OSB Product Report, PR-N610.

ASCE 7 Minimum Design Loads for Buildings and Other Structures

ASTM E564 (2018), Standard Practice for Static Load Test for Shear Resistance of Framed Walls for Buildings, American Society for Testing and Materials, Pennsylvania, USA.

ASTM E2126 (2018), Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings, American Society for Testing and Materials, Pennsylvania, USA.

Canfield, L. R., S. Niu, and H. Liu, (1991). "Uplift resistance of various rafter-wall connections." *Forest Prod. J.*, 41, 27-34.

Casagrande, D., Rossi, S., Sartori, T., and Tomasi, R. (2016). "Proposal of an analytical procedure and a simplified numerical model for the elastic response of single-story timber shear-walls." *Construction and Building Materials*, Volume **102**, Part 2, January 15, 2016, Pages 1101-1112.

City Adopts New Building Codes, First in the Nation. https://www.cityofmoore.com/node/2111>

Chen, Z., Chui, Y.H, Doudak, G., and Nott, A. (2016)." Contribution of Type-X gypsum wallboard to the racking performance of light-frame wood shear walls." *Journal of Structural Engineering*, Vol.142(5), p.04016008.

Dinehart, D. W., and Shenton, H. W., III. (1998a). "Comparison of the response of timber shear walls with and without passive dampers." *Proc., Structural Engineering Worldwide, Paper No. T207-5, Elsevier Science*, New York.

Dinehart, D. W., and Shenton, H. W., III. (1998b). "Comparison of the static and dynamic response of timber shear walls." *Journal of Structural Engineering*, 124(6), 686–695.

Design of Wood Structures ASD/LRFD 7th Edition by Donald E. Breyer, Kelly E. Cobeen, Kenneth J. Fridley, David G. Pollock.

Dolan, J. D. (1989). "The dynamic response of timber shear walls." *Ph.D. Dissertation*, Dept. of Civ. Eng., Univ. of British Columbia, Vancouver, B.C., Canada.

Dolan, J. D., and Madsen, B. (1992). "Monotonic and cyclic tests of timber shear walls." *Can. J. Civ. Eng.*, 19(3), 115–422.

Filiatrault, A. (1990a). "Analytical predictions of the seismic response of friction damped timber shear walls." *Earthquake Eng. Struct. Dyn.*, 19, 259–273.

Filiatrault, A. (1990b). "Static and dynamic analysis of timber shear walls." *Can. J. Civ. Eng.*, 17(4), 643–651.

Filiatrault, A., Christovasilis, I.P., Wanitkokul, A., and Van de Lindt, J.W. (2002). "Experimental seismic response of a full-scale light-frame wood building," *ASCE Journal of Structural Engineering*, 136(3), 246-254.

Gatto, K., Uang, C.M. (2002). "Cyclic response of wood frame shear walls: loading protocol and rate of loading rate effects." *CUREE Publication No. 13. Richmond, CA.*

Gatto, K., and Uang C-M. (2002). "Effects of loading protocol on the cyclic response of wood frame shear walls." *Journal of Structural Engineering*, V: 129 Issue 10.

Karacabeyli, E., and Ceccotti, A. (1996). "Test results on the lateral resistance of nailed shear walls." *Proc. Int. Wood Engineering Conf.*, 2, 179-186.

Karacabeyli, E., Dolan, J. D., Ceccotti, A., and Ni, C. (1999). "Discussion of 'comparison of the static and dynamic response of timber shear walls,' by David W. Dinehart and Harry W. Shenton III." *J. Struct. Eng.*, 125(7), 796–797.

Lafontaine, A., Chen, Z., Doudak, G., Ying He, C. (2017). "Lateral behavior of light wood-frame shear walls with gypsum wallboard." *American Society of Civil Engineers. Journal of Structural Engineering*, Vol.143(8), p.04017069Larry O'Dell, 2018. "Moore," *The Encyclopedia of Oklahoma History and Culture*, www.okhistory.org (accessed September 07, 2018).

Marshall, T. P., Bunting, W. F., Weithorn, J. D. (2003). "Procedure for assessing wind damage to wood-framed residences." *Symposium on the F-Scale and Severe-Weather Damage Assessment*. McMullin, K. M., and Merrick, D. (2002). "Seismic Performance of Gypsum Walls—Experimental test program." *CUREE Publication No. W-15*, San Jose State Univ., San Jose, CA.

Memari, A. M., and Solnosky, R. L. (2014). "In-plane shear performance of wood-framed drywall sheathing wall systems under cyclic racking loading." *Open J. Civ. Eng.*, 4(1), 54–70.

National Design Specification (NDS), Specification Design Provisions for Wind and Seismic (SDPWS) (2015).

Oliva, M. G. (1990). "Racking behavior of wood-framed gypsum panels under dynamic load." *Rep. No. UCB/EERC-85/06*, Earthquake Engineering Research Center, Univ. of California, Berkeley, CA.

OX Engineered Products- Build Strong: <https://www.oxengineeredproducts.com/product/> <https://modern-materials.com/wpcontent/uploads/2018/05/SI-STRONG-PRODUCT-INFO.pdf>

Pardoen, G.C., Kazanjy, R.P., Freund, E., Hamilton, C.H., Larsen, D., Shah, N., and Smith, A. (2000). "Results from the city of Los Angeles-UC Irvine shear wall test program." *Proc World Conference on Timber Engineering*. Paper 1.1.1 on CD.

Polensek, A., and Schimel, B. D. (1991). "Dynamic properties of light-frame wood subsystems." *J. Struct. Eng.*, 117(4), 1079–1095.

Rezazadah, S. M., (2016). "Shear wall sill plate behavior in wood frames." *Master Thesis, OSU*.

Seaders, P., Gupta, R., and Miller, T. H. (2009). "Monotonic and cyclic load testing of partially and fully anchored wood-frame shear walls." *Wood Fiber Sci.*, 41(2), 146–156.

Sinha, A., and Gupta, R. (2009). "Strain distribution in OSB and GWB in wood-frame shear walls." *Journal of Structural Engineering* (2009): 667-75. Print.

Shadravan, S., and Ramseyer, C.C. (2018). "Investigation of wood shear walls subjected to lateral load". *Elsevier, Journal of Structures,* Volume 16, Page 82-96.

Shadravan, S., Ramseyer, C. C., and Floyd, R.W. (2019), "Comparison of Structural Foam Sheathing and Oriented Strand Board Panels of Shear Walls Under Lateral Load". *Advances in Computational Design-Techno Press*. Volume 4, Number 3, July 2019, pages 251-272

<http://dx.doi.org/10.12989/acd.2019.4.3.251>

Shadravan, S., and Ramseyer, C. C. (2019), "Investigation of Design Values Computation of Wood Shear Walls Constructed with Structural Foam Sheathing". *Advances in Computational Design-Techno Press*. Volume 4, Number 3, July 2019, pages 223-238. DOI: http://dx.doi.org/10.12989/acd.2019.4.3.223

Shadravan, S., Ramseyer, C. C., and Floyd, R.W. (2019), "Lateral Resistance of Strapped Wood Shear Walls". *Journal of Structural Integrity and Maintenance, Taylor and Francis*, Volume 4, Pages 65-75, May 2019. https://doi.org/10.1080/24705314.2019.1603193.

Shadravan, S., and Ramseyer, C.C. (2018), "Investigation of Wood Shear Walls Subjected to Lateral Load." *Journal of Structures, Elsevier*, Volume 16, Pages 82-96, Nov. 2018. https://doi.org/10.1016/j.istruc.2018.08.007>

Vilasineekul, S., PE (2014). "Anchorage of wood shear walls to concrete for tension and shear." *Civil and Structural Engineer*. <https://csengineermag.com/article/anchorage-of-wood-shear-walls-to-concrete-for-

<https://csengineermag.com/article/anchorage-of-wood-shear-walls-to-concrete-fortension-and-shear/>

Zhou, N., and He, M. (2011). "Contribution of gypsum wallboard to lateral resistance capacity of wood shear wall." 2011 International Conference on Consumer Electronics, Communications and Networks. CECNet 2011 - Proceedings, p 3035-3039

Observations and Analysis of wind pressures on roof overhangs and underneath walls of a low-rise building.

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ABSTRACT

Roof overhangs are prone to wind damage as they are subjected to wind load at both the upper and bottom surfaces (soffit). Wind standards, like ASCE 7-16, assume that the pressure at the bottom covering of the roof overhang is the same as the external pressure coefficient on the adjacent wall surface. The current study aims to investigate possible limitations of such assumptions, i.e., at what point the wall pressure cease to affect the overhang. A large-scale wind tunnel study was carried out at the Wall of Wind Experimental Facility at Florida International University. The experimental setup considered two 1:10 scaled model configurations (2 ft and 6 ft inclined overhangs) of a low-rise hip roof building with roof slope 4:12, eave height of 24 ft, and horizontal dimensions of 40 ft by 50 ft.

The study provided information on pressure variations at top and bottom surfaces of the overhangs, adjacent roof area and underneath wall. Moreover, the effect of overhang length on the wind induced load, and the correlation between the wall and soffit pressures were investigated. The 2 ft overhang experienced higher suction coefficients at the edges compared to the 6 ft overhang. In addition, the results confirmed that, for both configurations, soffit pressure coefficients should be taken as the adjacent wall external pressure, as stated by ASCE 7-16 for positive pressure, while this might not be applicable for negative pressure (i.e. suction). Finally, by carrying out correlation and regression analyses between soffit pressure taps and upper wall taps, the 6 ft soffit seemed to be less correlated with the wall upper taps, than the 2 ft soffit.

Keywords: Roof overhangs, Wind loads, Pressure coefficient, Wind tunnel, Wind standards and codes of practice

INTRODUCTION

An overhang is an unenclosed continuation of the roof surface. Particularly on low-rise residential applications, overhangs may be open or covered by a soffit and may be cantilevered or supported. Most of the foundational belief about overhangs seems to

suggest that overhangs extend no more than 2 ft, whereas, in Florida, overhangs are often much longer and are necessary for energy efficiency and livability in this semi-tropical climate. Overhangs in Florida can be cantilevered 6 ft or more, or supported, as on a terrace or porch, for 10 to 12 ft or more.

Low-rise buildings are greatly affected by extreme wind events. The risk of windinduced failure is particularly increased on roofs and roof overhangs (Figure 1). The latter are commonly used in residential and industrial buildings for weather protection against wind, snow, rain, and sun. Roof overhangs are prone to damage because they are subjected to wind from both the upper and bottom surfaces (soffit). Taher (2007) suggested to limit the length of overhangs to 20 in (50 cm) especially for small slope roofs. Nevertheless, in warmer and sunny climates, it is common to use extended overhangs that go beyond the (2 ft) 60 cm and even reach 6 ft (1.8 m). Extended overhangs resemble a roof extension like a canopy or a patio cover that is attached to the main structure. Recent studies showed that canopies may experience lower wind loads compared to those specified for roof overhangs on ASCE 7 (Zisis and Stathopoulos 2010, Candelario et al. 2014, Zisis et al. 2017).



Figure 1. Aerial Footage of Great Guana Cay (Baker's Bay), Abaco after Dorian (Stephan, 2019)

ASCE 7-16 (2017) provides methods for analysis of the loads on overhangs, both for main wind force resisting systems (MWFRS) and component and cladding (C&C) loads, but the commentary does not provide any information as to the maximum length of overhang for which this analysis is valid. In section 30.9, it states that the pressure on the bottom covering of the roof overhang is the external pressure coefficient on the adjacent wall surface as implemented by Vickery (2008). This assumption was adopted more recently in the ASCE 7-16 (2017).

In this study a wind tunnel testing was carried out using two large-scale models with different overhang lengths to investigate how the pressures on the wall relate to the overhang and for what distance. In addition, it was important to investigate at what point does the wall pressure cease to affect the overhang for both positive and suction pressure. This paper presents the experimental setup and some of the experimental results and findings.

EXPERIMENTAL SETUP

The experimental test was conducted at the Wall of Wind (WOW) Experimental Facility at Florida International University (FIU). Two models with a hip roof of slope 4:12, and full-scale horizontal dimension of 40 ft (12.2 m) by 50 ft (15.25 m) with eave height 24 ft (7.3 m) were fabricated at a geometric scale of 1:10. The two models of two different inclined overhang length, 2 ft (60 cm) for model A and 6 ft (1.8 m) for model B (see Figure 2 and Figure 3), were placed on the turntable at the WOW. Pressure taps were added on the walls, the top surface of the overhangs and the bottom surface of soffits, as well as on the roof area adjacent to overhangs.



Figure 2. Model A placed on the turntable at the Wall of Wind.



Figure 3. Model B placed on the turntable at the Wall of Wind.

The pressure taps on the roof and overhangs were placed within zone 3 and 2e as specified in ASCE 7-16 (see Figure 4). The pressure taps were connected to a sensitive pressure scanning system (Scanivalve ZOC33). The experimental tests were conducted for 40 wind directions for each model (i.e., $0^{\circ} \rightarrow 360^{\circ}$ with increments of 10 degrees plus the four major cornering winds), (see Figure 5) with a target wind speed of 40 mph (17.88 m/s) generated by the fans. The sampling time for each direction was 60 seconds and the sampling frequency was 520 Hz. Model A had 345 pressure taps and model B had 360 pressure taps, placed on walls, soffits, and roof with overhangs. The pressure taps were added on two sides only, of each model since the models are symmetric and were tested for 360°.

The two models were tested for two terrain roughnesses (open terrain for $z_0=0.02$ m and suburban terrain for $z_0=0.2$ m, i.e., category 'C' and category 'B' per ASCE 7, respectively). The nominal wind speed at roof mean height varied between the two

terrains because of turbulence generated from the roughness elements and spires upstream of the turntable, resulting at 22.3 m/s for open terrain and 20.9 m/s for suburban terrain. Representative results from the open terrain are presented in this paper.





Figure 4. Assigned zones for hip roof adopted from ASCE 7-16 (2017) RESULTS AND DISCUSSION

Figure 5. Wind directions tested at the WOW.

The acquired raw data from each pressure tap measure the relative pressure between the pressure at the tap location and the static pressure at the WOW in psf. First, a transfer function was applied for correction of the tubing distortion - a onetime process done for any wind testing project using flexible tubing to connect pressure taps to the pressure scanners. The purpose is to correct the distortional pressure data caused by the length effect of the tubing (Irwin et al. 1979). Afterwards, a post-test Partial Turbulence Simulation (PTS) was performed to account for the missing low frequency part of the spectrum at WOW (Mooneghi et al. 2016; Moravej 2018).

Pressure Results

The pressure scanning modules used in the aerodynamic test measure the relative pressure in psf. These pressure values are presented in this paper as normalized pressure coefficients (Cp) computed using equation 1, where ΔP is the relative pressure at the tap location, ρ is the air density 1.225 kg/m^3 , and V_{ref} corresponds to the mean wind speed at mean roof height 34.5 in (87.5 cm). Statistical pressure coefficient parameters were also computed by using their corresponding pressure change parameters, as shown in equation 2 and 3. Peak pressure coefficients are referred to the minimum (highest suction/negative pressure) and maximum (highest positive pressure). The peak pressure is calculated as a function of the peak pressure coefficient occurred during the subinterval, the resultant wind speed for that subinterval and flow density (Moravej et al. 2019). The resultant wind speed composed of the mean velocity over the subinterval and each of the low frequency turbulent velocity component, u_{L} , u_{V} , u_{W} . The partial turbulence simulation method uses Fisher Tippet Type 1 distribution in estimating the probability of the peak pressure coefficient for not exceeding that peak pressure coefficient in the subinterval. The peak pressure coefficient for each interval is

calculated based on the peak pressure and the mean velocity of the full sample period with full spectrum turbulence and it is based on mean hourly dynamic pressure. The peak pressure coefficient for 3 sec is obtained by rescaling using equation 4 which is based on 3-second dust dynamic pressure.

$$Cp = \frac{\Delta P}{0.5 \,\rho \, V_{ref}^{2}} \tag{1}$$

$$C_{p\,mean} = \frac{P_{mean}}{0.5\rho V_H^2} \tag{2}$$

$$C_{p \, peak} = \frac{P_{peak}}{0.5\rho V^2} \tag{3}$$

$$C_{peak \, 3-sec} = C p_{peak} \left(\frac{U}{U_{3-sec}}\right)^2 \tag{4}$$

For model A, the peak min Cp near the overhang corner was -3.9 for open terrain, and -3.0 for model B (see Figure 6). It was apparent that the 2 ft overhang was exposed to higher peak min Cp near the edge compared to the 6 ft overhang. This was attributed to the high velocity in the z-direction at the edge, due to the walls that lead part of the flow over the roof (Wiik and Hansen 1997). Similarly, the 2 ft soffit and its adjacent wall was exposed to slightly higher positive Cp than the 6 ft soffit and its adjacent wall (see Figure 7 and Figure 8).



Figure 6. Peak Min Cp for part of the south roof with overhangs at wind direction of 180° for (a) Model A (b) Model B



(a)



(b) Figure 7. Peak Max Cp for soffit at wind direction of 180° for (a) Model A (b) Model B



(b) Figure 8. Peak Max Cp for walls at wind direction of 180° for (a) Model A (b) Model B

Correlation of Soffits and Adjacent Walls

The pressure taps in the walls and soffits were placed with equal spacing, to compare the Cp of upper taps in the wall with the adjacent taps in the soffit using correlation analysis (see Figure 9 and Figure 10). For all the figures that include the wall and the soffit, the shorter side of the soffit is the wall side (upper side), and the longer side of the soffit is the edge side (lower side). The taps in the black dashed box used as sample for middle taps correlation, between wall taps and soffit taps.

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Figure 9. Location of pressure taps of wall and soffit for Model A

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It is apparent from Figure 11 and Figure 12 that the peak max Cp were very similar along the adjacent taps in all wind directions, while the peak min Cp slightly changed for soffit taps located away from the wall. For instance, for wind directions from 135° to 225°, the wall and soffit taps were mainly exposed to positive pressure, thus, the peak min Cp ranged from 0 to -1.0, while the positive Cps values were very similar around 1 to 1.5. This supports the assumption in ASCE7-16 that the pressure coefficient at the bottom covering of the roof overhang shall be taken as the external pressure coefficient and appears not to be applicable for negative pressures. The edge pressure taps in the soffit experienced more suction compared to the middle or the inner row. The soffit exposed to more turbulence underneath and this turbulence increased near

the edge where more separation occurs. Consequently, pressure taps at the soffit edge had higher peak min Cp than the middle and inner taps.



Figure 11. Peak Max and Peak Min for wall and soffit middle taps for Model A



Figure 12. Peak Max and Peak Min for wall and soffit middle taps for Model B

Moreover, one of the objectives of this research study was to correlate the effect of wall pressure to the soffit pressure and investigate how the length of soffit would affect this correlation. Correlation coefficients are used to measure the relation between two variables and one of the most common forms is the Pearson's correlation (R factor) shown in equation 5 which ranges from 0 (no correlation) to 1/-1 (perfect correlation).

$$R = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}}$$
(5)

Figure 13 and Figure 14 provide correlation coefficient contour plots for soffit of model A and model B, respectively, for three wind directions (0° , 180° and 270°). As stated before, for all the soffit plots, the wall side is the upper side of the plots, and the soffit edge is the lower side. Both models show similar correlation coefficient when the models were placed in the windward direction (180° degree). The correlation coefficients for model A are significantly higher at the outer edges compared to case B, for all other shown directions. For wind direction 270°, where the taps dominantly exposed to suction, the correlation coefficients for model B decreased towards the edge. This indicates that the correlation coefficients for longer overhang significantly

decrease compared to shorter overhangs, especially when the taps are exposed to suctions.



Figure 13. Correlation Coefficients contour plots for Model A soffit.



Figure 14. Correlation Coefficients contour plots for Model B soffit.

CONCLUSIONS

Based on experimental testing results and discussion, the following concluding remarks can be drawn:

- The 2 ft inclined overhangs were found to have higher pressure coefficient at the edges compared to the 6 ft overhangs.
- The length of the overhang did not seem to have a considerable effect on the absolute positive pressure correlation between walls and soffits but has a recognized effect on the negative pressure correlation.
- The 6 ft soffit seemed to be less correlated at the edge with the wall upper taps compared to the 2 ft soffit.
- The correlation coefficients for longer soffits with the wall significantly decrease compared to shorter soffits, especially when the walls and soffits are exposed to suctions.
- The soffit pressure coefficients should be taken as the adjacent wall external pressure, as stated by ASCE7-16 for positive pressure only, while this shall not be applicable for suction pressure, especially for overhangs of length more than 2 ft (the most common length of overhangs).

References

ASCE. (2010). "Minimum design loads for building and other structures." American

Society of Civil Engineers, ASCE/SEI 7-10, Reston, VA.

- ASCE. (2017). "Minimum Design Loads and Associated Criteria for Buildings and Other Structures." American Society of Civil Engineers, ASCE/SEI 7-16, Reston, VA.
- Candelario, J. D., Stathopoulos, T., and Zisis, I. (2014). "Wind Loading on Attached Canopies: Codification Study." *Journal of Structural Engineering*, 140(5), 04014007.
- Irwin, H., Cooper, K. R., and Girard, R. (1979). "Correction of distortion effects caused by tubing systems in measurements of fluctuating pressures." *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 5(1–2), 93–107.
- Mooneghi, M. A., Irwin, P., and Chowdhury, A. G. (2016). "Partial turbulence simulation method for predicting peak wind loads on small structures and building appurtenances." *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 157, 47–62.
- Moravej, M. (2018). "Investigating scale effects on analytical methods of predicting peak wind loads on buildings." Florida International University.
- Moravej, M., Irwin, P., and Chowdhury, A. (2019). "A Simplified Approach for the Partial Turbulence Simulation Method of Predicting Peak Wind Loads." *The 15th International Conference on Wind Engineering*, (September), 4–7.
- Stephan [iamStephan] (2019, Sep 9). Aerial Footage of Great Guana Cay (Baker's Bay), Abaco after Dorian (2/2) [Video]. Youtube. https://www.youtube.com/watch?v=92PutXku0xU
- Taher, R. (2007). "Design of Low-Rise Buildings for Extreme Wind Events." Journal of Architectural Engineering, 13(1), 54–62.
- Vickery, P. J. (2008). "Component and Cladding Wind Loads for Soffits." *Journal of Structural Engineering*, 134(5), 846–853.
- Wiik, T., and Hansen, E. W. M. (1997). "The assessment of wind loads on roof overhang of low-rise buildings." *Journal of Wind Engineering and Industrial Aerodynamics*, 67–68, 687–696.
- Zisis, I., and Stathopoulos, T. (2010). "Wind-Induced Pressures on Patio Covers." *Journal of Structural Engineering*, 136(9), 1172–1181.
- Zisis, I., Raji, F. and Candelario, J. D. (2017). "Large scale wind tunnel tests of canopies attached to low-rise buildings." *ASCE Journal of Architectural Engineering*, Vol. 23 (1).

Analysis of Complex Flow Characteristics from Field and Simulated Hurricane Measurements

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ABSTRACT

Complex local flow regions occur on structures due to separation, edge vortices, reattachment, local acceleration and deceleration effect, which causes non-uniform pressure loads and even incipient structural failures. This effect is amplified further in scaled wind tunnel measurements as evidenced by many recent researchers. Researchers at the Florida Institute of Technology (FIT) have developed a wireless sensor network system (WSNS) for localized multi-point field measurement of hurricane/storm wind pressure on residential structures. This system with pressure sensors and an anemometer were installed on roof of a residential house located at Satellite Beach, FL to measure during Hurricane Isaias, when we collected 78 hours of data from August 1, 2020. Twenty-five pressure sensors and an anemometer were installed on the roof and walls of a full-scale house model mounted on a rotating table in the Florida International University (FIU) Wall-of-Wind (WoW) hurricane simulation facility. WoW measurements were made for 0° to 315° wind for wind speeds ranging from 30 to 145 mph under both dry and rainy conditions. Data for periods of strongest Hurricane Isaias wind, where the pressure variation is large were analyzed. The WoW test data for the similar conditions was then analyzed and compared. The power spectrum density (PSD) plots, for the intensity of the pressure fluctuations at different frequencies, showed similar trends for the regions of corner vortices and separation effect between Isaias and WoW test. However, the randomly changing wind speed and direction of natural hurricane caused an attenuated PSD distribution. Further details of similarity and differences between field and WoW measurements are discussed in the paper.

Experimental Process

To monitor the wind performance during hurricane, the WSNS is built to measure the absolute pressure, wind speed and direction on the residential house. The architecture of the system contains sensors, wireless network and software subsystems (Kostanic, et al., 2008; Subramanian, et al., 2020). The sensor subsystem contains pressure sensors and anemometer nodes. The sensors on the house also measure temperature and, humidity if required. A Reference pressure sensor is installed at the no-wind location (attic or near ground in patio). Wireless network created by Xbee modules carries the communication between all nodes (sensors) and a coordinator (base unit). The Xbee modules transfer the data packages to the coordinator wirelessly. The coordinator receives the packages from all nodes, and transfers to the data acquisition software
through serial port of the computer where the data are saved as csv file. The packages received are also uploaded to DesignSafe-CI project online storage if there is internet access during measurement, shown as Figure 1 (Subramanian, 2020).



Figure 1 WSN System deployment configuration with Anemometer, Pressure Sensors and Reference Pressure Sensor.

Hurricane Isaias, Category 1 hurricane, moved up along the east coast of Florida (Latto, Hagen, & Berg, 2020) with the tropical storm winds. The WSN system was installed on the roof of a house in Satellite Beach, Florida, referred to as Jack's house, the measurement included 10 pressure sensors and an anemometer of previous generation of the WSNS. In addition, to compare the performance of the new generation system, a pressure sensor and reference pressure sensor are installed on the Jack's house. The reference pressure sensor was installed under the porch of the house where the wind was blocked by the bushes. In Figure 2, sensors 72, 74, 75, 77, 79, 82, 83, 84, 85 and 87 were from old WSNS and sensors 1 and 11 were from the new system (Wang J. , 2021). Jack's house is 8.9m wide from east to west and 18.1m long from north to south. The length of the house is not shown completely in Figure 2 because no sensor is deployed on the rest area. The anemometer was located 2.2m above the ridge on east side to measure free stream velocity and direction during hurricane, as it shows in Figure 2. The location of the anemometer was chosen for less wind blockage of neighboring buildings and vegetations.



Figure 2 WSNS Deployment Sensor Locations on Jack's House During Isaias, 8.9m east to west and 18.1m north to south (incomplete sketch)

The FIU Wall of Wind (WoW) is the experimental facility that simulates hurricane wind. The large-scale model house (3.2 m x 3.4 m x 2.9 m) was fixed on the turntable in Figure 3. The 12-fan array can generate winds up to the strength of Category 4 (131 to 145 mph). Twenty-five pressure sensors (new system) including a reference pressure sensor and an anemometer of the system were installed. They were located, 4 sensors on the soffit, 6 sensors on the vertical sidewalls and 14 sensors on the roof. The WoW is equipped with adjustable spires to achieve different upstream terrain requirement, including open, suburban, and urban terrain conditions. Urban terrain is simulated for this test. The WoW tests were performed under dry and wet (simulating 2"/hr. rain) conditions for 30 to 145 mph wind speeds and directions of 0 to 315° with 45° increment, as indicated in Figure 4. In Figure 4, blue circles indicate the WSNS sensors and black dots the Scanivalve taps. The angles around the model indicate the wind direction with reference to the model (Wang J., 2021).



Figure 3 Setup of the Model House, showing the Turntable, and the Fans.



Figure 4 Test Layout of WSNS Sensors and Scanivalve Taps on the Roof

Each pressure sensors sampled at 10 samples per second, the anemometer sampled 1 speed and direction per second. Figure 5 shows a snapshot of wind speed and direction during Isaias (Wang J., 2021). We compare the fluctuating pressure characteristics by spectral analysis of the pressure measurement on the roof when the wind speed reaches the maximum value in Isaias WoW test. During Isaias, the maximum wind speed accrued at UTC 2250 August 2 when the pressure reached to the lowest level with the approximately 45 ° (Northeast) wind direction, see Figure 5. For WoW, we picked 2 minutes test of 60 mph at 45°, where the corner vortex is generated near the windward corner. The test Figure 6 shows the visualization of the corner vortex at 45° by testing in WoW of a flat roof at 45° (Chowdhury, Moravej, & Zisis, 2019), which shows that the vortex develops along two windward edges. Vortex develops two conical structures, where sensors are located as suggested in the results of a hurricane. The sensors were located in the conical structures along the edge for Isaias and WoW test where the vortex affects the intensity of pressure fluctuations. The acceleration effect acting on the roof downstream reduces pressure fluctuation, but the separation acting on the downstream area increases the pressure fluctuation.

The WoW can simulate the hurricane winds up to Category 5, the authors believe that the intensity of fluctuation of the pressure on a natural hurricane is not uniformly distributed with respect to the frequency, unlike in the simulated hurricane. The power spectrum density (PSD) is widely used to quantify the spectral energy distribution for a stationary window of data. The energy distribution with respect to the frequency reflects the average energy of fluctuating pressure. In this case, the frequency reveals the size of the eddies of flow, because the large eddies fluctuate slowly and produce the low frequency of PSD, or vice versa. The spectral analysis plots are accordingly from sensors 74, 77, 82 and 84 for Isaias and sensors 27, 26, 25, 23, 22 and 21, which

are located in the region of corner vortex in WoW test. Figure 7 shows the time series of absolute pressure variations for these WSNS sensors during Isaias. The PSD plots are created at the minimum point of pressure measurement (Wang J., 2021). The PSD plots of the sensor for both measurements show the similarity and differences between natural and simulated hurricanes. The magnitude of the PSD at a certain frequency indicates the domination of the power for a certain size of the flow eddies (Wang J., 2021). The smaller size of eddies reflects the higher frequency on PSD plots or vice versa.

The measurements in WoW are performed at the fixed angle and speed, by definition, the measurement is stationary. However, the field hurricane measurement data needs a stationarity check to determine the length of the data set used for spectral analysis. For the natural hurricane Isaias, where pressure varies with time, a time series of pressure data is assumed stationary with time (300 seconds of duration approximately). The length of the stationary window of pressure is determined by Mann-Kendall Test (MKT). The output of MKT is the Boolian value to indicate whether to reject the null hypothesis (no trend presented in the given data series). At the point where the pressure is at the minimum, and the speed is the highest level, the averaged maximum length of stationary on pressure among sensors is around 500 seconds to reject the null hypothesis of MKT. In the end, 400 seconds (80% of the averaged length of stationary) of pressure data at Isaias is used for spectral analysis to ensure stationarity.



Figure 5 Wind Speed and Direction Measured by WSNS Anemometer During Isaias

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Figure 6 Corner Vertex Visualization by Chowdhury, et al. 2019



Spectral Analysis Result

The PSD plots of sensors during the Isaias (Left) and WoW test (Right) at 45° and 60 mph along gable line are shown in Figure 8, where the y-axis is PSD, and the x-axis is the frequency. The range of the frequency axis is 0 to 0.6 Hz. Most of the PSD distribution peak occurs between 0 to 0.15 Hz for Isaias measurement. Also, 0.07 Hz separates the frequency between larger and smaller eddies. For the WoW test, the PSD is uniformly distributed.

First, the PSD showed similar trends for the regions of corner vortices and separation effect between Isaias and WoW test. Due to the corner vortices effect along the edge

of the roof, increasing PSD is observed from sensor 74 to 82 for Isaias and 27 to 25 for WoW where the energy of fluctuation of pressure grows. The separation effect acts right after the ridge at the leeward roof in addition to the effect of corner vortices, the strength of pressure fluctuation and suction peak during both Isaias (sensor 84) and WoW (sensor 23) Sensors 21 and 22 show the reattachment of the flow and gradually decreasing strength of fluctuation. The flow gradually "calms down. Unfortunately, there wasn't a sensor deployed on the corresponding location for Isaias, hence the reattachment effect could not be established for a natural hurricane.



Figure 8 The PSD Plot of Sensors Installed at East Eave During Isaias-2020 when the Speed Reached Highest Value (Left) and Sensors 27 to 21, Installed at North Eave during WOW-2020 (Right)

Second, the PSD plots of WoW shown in Figure 8 (right) are broadly distributed along the x-axis, which suggests a more uniform fluctuation with respect to frequency. In contrast, the PSD for the natural hurricane is concentrated in the lower frequency domain. Most of the energy is contained in the low-frequency fluctuations. This phenomenon is also occurring in the area without the corner vortices and separation effects such as Sensor 1 during Isaias, shown in Figure 8 (left). Hence the natural hurricane contains slow-moving flow eddies (large eddies) which make the pressure variations at long periods but keep the time-averaged pressure constant, as shown in Figure 9. On the top of Figure 9, Isaias pressure plot indicates some low-frequency fluctuations in pressure highlighted with the red lines, but the pressure of WoW doesn't show such low frequencies.





Figure 9 The Time Series Pressure Plots in Isaias (Top) and WoW Test (Bottom). The Red Line Shows the Trend of Slow Variation on Pressure at a Stationary Windowfor Isaias.

Discussions and Conclusions

The old version of WSNS was used for measurement during Isaias (Sensor 1 is the new version sensor), and the new version is used in WoW. The biggest approvement of the new WSNS is reducing the base noise of measurement which influences the spectral analysis as well. The base noise of pressure for new WSNS is much less than that of the old WSNS, enabling better resolution of the fluctuating pressure. This is evident in Figure 10, where the measurement by the new system has less root mean square and generates less noise than that measured by the old system, which indicates less PSD value contributed by the base noise, which is the reason that sensor 1 in Figure 8 (left) contains less PSD than other old WSNS sensors, but similar uneven distribution trend during Isaias.



Figure 10 The Comparison of the Pressure Measurement Noise Between New and Old System Measured at Same Time and Location.

The spectral analysis focus on the pressure fluctuations acting on the windward and leeward edge of house with the effects of acceleration, separation, and corner vortex. The qualitative comparisons and similarities of PSD at different sensor locations on a gabled roof between a natural hurricane and a WoW test are analyzed with the PSD plot. On the windward side, the acceleration of the flow, due to the sloped-up roof, acts at the same location of corner vortices to decrease the strength of pressure fluctuations. In contrast, the corner vortices increase the strength of pressure and PSD value with the frequency. Due to the obvious increasing PSD values with the position on the roof, shown in Figure 8, the corner vortices dominate PSD increment. The separation effect at the location after the ridge of the flow generates the disturbance of the flow

associated with the increment of intense PSD distribution in the frequency domain in both Isaias and WoW results. The corner vortex effect of experimental results is matched well with the hurricane. Both field and experiment results prove that the vortex strengthens the fluctuation of the flow and increases the PSD of pressure over the frequency domain.

The uneven PSD distribution in frequency domain for both measurements are different since hurricanes are not steady as the lab simulated condition, in which the constant speed hurricane affects the pressure. The freestream turbulent properties for a natural hurricane are not the same for simulated hurricane wind. Accordingly, the WoW's wind lacks large motions which change the flow properties, over a long period.

The WSNS measures the pressure on the surfaces of the house model at 30 mph, 90 mph 120 mph, and 145 mph. To show the spectral property independence with speed, pressure and PSD plots for corresponding sensors along the east edge at speeds 30 mph, 60 mph, 90 mph 120 mph and 145 mph at 45° are given in Figure 11 and Figure 12. Figure 11 shows absolute pressure fluctuation at different speeds on sensor 23 as an example. Apart from lower mean pressure readings, the magnitude of the pressure fluctuation is greater which enlarges the PSD values as shown in Figure 12. As shown in Figure 12, the increment of speed does not influence the distribution of PSD with respect to the frequency.



Figure 11 Pressure Fluctuation Magnitude for Sensor 23 at Different Speeds

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Figure 12 PSD Plot for Sensor 27, 26, 25, 22 and 21 for Wind Speed 30 mph, 60 mph, 90 mph 120 mph and 145 mph at 45°

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References

- Chowdhury, A. G., Moravej, M., & Zisis, I. (2019). Mitigation of Aerodynamic Uplift Load. *Frontiers in Built Environment*, 10. doi:10.3389/fbuil.2019.00010
- Kostanic, I., Subramanian, C., Pinelli, J.-P., Velazquez, A., Otero, C., Witterfeldt, A., . . . Bronzwaer, T. (2008). Wireless Sensor Network for Monitoring of the Hurricane Winds. *Sensors*, 1-12.
- Latto, A., Hagen, A., & Berg, R. (2020). TROPICAL CYCLONE REPORT-HURRICANE ISAIAS. National Hurricane Center.
- Subramanian, C., Pinelli, J.-P., Lazarus, S., Sridhar, S., Zhang, J., Wang, J., ... Besing, H. (2020). Wireless Networked Data Sensors for Hurricane Monitoring-

Deployment Guide and User Manual. Melbourne, FL: Florida Institute of Technology.

- Subramanian, C., Pinelli, J.-P., S., L., Sridhar S., Z. J., Sun, J., & Besing, H. (2020). *NIST Award # 70NANB19H088 - Performance (Technical) Report*. Melbourne, FL: NIST.
- Wang, J. (2021). Testing and Performance Analysis of a New Wireless Sensors Network (WSN) System for Hurricane Monitoring. Melbourne, FL: Florida Institute of Technology.
- Wang, J., Sun, J., Subramanian, C., Pinelli, J.-P., & Lazarus, S. (2021). Development ofaWireless Sensor Network forHurricane Monitoring. 6th American Association for Wind Engineering Worksho. Clemson, SC.

Development of Smart Watering Algorithm To Improve Biowall Performance

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ABSTRACT

A 1920's era bungalow-style home located in West Lafayette, IN was recently renovated to demonstrate a variety of sustainable and energy efficient technologies. The upgrades include high levels of insulation and air sealing, geothermal heat/cooling, energy recovery ventilation, and solar energy. The house also demonstrates several novel technologies, such as a system for water re-use and a Biowall that improves indoor environmental quality and aesthetics inside the home. The Biowall consists of plant trays with loose growth media that are integrated into the return duct of the central air conditioning system. As the ventilation air is gradually pulled through the root zone of the plants, microbes slowly metabolize Volatile Organic Compounds that can accumulate in airtight homes.

This paper describes the overall Biowall, but also introduces a smart watering algorithm that improves performance by automatically adjusting the amount of water to the plants. Experience with the Biowall has shown that a simple time-based watering sequence tends to over-water or under-water depending on the season, varieties of plants, and the characteristics of the plant growth media. The improved watering algorithm uses real-time measurements to increase/decrease the amount of water delivered to the plants on a given day. This is accomplished with a local controller that regulates watering, lighting, and air flow and collects data on Biowall performance. Preliminary data shows that the smart watering algorithm improves the health of the plants by delivering the right amount of water based on the season and other operational constraints.

INTRODUCTION

Figure 1 is a 1920's era bungalow style home located in West Lafayette, IN called the ReNEWW house. The home was used for many years as a rental for university students, but since 2015 it has become a living laboratory for demonstrating sustainable technologies for residences. Recent renovations added high levels of insulation and air sealing, triple paned windows, geothermal heating/cooling, water re-use and storage, energy recovery ventilation, and solar energy (ReNEWW, 2021). Graduate students who live in the house while attending school also manage many of the ongoing research projects. The home's energy, water, waste, and environmental conditions are tracked as part of the comprehensive site monitoring plan.



Figure 1. A 1920's era bungalow-style home showcases sustainable technologies.

The ReNEWW house is also hosting a field demonstration for a Biowall, which has a goal of improving indoor environmental quality and overall aesthetics. Figure 2 shows the Biowall's prominent location in the main living/dining room. The green plants add visual appeal to the room that would otherwise be rather plain. Although lighting and watering is controlled automatically, the homes' occupants are encouraged to pay attention to the Biowall's plants by occasional light maintenance of the trays.



Figure 2. The Biowall is located in the living room of the ReNEWW house.

BIOWALL DESCRIPTION

Figure 3 shows that the Biowall consists of a stainless steel frame and four removable plant trays. Perforations in the bottom of each tray allow air to pass through the loose growth media, through the back duct in the closet, and into the return duct of the central air conditioning system. A fan on the back of the Biowall operates along with the central air conditioning system, gradually pulling return air from the living room and through the root zone of the plants. Microbes in the loose soil slowly metabolize Volatile Organic Compounds that can accumulate in indoor air of airtight homes.



Figure 3. Air passes through the loose soil media in the Biowall.

U.S. Patent #10,477,779 was issued in 2019 for this design (Biowall, 2021). There are a number of other competing patents with similar features, so the claims of the patent are narrowly interpreted in terms of the physical implementation described here. There are no claims relative to the natural ability of plants to metabolize airborne contaminants because that aspect has been widely demonstrated and deployed by other researchers and commercial enterprises. The three primary claims of the patent are the:

- enclosure with removable plant trays
- controls for lighting, watering, and airflow
- integration with the HVAC system of a building

The Purdue University Office of Technology estimates that the Biowall is at Technology Readiness Level of 8. This means that the Biowall system has been shown to work in a demonstration setting but additional work may be needed before commercialization. This paper describes both the overall Biowall demonstration and recent efforts to improve the operation of the watering algorithm.

Figure 4 is a front view of the Biowall showing the plants, which were selected based on a widely cited report compiled by NASA for plants that have beneficial air cleaning characteristics (Wolverton, 1989). Other factors in the plant selection process include overall hardiness and a desirable physical appearance/color. The entire upper tray in Figure 4 is a wandering jew, a fast-spreading plant with a green/purple color. The remaining plants are a mix of Golden Pothos, Philodendron, Candelilla, Aloe Vera, Spider Plant, and Snakes Tongue.

Figure 4 also shows the LED grow lights in each tray that provide artificial sunlight. The lights operate on a timed basis, typically from 8 AM in the morning to 6 PM at night. The occupants of the house have a local over-ride to turn on/off the LED lights as needed.

Figure 5 is a close up of one plant tray that shows the growth media that was specifically designed to allow air to flow through it. The growth media is a three part mix containing growstone (gray) for porosity, coco-coir (brown) for water holding capacity, and activated carbon (black) to capture airborne contaminants.

Figure 5 also shows the simple watering mechanism for each tray. A solenoid valve (not shown) turns on/off the water on a timed basis. A small pressure independent emitter, more typically used for outdoor gardens, supplies a steady water flow. Emitters range from 0.5 to 5 gph. The emitter is connected to a weeper hose that distributes water.



Figure 4. The Biowall has several types of plants.



Figure 5. Water is supplied to the plants by a weeper hose.

Figure 6 shows the back of the Biowall in the cramped living room closet. The green dashed line is the path of the air through the Biowall, past an axial fan, and into the return duct for the home. This view also shows the blue and white PEX water lines to the plants, sensors that monitor air characteristics, and the computer that enables webbased monitoring and control.



Figure 6. The back of the Biowall connects to a return duct.

Figure 7 is one part of a graphic user interface that provides a homeowner with a basic overview of Biowall performance via a smart phone or table (Hutzel, 2021). The dial gage on the left is an "Environmental Index" a simple metric for Indoor Environmental Quality that is computed in real time from measurements of temperature, humidity, and VOC levels inside the home. The dial gage on the right shows the amount of air flowing through the Biowall based on air changes per day. Additional graphics with detailed information on lighting, watering, airflow, and power consumption are also available, but those screens are primarily intended for individuals responsible for day to day Biowall operation.



Figure 7. A graphic user interface summarizes Biowall operation.

It is difficult to quantify the air cleaning performance of a Biowall in a field demonstration because there are so many external factors that influence the measurements. The best assessment of Biowall operation so far was conducted in an environmental chamber with controlled conditions (Alraddadi, 2016). A 'pull-down' test method, in which a known amount of contaminant was introduced to the chamber so that its decay could be monitored over time, was used for the evaluation. The decay rate of the contaminants with the Biowall present was then compared to the decay rate of an empty chamber and the growth media alone (without plants). The experiments also evaluated the filter at different airflow rates across the filter and different moisture content inside the growth media.

Based on the experimental data, the Clean Air Delivery Rate (CADR) of the Biowall were quantified. The preliminary results showed that the Biowall removed up to 90% of the introduced contaminants within two to three hours inside a sealed environmental chamber. This could potentially translate into energy savings on the ventilation systems of up to 25% by partially offsetting the need for outdoor air for fresh air ventilation. In addition to savings on ventilation, the Biowall could contribute to savings in heating and cooling energy by reducing the air temperature during summer months, and reducing the air dryness during the winter months. Beyond these quantifiable benefits, a Biowall provides an intangible benefit by adding a pleasant natural aesthetic to a home.

BIOWALL WATERING MECHANISM

The Biowall watering mechanism is a relatively simple apparatus to provide a small amount of water at regular intervals to help maintain the plants. The water is supplied to the Biowall by the domestic water in the house at approximately 60 psi. The seven main components of the watering mechanism are:

- 1. pressure reducing valve manual valve that reduces the water pressure to 40 psi
- 2. **solenoid valve** automated valve that opens or closes based on a signal from the controller
- 3. **manual valve** one of four manual valves that turns on/off water to individual trays of plants
- 4. **emitters** a flow regulating device more commonly used in outdoor irrigation systems to maintain a constant water flow. Emitters are rated from 0.5 to 5 gph
- 5. **weeper hose** a perforated hose more commonly used in outdoor irrigation systems to slowly distribute water to plants as the hose slowly leaks
- 6. **leak detector** a 10' cable is routed beneath the Biowall to sense water. If any part of the cable is wet, it signals the controller to shut down Biowall operation
- 7. **drain** a catch basin beneath each plant tray captures and diverts water to a floor drain in the event of a leak or excess watering

The Biowall watering algorithm operates on a simple timed schedule. The controller opens the solenoid valve for several minutes at regular intervals each day. Each of the four trays of plants receives roughly the same amount of water. The plants thrive and have a pleasant appearance for several months, but over time the limitations of this basic watering strategy become apparent. Some of the plants begin to show stress by dropping their leaves when the airflow through the Biowall causes the moisture content of the growth media to fall outside the optimal range for the plants.

Experience has shown that the amount of water for a healthy Biowall is not static, but instead is dictated by the weather because of the run-time for the central HVAC system. During mild weather, when the central HVAC system does not run as often, excess moisture can accumulate in the Biowall growth media. During hot or cold weather, when the HVAC system runs for longer periods of time, the Biowall growth media can get too dry. The cycle of growth media that is either too wet or too dry puts stress on the plants and hurts the Biowall's appearance.

One obvious solution is to add soil moisture sensors to the Biowall growth media. The feedback from the sensors could be used to vary the amount of water provided to the growth media. This option has been tested and shown to be helpful, but soil moisture sensors have drawbacks. The main limitation is that they add additional cost and complexity to the controls. It is highly desirable to keep the amount of instrumentation to a minimum when pursuing Biowall commercialization.

IMPROVED WATERING ALGORITHM

A "smart" watering algorithm was developed to improve Biowall performance by varying the amount of water to the growth media based on environmental conditions. The main feature of this approach is that no additional instrumentation is needed. The algorithm uses a psychrometric analysis of the air entering and leaving the Biowall to quantify the rate that water is absorbed by the growth media. The goal of the algorithm is to achieve a steady-state moisture balance, where the rate of water being added is equal to the rate that moisture is being picked up by the air flowing through the growth media. The psychrometric evaluation identified three primary parameters that impact this moisture balance.

The first parameter for the watering algorithm is the amount of air and the state of the air flowing through the Biowall. Simply stated, the Biowall needs more water 1) at higher air flow rates and 2) when the air is dry. More water is needed in the cold winter months, when the HVAC system runs for longer periods of time and the dry air in the home extracts more moisture from the growth media. The watering algorithm quantifies the air characteristics based on real time measurements of temperature, humidity, and flow rate (cfm).

The second parameter for the watering algorithm is the characteristics of the growth media where the plants are grown. It is not surprising that soil with a higher amount of fibrous material retains moisture, while rocky soil gives up moisture more easily. The watering algorithm quantifies the growth media by measuring its moisture holding capacity. This parameter is constant, so it is measured one time, as the plants are initially deployed into the Biowall. This parameter is only changed when the mixture for the growth media changes.

The third parameter for the watering algorithm is the type of plants. Some plants want more water while others prefer drier conditions. This is partially determined by the root structures of the plants, but also by transpiration, the rate at which plant give off moisture to the surrounding environment. It can also be impacted by the maturity and physical size of the plants as they grow and develop. This parameter changes slowly, so this parameter is manually adjusted in the watering algorithm as the plants evolve.

Figure 8 shows the implementation of the watering algorithm in the Biowall controller. The vertical axis is the amount of time in minutes that water is provided to the Biowall each day. The horizontal axis is the amount of time in hours that the home's HVAC system operates each day. The three dashed lines in Figure 8 show various air flow ranges from "low" to "high". The Biowall changes from one airflow mode to another based on how much air is being pulled through the return duct. The Biowall is in a "low" airflow mode when only the Biowall fan is "on". The Biowall is in a "mid" airflow mode when the Biowall fan and the home's energy recovery ventilator are "on". The Biowall is in a "high" airflow mode when three fans (Biowall fan, energy recovery fan, and fan-coil unit) are "on".



Figure 8. The watering algorithm adjusts based on HVAC operation.

The red lines in Figure 8 show the upper and lower bounds of watering. These limits were determined based on direct observations of the Biowall over time. The watering algorithm is programmed to deliver at least 5 minutes of watering each day in any airflow setting. To prevent over-watering, the watering valve will not open for more than 15 minutes each day. These limits help maintain plant health by avoiding extreme watering events.

This smart watering algorithm is being evaluated in 2021. It has been shown to functionally operate as intended. The amount of time that the valve is open changes based on operating conditions. It is harder to evaluate the impact of the watering algorithm on Biowall performance because it is seasonally driven. The plants do not change on a daily or weekly basis, it is a mater of months until changes are detected. The qualitative data collected so far suggests that the smart watering algorithm will be a significant improvement to Biowall operation by helping maintain healthy plants.

CONCLUSION

An improved Biowall watering algorithm uses real-time measurements to increase/decrease the amount of water delivered to the plants on a given day. This is accomplished with a controller that regulates water, light, and air flow while collecting data on Biowall performance. Preliminary observations show that the "smart" watering algorithm improves the health of the plants by delivering the right amount of water based on the season and other operational constraints.

References.

- Alraddadi, O., Leuner, H., Rajkhowa, B., Boor, B., Dana, M., and Hutzel, W. (2016), Air cleaning performance of a biowall for residential applications, *Proceedings of the 4th International High Performance Buildings Conference at Purdue*, West Lafayette, IN, July 11-14, 10 p.
- Biowall for Residential Applications (2021), Purdue Office of Technology Commercialization, <u>https://inventions.prf.org/innovation/5918</u>, visited site on September 12, 2021.
- Hutzel, W., Liu, Henry, and Kim, J., (2021), Environmental index for real-time feedback on biowall indoor air quality, *Proceedings of the 6th International High Performance Buildings Conference at Purdue*, West Lafayette, IN, July 13-16, 10 p.
- ReNEWW House. (2021). Retrofit Net Zero Energy, Water & Waste, <u>https://www.whirlpoolcorp.com/reneww-house/</u>, Visited site on 9/9/2021.
- Wolverton, B.C., Johnson, A., and Bounds, K. (1989). Interior landscape plants for indoor air pollution abatement, NASA, John C. Stennis Space Center Science and Technology Laboratory.

Machine learning based surrogate model for faster daylighting estimation in building design

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ABSTRACT

Over the years, computational lighting simulation software have become the industry standard for conducting daylighting analysis in the design of buildings. Such tools predominantly rely on computational graphics intensive algorithms such as ray casting and ray tracing to estimate daylighting inside buildings. Such ray tracing algorithms take longer computational time to execute even for a single point-in-time simulation of a single building design option, let alone analyzing multiple design alternatives. The overdependence on such complex daylighting simulation tools has led to limited exploration of the design space. Recent research suggests the benefits of leveraging machine learning techniques, where input and output data from large sets of previous daylighting simulations can be used to train an artificial neural network (ANN) model, which upon sufficient training shall be able to predict daylighting metrics for new building designs without having to perform an actual simulation. Building on top of this hypothesis, this paper presents a novel ANN based metamodel (also called as surrogate model) for spatial daylight autonomy (sDA) estimation along with a detailed explanation of the model architecture, training and testing process. Preliminary training results showcase promising trends in terms of the capability of the ANN based metamodel to predict daylighting values at lesser computational time and lower error as well.

1. INTRODUCTION

If building energy modeling are physics intensive computational problems, building daylighting simulations on the other hand are graphic intensive computational problems (Ayoub, 2020a). Over the years, computational lighting simulation software have become the industry standard for conducting point-in-time daylighting analysis as well as seasonal daylighting studies (seasonal averages) for any given building design.

To calculate the amount of light inside a building, simulation tools use a variety of information such as the building geometry (position, orientation, windows, apertures and openings, and shading devices), artificial lighting details (position and operating schedules), location of the building (latitude and longitude), adjacent building geometries (if any), and sky model of that particular location (an imaginary hemispherical dome with standardized illuminance distribution of the sky for various positions of the sun published by the International Commission on Illumination) (CIE DS 011.1/E-2001). Further, daylighting simulations help calculate a variety of metrics such as illuminance, daylighting factor (DF), daylight autonomy (DA), spatial daylight autonomy (sDA), continuous daylight autonomy (cDA), useful daylight illuminance (UDI) and daylight saturation percentage (DSP) that help evaluate the lighting quality of the building design. A summary of the definitions, calculation procedures and units of measurement of these metrics is provided in Table 1.

Predominantly, daylighting simulation tools rely on complex ray tracing or ray casting (relatively simple) algorithms to estimate the metrics in Table 1. On an intuitive level both these algorithms involve casting a ray from a light source (sun if natural and lighting fixture if artificial) to a point of interest inside the building and analyzing how this ray gets partially or completely obstructed or reflected by potential obstacles such as walls, windows, floors, roofs, etc., before reaching the target point. Based on the difference in illuminance at the source and target, it is possible to arrive at the lighting level (decreases if ray is obstructed and increases if multiple rays are reflected towards target) (Aizlewood et al., 1994; Carrol, 1999). Simple lighting simulation tools like EcotectTM (now defunct), HoneybeeTM and DIVA-for-RhinoTM model lighting as a function of daylighting (meaning ray tracing from sun), whereas more complex simulation tools like RadianceTM (uses ray tracing technique) and AGi32TM (uses radiosity technique) model lighting as a function of both daylighting and artificial lighting in buildings (meaning ray tracing from sun and other lighting fixtures in building) (Figure 1).



Figure 1: Simple daylighting simulations executing ray tracing to multiple grid point inside building from natural sources (skydome) (left). Complex lighting simulations executing ray tracing from both natural and electrical light sources (adapted from AGi32 Inc., 2018 manual) (right).

Unit	Lumen	lux	%	%	%	%	%	%
Calculation Procedure		 Divide floor into grid of points. Calculate illuminance at each point (Li et al., 2009). Plot grid points on floor with calculated illuminance values. 	 Divide floor into grid of points. Calculate illuminance at each point. Divide illuminance at each point by illuminance outside building. Plot grid points on floor with calculated DF values. 	 Divide floor into grid of points. Calculate illuminance at each point for different times of the day and the year (user defined time steps). Calculate number of hours where illuminance is above specified threshold (say 300 lux) for each point. Calculate (3) as a percentage of total number of daytime hours for each point. Plot grid points on floor with calculated DA values (4). 	 Divide floor into grid of points. Calculate illuminance at each point for different times of the day and the year (user defined time steps). Calculate number of points with illuminance above specified threshold (say 300 lux) for at least 50% of the time. Calculate (3) as a percentage of total number of grid points (which gives % of floor area above DA_{300lux} for at least 50% of the time. 	 Divide floor into grid of points. Calculate illuminance at each point for different times of the day and the year (user defined time steps). Calculate number of hours where illuminance is above specified threshold (say 300 lux) for each point. Calculate (3) as a percentage of total number of daytime hours for each point. For points with illuminance level below specified threshold, calculate number of hours based on a weighted mechanism where partial credits are assigned. Plot grid points on floor with DA values (4) for points exceeding threshold and weighted values (5) for points below threshold. 	 Divide floor into grid of points. Calculate illuminance at each point for different times of the day and the year (user defined time steps). Calculate number of hours where illuminance is between specified threshold (say 100-2000 lux) for each point. Calculate (3) as a percentage of total number of daytime hours for each point. Plot grid points on floor with calculated UDI values (4). 	 Divide floor into grid of points. Calculate illuminance at each point for different times of the day and the year (user defined time steps). Calculate number of hours where illuminance is between specified threshold (say 430-4300 lux) for each point. Calculate (3) as a percentage of total number of daytime hours for each point. Plot grid points on floor with calculated DSP values (4).
Definition	Amount of light that a source emits	Total luminous flux incident on a surface, per unit area	Ratio of illuminance inside building to illuminance outside building	Percentage of annual daytime hours that daylight exceeds a specified illuminance (say 300 lux)	Percentage of floor area where specified illumination threshold (say 300 lux) is achieved for at least 50 percent of the annual daytime hours.	Illuminance at a point at a particular hour/ illuminance threshold. For e.g., if Illuminance threshol = 300 lux and $\text{E}_{\text{point}} = 200 \text{ lux}$ DA = 0 cDA = $200/300 = 0.66$	Modified version of DA where the illuminance threshold is specified as a range (say 100- 2000 lux) instead of a single value.	Modification of UDI where the threshold range for illuminance is modified to 430 – 4300 lux.
Metric	Luminous Flux (φ) ϵ	Illuminance (E)	Daylighting Factor 1 (DF)	Daylight Autonomy [DA] (Association Suisse des Electriciens, 1989)	Spatial Daylight B Autonomy (sDA) ((LM, 2013) [Continuous Daylight Autonomy (cDA) (Reinhart et al., 2006b) t I I	Useful Daylight Useful Daylight (Iluminance (UDI) t (Nabil et al., 2005) 5	Daylight Saturation Percentage (DSP)
No.	1.	2.	3.	4	5.	é.	7.	<u>%</u>

Table 1: Various metrics for daylight evaluation of building design.

Further, such sophisticated daylighting simulation tools give better control such as finer discretization of geometry (more grid points), selection of more surfaces for evaluation (walls ceiling, desks and so on in addition to floors), a variety of output metrics from the above list in Table 1, finer discretization of time steps for annual daylighting level calculations and so on (Reinhart et al., 2006c). Most of these computational lighting simulation tools support rendering of false color renderings (grid cells color coded per the calculated daylighting values) on top of the evaluated surfaces (Figure 2).



Figure 2: Sample false color rendering showing spatial daylight autonomy values for an interior space with windows on one of the walls.

Simple tools are mostly confined to ray tracing to multiple grid points on the floor (providing false color renderings of floors), whereas complex tools can perform ray tracing to multiple grid points on all surfaces in a building (providing false color renderings of all surfaces) (Lehar et al., 2007) (Figure 3).



Figure 3: Simple lighting simulation of interior space in Diva-For-RhinoTM (Daylight only) (left) and detailed lighting simulation of interior space in RadianceTM (Daylight + Artificial light) (Ward, 1994) (right).

All these tools support both point-in-time simulations as well as lighting studies, which provide seasonal averages. Out of the various metrics used to evaluate the design for daylighting, spatial daylight autonomy is one of most useful metrics that helps determine if the interior of the building has sufficient daylighting (LM, 2013). However, executing ray tracing for multiple grid points for multiple timesteps is a computationally intensive process. Such ray tracing algorithms take longer computational time to execute even for a single point-in-time simulation of a single building design option, let alone conducting daylighting studies for multiple design alternatives.

2. METAMODELS FOR DAYLIGHTING ESTIMATION

To tackle this, AEC researchers have recently started to explore the use of real time raytracing algorithms that are used in games to render every frame in real time (Jones et al., 2017). Though these methods showcase promising trends in terms of drastically reducing the daylighting computation time as opposed to the traditional ray tracing algorithms (Ayoub, 2020b), they are still GPU (Graphic Processing Unit) intensive processes that require specialized computational hardware and setup. The overdependence on such computationally intensive daylighting simulations has led to limited exploration of the design space (lesser number of building design options evaluated for daylighting) (Cassol et al., 2011). Such limited exploration of the design space is detrimental for optimization.

Alternatively, recent research suggests the benefits of leveraging machine learning techniques, where input and output data from large sets of previous daylighting simulations can be used to train an artificial neural network (ANN) model, which upon sufficient training shall be able to predict sDA values for new building designs without having to perform an actual simulation (Ayoub, 2020a). Such daylighting prediction ANN models can be used as surrogate model (also called as metamodel – Simpson et al., 2001) to evaluate large sets of building design options for sDA at lower computational expense during early stages as opposed to using computer graphics intensive ray tracing or radiosity based simulations (Wortmann et al., 2015). Building on top of this hypothesis, an ANN based metamodel for sDA estimation was developed as shown in Figure 4.



Figure 4: Comparison of inputs, features and outputs of RadianceTM and DIVA-for-RhinoTM along with the ANN based metamodel for spatial daylight autonomy estimation.

3. MACHINE LEARNING BASED METAMODEL

Typically, any ANN model can be represented by a neural net architecture (or diagram) which has an input layer, hidden layer(s) and an output layer with each layer containing several neurons. Further, this model can be trained by processing large sets of samples (called as training data) each of which has a combination of known input and output values. Using the known input values and randomly assigned weights and biases to the neural net, an output value is predicted. Subsequently, the error between the predicted output and the known output is minimized by statistically adjusting the weights and biases using a technique called back propagation of errors (Rumelhart et al., 1986; LeCun et al., 1988). To understand this training process more intuitively, let us build a simple ANN model to predict the spatial daylighting when simple room geometries with a window on a wall are provided. To train this ANN model, let us use a simple dataset of four rooms with varying room and window sizes (inputs) and their corresponding sDA values (outputs) simulated by the tool RadianceTM (Table 2).

Samples	Room Length (ft) (x_1)	Room Width (ft) (x_2)	Window Length (ft) (x_3)	Window Height (ft) (x_4)	Simulated sDA (%) (y ₁)
Room1	10	15	6	3	47
Room2	20	25	9	3	89
Room3	30	35	12	3	74
Room4	40	45	15	3	63

Table 2: Sample training dataset containing input values and output (sDA) for four room design options.

In this example, the ANN model shall have one input layer with four neurons $(x_1, x_2, x_3, x_4$ representing room length, width, window length and height respectively), one hidden layer with three neurons (h_1, h_2, h_3) and one output layer with one neuron $(y_1$ representing the sDA) (Figure 5). In any machine learning model (ANN model), random weights $(w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9, w_{10}, w_{11}, w_{12}, w_{13}, w_{14}, w_{15})$ are assigned to each connection in the neural net whereas biases (b_1, b_2) are assigned to the hidden and output layers as shown in Figure 5. For ease of understanding, consider these weights as the statistical importance of each input node and bias as a mathematical constant in the hidden layer neurons and output neuron.



Figure 5: Sample setup for a simple ANN model to predict sDA using four inputs.

Subsequently, input values from each sample are assigned to the input layer. It should be noted that all values in the training database (in feet) should be normalized before assigning them to the neurons. For example, the room length, room width, window length, and window height values of the first sample in the training dataset (Room1) is normalized as 0.10, 0.15, 0.06 and 0.03 respectively and assigned to the respective neurons (Figure 6). Let us assume that the random values as shown in Figure 6 are assigned as the initial weights and biases.



Figure 6: Assigning random weights and biases.

Further, the output of each hidden layer neuron is calculated as the sum of a) the summation of the product of input values connected to that neuron and the respective weights assigned to those connections, and b) the bias assigned to the hidden layer neuron. For example, the value of hidden layer neuron h_1 is calculated shown in Figure 7.



Figure 7: Sample calculation of the value of a single neuron in the hidden layer.

In a similar fashion the values of the other hidden neurons h_2 and h_3 are also calculated (Figure 8).



Figure 8: Calculated values of all neurons in the hidden layer.

Next, in order to add non-linearity to the training dataset, activation functions are used. For example, sDA might not increase linearly by increasing any of the four input parameters or vice versa. Sometimes despite a larger window, the daylighting inside the building might be lower due to the depth of the building. When an actual daylighting simulation tool is leveraged, such relationships and interactions between the design variables are solved using pertinent building physics equations and ray tracing methods. On the other hand, to account for such aspects in ANN models which are statistically trained, non-linearity is introduced artificially by using mathematical functions called as activation functions. There are a variety of such functions such as sigmoid, tanh, Softmax, ReLU, Leaky ReLU (Hassoun., 1995). For example, if the value of hidden layer neuron h_1 (1.04) is substituted in the sigmoid activation function ($S(h_n) = 1/1 + e^{-h_n}$), we get a modified value of 0.74 as shown in Figure 9. Similarly, the other hidden layer neurons are also modified by substituting h_2 and h_3 values in the sigmoid activation function.



Figure 9: Modified values of hidden layer neurons after applying activation function.

Using these modified hidden neuron values, the output neuron value is estimated using the same procedure used for the hidden layer neuron value calculation (Figure 10). For the sample in consideration (Room1), the predicted output value is 0.65 (65%) (predicted sDA), whereas the simulated value for the same sample from RadianceTM is 0.47 (47%) (simulated sDA). The delta between the predicted and simulated value for this sample (Room 1) is called as loss function or simply error. All the sequence of steps illustrated above can be called as one feed forward cycle where inputs were used to predict the output neuron value.



Figure 10: Sample calculation of the output node value using a single hidden layer node.

Now, using a technique called as backpropagation of errors (Rumelhart et al., 1986), the randomly assigned weights and biases are adjusted with an objective of minimizing the loss function. It should be noted that the above prediction was done for one sample (Room1) from the training dataset (Table 2). Similarly, the feed forward cycle and back propagation mechanism are executed for all samples in the training dataset and the weights and biases are adjusted at every step. When the feedforward and backpropagation for all the samples in a training database are executed, it is called as one epoch (one learning cycle) in machine learning terminology (Müller et al., 2016; Géron, 2019).

In our example, one epoch is when all four samples are processed both forwards and backwards until the error converges. It should also be noted that it is essential to train the ANN model for multiple epochs, since adjusting the weights and biases based on back propagation with just one epoch is not enough. However, training the ANN model for large number of epochs might sometimes lead to a condition called as overfitting, where the ANN model becomes overly accustomed to the training dataset and hence will result in low error during training. The downside of overfitting is that the trained ANN model has less generalizability to newer data, meaning the prediction error will be very high for new samples apart from those used in the training dataset. Such new data samples used to validate the accuracy of the trained ANN model is called as the validation dataset. Similarly, training the ANN model for very limited number of epochs might lead to another condition called as underfitting, where the error is very high for both training as well as validation dataset. In summary, an underfitted model

has low accuracy in both training and validation dataset, an overfitted model has high accuracy while training, but low accuracy for samples from the validation dataset (i.e., less generalizability), whereas a model with optimal fitting will have high accuracy in both training and validation datasets (i.e., high accuracy as well as generalizability) (Goodfellow et al., 2016).

For example, in the case of our example, four new room options (Room5, 6, 7 and 8) with varying room length, width, window length and height were generated and their corresponding sDA values were simulated using RadianceTM. The input output combinations as shown in Table 3 were used as a validation dataset to test the accuracy of the trained ANN model.

Table 3: Sample validation dataset containing input values and simulated output (sDA) for four additional room								
design options.								

Samples	Room Length (ft) (x ₁)	Room Width (ft) (x_2)	Window Length (ft) (x ₃)	Window Height (ft) (x ₄)	Simulated sDA (%) (y ₁)
Room5	19	25	9	4	51
Room6	45	32	3	6	44
Room7	23	21	7	3	66
Room8	36	67	10	5	61

The impact of underfitting, optimally fitting and overfitting the ANN model to the training dataset (Table 2) is shown using plots comparing the prediction error of the ANN model for the training and validation dataset respectively (Figure 11). In these plots, the distance between the blue dots (simulated values) and the orange line (predicted values) is the error. When the ANN model is underfit, these distances are large in both training as well as validation datasets indicating high error, whereas in the case of overfitting, training error is nearly zero, whereas the validation error is high. ANN models that are trained optimally, will have lower prediction error in both training as well as validation datasets (good fitting) as seen in Figure 11.



Figure 11: Plots comparing predicted and simulated values of sDA using the ANN model for the training and validation datasets.

The optimal number of epochs for good fitting of an ANN model is usually arrived through a trial-and-error process (Goodfellow et al., 2016; Géron, 2019; Matthew, 2020). In this example, due to the small size of the training dataset (four samples), training for multiple epochs can be executed easily. However, in reality where training datasets are large (usually above 10^3 samples), it is difficult to complete even one epoch (i.e.) to feed all samples to the computer at once. In such cases, the training dataset is split into smaller batches containing specific number of samples (Géron, 2019; Sharma, 2019). For example, a training dataset containing 1000 samples can be split into five batches of 200 samples each (batch size), thereby taking five iterations to complete one epoch. The training of the ANN model is carried out until a stopping criterion is achieved, which is usually either until a specific number of epochs or until the prediction error of the overall model converges to a threshold value specified by the user (Prechelt, 1988; Nguyen et al., 2005). The trained and validated ANN model is further tested for accuracy by using it to predict the daylighting values for totally new samples foreign to the testing and validation datasets. A collection of such new data samples constitutes what is called a testing dataset.

The minimization of prediction error is dependent on how much the weights and biases are adjusted which in turn is dictated by several factors such as number of hidden layers, number of neurons per hidden layer and learning rate (a variable hyperparameter set by the user) (Goodfellow et al., 2016; Géron, 2019; Sharma, 2019; Matthew, 2020). These values are generally set using trial and error methods based on the size of the dataset, computation time required for each iteration (batch in an epoch) and the overall epoch, and the loss convergence plot for training and validation datasets. The loss convergence plot shows how the loss (error) is reduced between the predicted values and the simulated values over time (epochs).

Building on top of this example, an ANN model for daylighting (sDA) prediction is developed. However, it should be highlighted that, unlike the example discussed above, in addition to the overall building dimensions and window dimensions, sDA inside a building is sensitive to other input variables such as orientation of the building, floor level in consideration, wall to window ratio, window positions, number of glazing panes in windows, operating schedule and so on (Köster, 2004). Hence, it was strategized to generate a large catalog of building design options with different combinations of these input variables to train the ANN model for sDA prediction. Based on an iterative trial and error process, the ANN for daylighting (sDA) prediction was developed using the following steps:

3.1. Data Collection – In general, based on best practices in the area of applied machine learning research, large and diverse datasets in the order of $>10^3$ data samples tend to yield meaningful model performance (Smith et al., 2018; Brownlee, 2019). With the computational resources available at hand, a practically viable dataset of 4000 different variations of sample office building 3D models was generated by parametrically varying input parameters such as floor length, floor width, floor height, floor level,

orientation, wall to window ratio, window positions, window sizes, number of glazing panes in each window and operating schedule as shown in Table 4. The 4000 design options were split into three sets as 2500, 1000 and 500 options to be used as training, validation and testing datasets, respectively. A generative algorithm was used for this process (Muthumanickam et al., 2021) and the input variables were computationally stored per the hierarchy mentioned in Figure 12. These models were then simulated for sDA using RadianceTM. For the sake of the study, Chicago was used as the location with overcast sky conditions. The input and corresponding outputs for design options in the three datasets were recorded into three separate .csv files to be used as training, validation and testing datasets, respectively.

Input variables		Туре		
	Training dataset (2500 samples)	Validation Dataset (1000 samples)	Testing Dataset (500 samples)	
Floor length	20 ft to 400 ft	10 ft to 450 ft	10 ft to 500 ft	Random values between range
Floor width	20 ft to 400 ft	10 ft to 450 ft	10 ft to 500 ft	Random values between range
Floor height	10 ft, 12 ft	10 ft, 12 ft	10 ft, 12 ft, 15 ft	Discrete values
Floor level	1 to 25	1 to 30	1 to 35	Discrete values
Orientation		Intervals of 10 degrees between range		
Wall to window ratio		Random values between range		
Glazing panes		Discrete values		
Operating schedule	6,8,10 hr	6,8,10,12 hr	6, 8, 10, 12, 14 hr	Discrete values

Table 4: Input variable range used in the generative algorithm for generating building models to be used as training and testing datasets.

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Figure 12: Sample data structure followed to record input variables of various building shapes.

The length, breadth and wall to window ratio were varied using a randomizer in the generative algorithm which enables selection of random combinations between the specified range. This was done to introduce irregularity within the dataset (as opposed to a uniform pattern), which helps increase the robustness during training. Further, the ranges length, breadth, floor to ceiling height, number of floors and operating schedule were also varied between the training and testing datasets. The inclusion of new values in the testing dataset apart from the original ranges used in the training dataset shall help test the trained ANN model for its prediction performance and generalizability to new conditions.

3.2. ANN Training – The ANN model was configured to have one input layer with eight neurons (representing length, breadth, height, number of floors, orientation, wall to window ratio, glazing type and operating schedule respectively), two hidden layers with three neurons and four neurons per hidden layer respectively (per best practices) (Müller et al., 2016; Géron, 2019; Sharma, 2019; Matthew, 2020), and one output layer

with a single neuron (representing spatial daylight autonomy value). A ReLU (Rectified Linear Unit) activation function was used considering its effectiveness as suggested in the literature (Karlik et al., 2011; Ramachandran et al., 2017; Sharma et al., 2017; Nwankpa et al., 2018). The number of learning cycles (epochs) and the iterations were set based on trial-and-error methods (Sharma, 2019; Matthew, 2020). The predicted values were compared with the actual simulation results of these 2500 design options to arrive at the training loss function (error) of the ANN model.

3.3. ANN Validation – Concurrently, during the training, the partially trained ANN model was used to predict the sDA values for the validation dataset (1000 design options). The predicted values were compared with the actual simulation results of these 1000 design options to arrive at the validation loss function (error) of the ANN model.

3.4. ANN Testing – The pre-trained and validated ANN model was used to predict the sDA values for a testing dataset (500 design options). The predicted values were compared with the actual simulation results of these 500 design options to arrive at the loss function (error) of the overall ANN model. This model can then be used to predict sDA values for any given building design model instantly without the need to run actual simulations.

The daylighting simulations in RadianceTM were run using a high performance computer with multiple-core, multi-thread processor (Intel® CoreTM i9-10900K 3.5GHz) and a graphic processing unit (NVIDIA® QuadroTM RTX 5000). The ANN setup (Figure 13) was computationally developed using an opensource library called Keras and implemented in TensorFlowTM (Géron, 2019) utilizing the same local resources (computational setup used for RadianceTM simulations. The computation time for the simulations in RadianceTM, training of the ANN model and validation and testing of the pre-trained ANN model were saved from log files and TensorBoardTM respectively, for the sake of comparative analysis (Muthumanickam, 2021).



Figure 13: Conceptual representation of the ANN based daylighting (sDA) prediction model construction.

4. TRAINING, VALIDATION AND TESTING OF ANN MODEL

Initially, the training and validation datasets were divided into batches of 250 samples contributing to 10 batches per epoch (2500 training samples) and 4 batches per epoch (1000 validation samples), respectively. The learning rate was set at 0.01 (Thimm et al., 1996; Wilson et al., 2001; Smith, 2017). Four standard metrics namely, mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE) and R-squared (R^2) were calculated to analyze the error between the predicted and simulated sDA values. The training and the validation processes were run

simultaneously in TensorFlowTM and the loss convergence for both datasets were plotted. Based on observations of the training and validation loss in TensorFlowTM, the learning rate was adjusted to 0.25 to decrease the computation time taken to complete one epoch (Wilson et al., 2001; Smith, 2017). The ANN model was initially given a stopping criterion of 1000 epochs (meaning run the forward feed and backpropagation over the samples in the training and validation datasets 1000 times). This resulted in poor convergence towards the stopping criterion (1000 epochs) for both the training (indicated by high MSE value = 0.0763 - red color in Figure 14) and validation datasets (indicated by high MSE value = 0.0883 - green color in Figure 14). Further, the R-squared values were very far below 1 (the closer to 1 the better) for both the training ($R^2 = 0.3033$) and the validation dataset ($R^2 = 0.2586$), indicating high error between the predicted and the simulated sDA values (Figure 15).



Figure 14: Training and validation loss over 1000 epochs (Stopping criterion = 1000 epochs).



Figure 15: Prediction plots comparing ANN models performance for training (left) and validation (right) datasets when trained using a stopping criterion of 1000 epochs.

To lower the error of the ANN model, the stopping criterion was changed from 1000 epochs to until the R-squared value of the ANN model reaches above 0.8 for the
training dataset. The ANN model showcased good convergence for both the training (MSE = 0.0106) and validation (MSE = 0.0150) datasets at around 2500 epochs and reached the stopping criterion at 2723rd epoch (Figure 16). The ANN-model was able to yield relatively better R-squared value for both the training ($R^2 = 0.8729$) and validation dataset ($R^2 = 0.8204$) at around 2723 epochs (Figure 17).



Figure 16: Training and testing loss over 2723 epochs (Stopping criterion = $R^2 > 0.8$).



Figure 17: Prediction plots comparing ANN models performance for training (left) and validation (right) datasets when trained using a stopping criterion of R²>0.8 (2723 epochs).

In an attempt to increase the accuracy of the predictions even more, the stopping criterion was extended to 3500 epochs. Training the model for a greater number of epochs resulted in excellent convergence for the training dataset (MSE = 0.0028) but showed trends of the validation loss (MSE = 0.0688) diverging drastically from the training loss (Figure 18). This could be further asserted by comparing the predicted and simulated values where the training dataset had highly accurate predictions ($R^2 = 0.9654$), whereas the validation dataset had poor prediction ($R^2 = 0.3664$) (Figure 19). This was possibly due to the overfitting of the model due to extended training for a

greater number of epochs, hence reducing the generalizability of the ANN model to new data samples other than the training dataset.



Figure 18: Training and validation loss over 3500 epochs (Stopping criterion = 3500 epochs).



Figure 19: Prediction plots comparing ANN models performance for training (left) and validation (right) datasets when trained using a stopping criterion of 3500 epochs.

A summary of the various error metrics recorded for the three stopping criteria (training for 1000 epochs, training until $R^2>0.8$, and training for 3500 epochs) is shown below in Table 5.

Table 5: Comparison of model performance in training and validation datasets using three stopping criteria.

Stopping Criterion	Epoch = 1000		R ² >0.8		Epoch =3500	
Dataset	Training	Validation	Training	Validation	Training	Validation
MAE	0.2149	0.2304	0.0819	0.0971	0.0420	0.2056
(Lower the better)						
MSE	0.0763	0.0883	0.0106	0.0150	0.0028	0.0688
(Lower the better)						
RMSE	0.2762	0.2971	0.1029	0.1224	0.0530	0.2623
(Lower the better)						
R ²	0.3033	0.2586	0.8729	0.8204	0.9654	0.3664
(Closer to 1 the better)						

5. RESULTS AND DISCUSSION

In summary, it could be observed that the ANN-model performs poorly in both training and validation when trained for 1000 epochs, relatively better in both training and validation when trained for 2723 epochs, and better in training but poor in validation when trained for 3500 epochs. Based on these observations, it can be asserted that the ANN-model with a stopping criterion of $R^2>0.8$ (2723 epochs) has high accuracy in predicting spatial daylight autonomy values when presented with data samples from both known conditions (training dataset) as well as new conditions (validation dataset).

To scrutinize this trained and validated ANN-models efficiency for new data samples, it was used to predict the sDA values for the 500 completely new data samples from the testing dataset (refer Table 4). The model was able to predict the sDA values with a significant level of accuracy (R^2 = 0.7823). A plot comparing the predicted and simulated sDA values for the 500 data samples in the testing dataset is shown in Figure 20. Additionally, a comparison of predicted and simulated values for a small subset of 25 design options from the testing dataset is shown in Figure 21.



Figure 20: Comparison of sDA values simulated by RadianceTM and predicted by ANN model for 500 data samples in the testing dataset.



Figure 21: Zoomed in comparison of sDA values simulated by RadianceTM and predicted by ANN model for a sample subset of 25 data samples in testing dataset.

Further, the ANN based daylighting (sDA) prediction model upon successful training was able to predict the sDA given a set of input values at a staggeringly lesser computational time than the actual simulations (1000 design compute time – RadianceTM = 8500 minutes; ANN = 457 minutes) while using the same computational resources.

6. CONCLUSION

Given such benefits, the developed ANN model can be used as a potential metamodeling candidate in a multi-fidelity modelling approach to optimize the building for daylighting across multiple phases at lesser computational expense (Figure 22). More details about how the ANN based daylighting metamodel was used in the design of an office building is covered in Muthumanickam et al., 2021. However, more research in terms of systematically analyzing the sensitivity of the computational time to more variations of the dataset and hyperparameters such as number of epochs, learning rate, hidden layers, type of activation functions used is needed. For example, increasing the number of epochs to 3500 in the scope of this research resulted in good training accuracy and poor validation accuracy making the model less generalizable. However, the same inference might not hold good for a dataset that is drastically different from the one utilized in the scope of this research. It should be highlighted that the scope of this research did not include organic shapes of forms of buildings, thereby limiting the model results to rigid geometrical shapes. Limited availability of readily usable public datasets of building models is a limiting factor for machine learning research in the construction sector and efforts in terms of curating such datasets if any is needed to aid researchers. Hence, expanding the data collection range to include organic geometries and sensitivity analysis of hyperparameters to the expanded dataset is a potential avenue for future research. This shall help in the optimal fine tuning of the hyperparameters to enhance the model performance further. In summary, such machine learning based metamodels for daylighting analysis showcase promising potential in aiding designers to perform rapid daylighting analysis on large sets of design options at lower computational costs.

7. REFERENCES

- AGi32 Inc. (2018). AGi32 Manual: Daylighting Overview. Daylighting Overview. https://docs.agi32.com/Agi32/Content/daylighting/Daylighting_Overview.htm
- Aizlewood, M. E., & Littlefair, P. J. (1994). Daylight prediction methods: A survey of their use.
- Association Suisse des Electriciens. (1989). Éclairage intérieur par la lumière du jour. Association Suisse Des Electriciens, Swiss Norm SN 418911.

- Ayoub, M. (2020a). A review on machine learning algorithms to predict daylighting inside buildings. *Solar Energy*, 202, 249-275.
- Ayoub, M. (2020b). A review on light transport algorithms and simulation tools to model daylighting inside buildings. *Solar Energy*, *198*, 623-642.
- Brownlee, J. (2019, May 22). How much training data is required for machine learning? Machine Learning Mastery. Retrieved December 2, 2020, from <u>https://machinelearningmastery.com/much-training-data-required-machine-learning/</u>
- Carroll, W. L. (1999). Daylighting simulation: methods, algorithms, and resources.
- Cassol, F., Schneider, P. S., França, F. H., & Neto, A. J. S. (2011). Multi-objective optimization as a new approach to illumination design of interior spaces. *Building and Environment*, *46*(2), 331-338.
- CIE DS 011.1/E-2001 (2001). Spatial distribution of daylight CIE standard general sky, Draft standard, *CIE Central Bureau Vienna*.
- Géron, A. (2019). Hands-on machine learning with Scikit-Learn, Keras, and TensorFlow: Concepts, tools, and techniques to build intelligent systems. O'Reilly Media.
- Goodfellow, I., Bengio, Y., & Courville, A. (2016). Back-propagation and other differentiation algorithms. Deep Learning, 200-220.
- Hassoun, M. H. (1995). Fundamentals of artificial neural networks. MIT press.
- Karlik, B., & Olgac, A. V. (2011). Performance analysis of various activation functions in generalized MLP architectures of neural networks. International Journal of Artificial Intelligence and Expert Systems, 1(4), 111-122.
- Köster, H. (2004). Dynamic daylighting architecture: basics, systems, projects. Springer Science & Business Media.
- LeCun, Y., Touresky, D., Hinton, G., & Sejnowski, T. (1988, June). A theoretical framework for back-propagation. In Proceedings of the 1988 connectionist models summer school (Vol. 1, pp. 21-28).
- Lehar, M. A., & Glicksman, L. R. (2007). Rapid algorithm for modeling daylight distributions in office buildings. Building and Environment, 42(8), 2908-2919.
- LM, I. (2013). Approved method: IES spatial Daylight autonomy (sDA) and annual sunlight exposure (ASE). *Illuminating Engineering Society*. <u>https://www</u>/.Ies. Org/product/ies-spatial-daylight-autonomy-sda-and-annual-sunlight-exposure-ase.
- Matthew Stewart, P. D. R. (2020, July 29). Simple guide to hyperparameter tuning in Neural Networks. Medium. Retrieved January 14, 2021, from

https://towardsdatascience.com/simple-guide-to-hyperparameter-tuning-inneural-networks-3fe03dad8594

- Müller, A. C., & Guido, S. (2016). Introduction to machine learning with Python: a guide for data scientists. "O'Reilly Media, Inc.".
- Muthumanickam. N. K. (2021). Multidisciplinary Design Optimization Framework For Multi-Phase Building Design Process Technology Demonstration Using Design Of Office Building And Robotically 3D Printed Habitat. Dissertation. *The Pennsylvania State University*.
- Nabil, A., & Mardaljevic, J. (2005). Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research & Technology*, *37*(1), 41-57.
- Nguyen, M. H., Abbass, H. A., & McKay, R. I. (2005). Stopping criteria for ensemble of evolutionary artificial neural networks. Applied Soft Computing, 6(1), 100-107.
- Nwankpa, C., Ijomah, W., Gachagan, A., & Marshall, S. (2018). Activation functions: Comparison of trends in practice and research for deep learning. arXiv preprint arXiv:1811.03378.
- Ramachandran, P., Zoph, B., & Le, Q. V. (2017). Searching for activation functions. arXiv preprint arXiv:1710.05941.
- Reinhart, C. F., & Andersen, M. (2006a). Development and validation of a Radiance model for a translucent panel. *Energy and buildings*, *38*(7), 890-904.
- Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006b). Dynamic daylight performance metrics for sustainable building design. Leukos, 3(1), 7-31.
- Reinhart, C., & Fitz, A. (2006c). Findings from a survey on the current use of daylight simulations in building design. Energy and buildings, 38(7), 824-835.
- Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning representations by back-propagating errors. *Nature*, *323*(6088), 533-536.
- Rumelhart, D. E., Durbin, R., Golden, R., & Chauvin, Y. (1995). Backpropagation: The basic theory. Backpropagation: Theory, architectures and applications, 1-34.
- Sharma, S., Sharma, S., & Athaiya, A. (2017). Activation functions in neural networks. towards data science, 6(12), 310-316.
- Sharma, S. (2019, March 5). Epoch vs Batch Size Vs iterations. Medium. Retrieved January 7, 2021, from <u>https://towardsdatascience.com/epoch-vs-iterations-vs-batch-size-4dfb9c7ce9c9</u>
- Simpson, T. W., Poplinski, J. D., Koch, P. N., & Allen, J. K. (2001). Metamodels for computer-based engineering design: survey and recommendations. Engineering with computers, 17(2), 129-150.

- Smith, L. N. (2017, March). Cyclical learning rates for training neural networks. In 2017 IEEE winter conference on applications of computer vision (WACV) (pp. 464-472). IEEE.
- Smith, L. N. (2018). A disciplined approach to neural network hyper-parameters: Part 1--learning rate, batch size, momentum, and weight decay. arXiv preprint arXiv:1803.09820.
- Thimm, G., Moerland, P., & Fiesler, E. (1996). The interchangeability of learning rate and gain in backpropagation neural networks. Neural computation, 8(2), 451-460.
- Ward, G. J. (1994). The RADIANCE lighting simulation and rendering system. In Proceedings of the 21st annual conference on Computer graphics and interactive techniques (pp. 459-472).
- Wilson, D. R., & Martinez, T. R. (2001, July). The need for small learning rates on large problems. In IJCNN'01. International Joint Conference on Neural Networks. Proceedings (Cat. No. 01CH37222) (Vol. 1, pp. 115-119). IEEE.
- Wortmann, T., Costa, A., Nannicini, G., & Schroepfer, T. (2015). Advantages of surrogate models for architectural design optimization. AI EDAM, 29(4), 471-481.

Parametric Evaluation of Embodied Carbon within Design for Hybrid Mass Timber Floor Systems

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ABSTRACT

Building materials, construction project delivery, and facility operations over a building lifespan contribute significantly to global greenhouse gas (GHG) emissions. As building operations are being improved to reduce their environmental impact, the building materials portion of construction has become a larger contributor to a building's lifecycle GHG emissions. The structural system contribution to GHG emissions is significant and depends on the material types and quantities. Substituting traditional building materials such as structural steel and reinforced concrete with sustainable materials such as mass timber can reduce environmental impact. Further, the use of hybrid systems can use various structural materials more effectively by taking advantage of each material's strengths, thus further reducing a structure's environmental impact by needing less overall structure material.

This paper presents a parametric evaluation of mass timber and hybrid-mass timber / concrete floor systems for their design performance and environmental impact. Several floor systems are considered at an early-stage design level of detail across a range of dimensions. The systems include CLT floor with Glulam girders (TG), a CLT floor with Glulam girders and Glulam beams (TGB), and a concrete-timber composite system (TCC). Model variables include bay length and bay aspect ratio. Initial results show that the TGB system generally results in the lowest embodied carbon (EC) out of all three systems. Additionally, for a given floor bay aspect ratio, each system has an ideal range of bay sizes which result in the lowest EC values for that floor system. Finally, there appears to be a higher-order relationship between bay size and total system depth. The results from this study will be used to develop design aids that will inform decision-making during the early design phase of mass timber projects.

1.0 INTRODUCTION

Embodied carbon (EC herein) is one of several measures, such as embodied energy, CO₂ emissions, and global warming potential, which approximates a material's or product's negative impact on the environment. Building "operations" and building "materials and construction" make up 28% and 11% respectively of global carbon dioxide emissions (Architecture 2030, 2011). As building operations are becoming more efficient, the energy from building materials and construction, commonly quantified as EC, will contribute more significantly to a building's overall

environmental impact (Hens, 2020). The structure makes up a large portion of a building's EC, and the substitution of concrete and steel structural elements with timber has been shown to reduce a structure's environmental impact (Skullestad et al., 2016). Further, although timber is generally accepted to have a lower environmental impact as compared to other structural materials, its lower strength can result in a structure requiring more material. Therefore, the use of hybrid structural systems, which mix timber and steel or concrete, using materials where they are best suited, has the potential to optimize a structure's EC (Stern, 2018).

Mass timber is gaining traction in the construction industry for a variety a reasons, including its suitability for prefabrication, short erection schedules, small crew sizes for installation on site, and potential environmental benefits. There are many new midto high-rise residential buildings incorporating mass timber structural systems, including the Ascent project in Milwaukee, WI, the Crescent Terminus project in Atlanta, GA, and the University of Washington West Campus Student Housing project in Seattle, WA. With the increase in mass timber construction, there has been more research into new timber systems and system configurations to expand design possibilities. Jelusic and Kravanja (2017) studied the optimization of timber-concrete composite floors for structural and cost objectives (Jelusic & Kravanja, 2017). Movaffaghi et al. (2020) studied long-span timber-concrete composite floor systems, developing design and optimization procedures for deflection and vibration objectives (Movaffaghi et al., 2020). Mayencourt and Mueller (2019) studied the optimization of CLT floor panels for flexure (Mayencourt & Mueller, 2019). Despite ongoing research into specific systems for structural and cost-related design objectives, industry professionals have limited guidance during the early stage of a mass timber project to aid whole building design decision making that supports sustainability goals. Taking inspiration from architectural design, parametric analysis offers designers greater design exploration capabilities and flexibility over traditional design methods. Here designers can study large varieties of design options at an early stage of design (Brown et al., 2020). Therefore, the study presented in this paper used parametric analysis methods to explore a variety of timber floor systems and configurations for EC performance. The goal is to provide guidance across a range of possible grid dimensions regarding which systems are most sustainable, as well as secondary considerations such as the impacts of system selection on floor system depth.

2.0 METHODS

To conduct this study, a series of parametric models of potential floor systems was created. An automated sizing procedure was then written based on U.S. timber design codes. Finally, the parametric models were sampled across a range of variables to return the required structural element dimensions and subsequent embodied carbon required. This detailed methodology is similar to those found in Jelusic and Kravanja (2017), Mayencourt and Mueller (2019), and Hens (2020). The following aspects of the project will be discussed next: studied floor systems, parameters, model development, structural performance and EC metrics.

2.1 Floor Systems

This study currently includes three one-way spanning floor system models (Figure 1): a CLT floor (acting as the structural deck) with Glulam girders (TG), a CLT floor with Glulam girders and infill beams (TGB), and a concrete-timber composite system in which steel connections are utilized to provide composite action between the timber deck and concrete topping slab (TCC). The first two systems' structures are composed entirely of timber with a nonstructural concrete topping slab to meet acoustic and vibration serviceability requirements, while the third uses both concrete and timber as structural materials.



2.2 Parametric Design

This study takes a parametric design approach to the analysis of each floor system. Here, parametric design uses one or more input variables which can be changed to create a set of designs, known as the design space. Each design in the design space is evaluated for performance objectives of interest to define an objective space where each point corresponds to a point from the design space. The data produced through creating the design and objective spaces can then be analyzed to produce insights and an improved understanding of the trends and behaviors of the model. This methodology is commonly referred to as Design Space Exploration (Brown et al., 2020). In this study, the variables in the models include bay length and floor bay aspect ratio for each system, while performance objectives include total floor system depth (ft) and estimated EC (lbs CO_2 e per SF). Representative bay aspect ratios used in this study are illustrated in Figure 2.



Figure 2: Floor bays illustrated in plan view for each aspect ratio used in the study, where the aspect ratio is in terms of L:W

2.3 Modeling Overview and Process

The models generated for each system were tailored to the specific design process and requirements for that specific system. The TG and TGB systems start with a design which has a defined bay size, occupancy, and loading conditions, and designs the floor system needed to meet all relevant strength and serviceability requirements. Designs which did not meet the requirements were removed in post-processing. The TCC

system analysis process requires that all information about the bay size and structural design be known. Therefore, the TCC model begins with a full design which is analyzed and checked for its ability to meet the strength and serviceability requirements. Designs that did not meet the requirements were removed during post-processing. All system models produced results which included information about the final designs that work, as well as their corresponding system depths and estimated EC.

To implement the design processes described above, the models each use a combination of Grasshopper scripts, custom python code written inside Grasshopper, Excel tables, and custom python code written inside Spyder. A flowchart depicting this overall process is provided in Figure 3.



Figure 3: Flowchart depicting overall modeling process

Grasshopper is a powerful visual scripting platform commonly used in parametric design for its ability to analyze a large number of designs in a design space, and then provide the results in a form which can be exported to other applications for data visualization, analysis, and other post-processing tasks. This study developed custom script components to perform all timber structural design, and grasshopper script components were used to manage the resulting data. For the TCC model, design configurations were generated using GH scripting components, and the girder required for the design was designed using the previously noted custom script components. The design configuration and girder information for the design space were exported and copied into an Excel spreadsheet file. The Excel file contains several tabs with cells coded to analyze each design, determine the acceptability of the design, and calculate additional information about system depth and EC. The data for all three models was exported into .csv files for post-processing and analysis using custom python code in Spyder.

2.4 Structural Design

Each floor system was designed and checked for flexure, shear, short and long-term deflections, and vibration control. Other design considerations included acoustic performance, fire design, and manufacturing and transportation limitations. Bays are

uniform and rectangular, and the designs assume a residential occupancy. All floor systems were designed following the relevant codes, standards, and guides for each system. The TG and TGB systems are designed following the 2021 IBC (International Code Council Inc., 2020), the 2018 NDS (American Wood Council, 2018), the 2013 US Edition of the CLT Handbook (Karacabeyli & Douglas, 2013), the 2019 Canadian Edition of the CLT Handbook (Karacabeyli & Gagnon, 2019), ASCE 7-10 (Coulbourne et al., 2017), and the US Mass Timber Floor Vibration Design Guide (WoodWorks Wood Products Council, 2021). For the TCC system, the most relevant design guidance is coming out of Canada, and therefore this study followed the Design Guide for Timber-Concrete Composite Floors in Canada (Cuerrier-Auclair, 2020).

Other assumptions in the structural design process are as follows. All floor systems were considered simply supported and one-way spanning. Multi-span floors were considered in the TG and TGB systems, where the number of spans depends on manufacturing and transportation limitations. The TCC model considered only two-span conditions. To meet requirements for acoustics and walking-induced vibrations, panels were assumed to be arranged to limit continuity between separate dwelling units, and a concrete topping was provided, which is either considered structural or nonstructural depending on the system. Loads were assumed uniform expect at girders where the girder supports three or fewer beams. Dead loads include the self-weight of the structural members. Dead loads also include superimposed dead loads, which includes ten pounds per square foot (psf) for mechanical equipment, utilities, and finishes, six psf for partitions, and, in the TG and TGB systems, 35 psf for a 1.5-inch normal weight concrete topping. The concrete topping was included in the self-weight for the TCC system. Lives loads are forty psf for the assumed residential occupancy.

2.5 Embodied Carbon Estimation

The intent of the EC estimation study was to focus on the structure at a design stage level of detail with cradle to gate boundaries. While there are several methods used to measure the environmental impact of materials and products, this research uses EC, which is an estimate of the carbon dioxide emissions equivalent of a material. (Hammond et al., 2019). EC values for each material in the model were obtained from the Inventory of Carbon and Energy Database V3.0 (ICE), developed by Craig Jones and Geoffrey Hammond at the University of Bath. EC values are provided in units of mass of carbon dioxide equivalent per mass of material. The ICE database is a meta database which compiles data from the available literature to determined EC values. The values from ICE are often global averages, depending on the specific material. (Hammond et al., 2019) Values used for this study are summarized in Table 1.

	• •	DOM 1			
Material		EC Value	General Notes		
Timber	CLT	0.437	Carbon Storago is poglasted		
	Glulam	0.512	Carbon Storage is neglected		
Concrete - Superstructure		0.13	RC 32/40 (32/40 Mpa), 25% replacementt of cement with fly ash		
Plasterboard		0.39			

 Table 1: Embodied Carbon of Materials (lb CO2 e/lb)

This study used values which do not include carbon storage; however, future work will incorporate the carbon storage-based database values by evaluating floor systems with varying percentages of sustainably sourced timber, or timber which can be considered carbon-storing. The floor system EC estimates in this study were obtained by multiplying the outputs of structural mass for each material from the structural model by the corresponding value from the ICE database to obtain an estimated value for the bay and on a per-square-foot basis.

3.0 RESULTS AND DISCUSSION

Upon completing the floor system model simulations along with extracting the data, results were plotted in a series of combinations to perform a visualization of data for initial exploratory trends. The insights gained from this visualization phase inform future data analysis strategies to better understand the data. This section includes the most relevant data visualizations which were the most helpful in understanding the resulting design and objectives spaces from the analysis.

3.1 Overview of Results for All Systems

The first data visualization (Figure 4) provides an overview of the multi-objective space for all the studied systems, comparing EC versus total system depth. Total system depth includes the sum of the of the floor panel, girder, and concrete topping depths. In general via the data plots, all three systems have at least some designs with both low system depth (1-2 ft) and low EC (10-12 lb CO₂ e/SF). Figure 4 further shows a general trend of increasing system depth for increasing bay area; bays less than 400 SF are less than 2 feet deep, and bays larger than 1000 SF are typically greater than 3 feet deep, some approaching 5 to 6 feet. This trend is consistent with established knowledge of structure design. Systems with the largest depths may not be practical, but initial data analysis suggests that these depths occur mainly for systems with long-spanning, deep girders, which is not common for mass timber design in residential occupancies. There does not appear to be any strong correlation between bay area and EC (based on inconsistent patterns in Figure 4's data), suggesting that there may be some flexibility for architects selecting a bay size if the main goal is reducing EC, as opposed to current perceptions that larger bays must have more EC due to more material.

The data across the objective space becomes more widely spread among designs with either or both high system depth and EC. For example, The TCC system has designs between 2 and 6 ft deep with an EC greater than 15 lb CO_2 e/SF, while the TGB system designs all fall between about 11 and 15 lb CO_2 e/SF. Based on the data presented in Figure 4, the TGB system has the lowest EC and the TG system has the highest EC, as compared to equivalent bay sizes within the other systems. These are general trends, and the next stage of data analysis will include curve fitting and the development of equations to describe data relationships where appropriate. Additionally, the TGB system has the most linear relationship in the data out of the three systems, which warrants further investigation into the causes of this behavior.



Figure 4: Total System Depth vs Embodied Carbon for All Systems, Sorted by Floor System Type and Colored by Bay Area

3.2 Systems Comparison

In looking more closely at each system, Figure 5 shows the relationship between the bay width and aspect ratio variables and the objective of EC for each system. As it can be seen, each floor system has a distinct pattern in how the EC changes relative to increases in bay width for five distinct aspect ratios. Cutoffs in the data lines at varying ranges of bay widths are due to the preset range of and relationships between the bay length and aspect ratio inputs.



Figure 5: Embodied Carbon versus Bay Width, sorted by the floor bay aspect ratio and plotted separately for each system

The TCC system has distinct horizontal bands for each aspect ratio across which the EC varies very little with changing bay size. This suggests that depending on a floor systems aspect ratio, there may be an ideal range of bay sizes if the main goal is reducing EC, which is not necessarily the smallest bay size. For example, for a square bay, a designer could select a bay width anywhere between about 12 and 24 feet to achieve a low EC per SF (~12 lb CO₂ e/SF), while a rectangular bay that is half as wide as its span, or length, should be between about 9 and 15 feet wide to minimize EC (~12

lb CO₂ e/SF). The TG system more pronounced stepping of the data, and as a result, the apparent ideal bay width range for a given aspect ratio is narrower as compared to the timber concrete system. A square bay would need to be designed for a width between about 10 and 13 feet to achieve ~10 lb CO₂ e/SF. The TGB system has significantly less variation in EC along the total range of each aspect ratio category, and has overall lower EC as shown in Figure 4. Most aspect ratios have the freedom to select bay widths from 7 to 25 feet with low EC (11 to 13 lb CO₂ e/SF). Figure 6 similarly represents the data for the other objective, total system depth. All systems exhibit less variation in system depth, and appear to follow a quadratic-like relationship between bay width and system depth for a given category of aspect ratio.



Figure 6: Total System Depth versus Bay Width, sorted by the floor bay aspect ratio and plotted separately for each system

The "stepping" behavior observed in the TG system's EC in Figure 5 is explored further to understand what design feature or features are driving this behavior. Figure 7 takes the same TG system data but colors the data in a scatterplot based on the CLT panel's contribution to total floor system EC. This helps explain the stepping behavior because CLT EC is clearly related to each level of EC for the system designs. This is likely due to the use of a discrete number of CLT panel types in the parametric model, as panels are manufactured in discrete sizes, typically with an odd number of plies using dimensional lumber.



Figure 7: TG system embodied carbon subplot colored by CLT's contribution to EC

4.0 LIMITATIONS AND FUTURE WORK

4.1 Limitations

There are several limitations to this study. Only gravity loads are considered, and the effects of lateral loads on floor diaphragm design will be studied in future work. Connections are not considered in this initial study, and therefore steel takeoffs are not performed or included in the EC calculations. Regular bay layouts are considered, and other configurations or floor openings are beyond the scope of the study. A residential occupancy is assumed, and occupancies with higher live loads may behave very differently than the system models here.

4.2 Future Work

This is an initial study, and future follow-up work is planned. A thorough validation of the TCC model will be completed, during which various modeling assumptions will be assessed for their appropriateness, including connection selection and composite behavior. The TCC model will be expanded to consider different fire protection options. Additional floor systems will be modeled, including a TCC system with beams and a timber system with steel girders and the option to add steel beams. Where appropriate, equations will be developed to describe the relationships observed during the data visualization process. Additionally, smaller related studies will be performed to assess the contributions to EC of other design elements and requirements, including connections and acoustic performance. The model will also be expanded to include separate design spaces for various fire performance design options and different levels of sustainable timber sourcing which may introduce some carbon storage benefits.

5.0 CONCLUSIONS

This paper presented the initial results of an early parametric evaluation of mass timber and hybrid-mass timber / concrete floor systems for their design performance and environmental impact. The study consisted of a parametrically driven design investigation which compared a CLT floor system with Glulam girders, a CLT floor system with Glulam girders and Glulam beams, and a concrete-timber composite system. Each system was analyzed using computational design space exploration techniques to compare the systems at an early-stage-design level of design detail and technical performance.

The initial results show that the timber system with girders and beams generally results in the lowest embodied carbon (EC) out of all three systems. Additionally, for a given floor bay aspect ratio, each system has an ideal range of bay sizes which result in the lowest EC values for that floor system. Finally, there appears to be a higher-order relationship between bay size and total system depth. The results from this study are beginning to provide the information necessary to develop design aids and/or rules of thumb that will inform decision-making during the early design phase of mass timber projects.

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REFERENCES

- American Wood Council. (2018). 2018 National Design Specification (NDS) for Wood Construction (2018 Editi). American Wood Council.
- Architecture 2030. (2011). The 2030 Challenge for Products. In Architecture 2030.
- Brown, N. C., Jusiega, V., & Mueller, C. T. (2020). Implementing data-driven parametric building design with a flexible toolbox. *Automation in Construction*, *118*(June), 103252. https://doi.org/10.1016/j.autcon.2020.103252
- Coulbourne, W. L., Bracken, W., Lindt, J. van de, & Prevatt, D. (2017). Design Loads for Residential Buildings. *Residential Structural Design Guide*.
- Cuerrier-Auclair, S. (2020). *Design guide for timber-concrete composite floors in Canada* (C. Dagenais, L. Hu, & S. Gagnon (eds.); First Edit). FPInnovations.
- Hens, I. (2020). *Design space exploration for comparing embodied energy in tall timber structural systems*. The Pennsylvania State University.
- International Code Council Inc. (2020). *2021 International Building Code* (2021 Editi). International Code Council Inc.
- Jelusic, P., & Kravanja, S. (2017). Optimal design of timber-concrete composite floors based on the multi-parametric MINLP optimization. *Composite Structures*, *179*, 285–293. https://doi.org/10.1016/j.compstruct.2017.07.062
- Karacabeyli, E., & Douglas, B. (2013). Cross Laminated Timber Handbook. In E. Karacabeyli & D. Brad (Eds.), *Book* (2012 US Ed). FPInnovations and Binational Softwood Lumber Council.
- Karacabeyli, E., & Gagnon, S. (2019). Canadian Cross Laminated Timber Handbook: 2019 Edition (E. Karacabeyli & S. Gagnon (eds.); 2019 Canad). FPInnovations.
- Mayencourt, P., & Mueller, C. (2019). Structural Optimization of Cross-laminated Timber Panels in One-way Bending. *Structures*, *18*(December 2018), 48–59. https://doi.org/10.1016/j.istruc.2018.12.009
- Movaffaghi, H., Pyykkö, J., & Yitmen, I. (2020). Value-driven design approach for optimal long-span timber-concrete composite floor in multi-storey wooden residential buildings. *Civil Engineering and Environmental Systems*, *37*(3), 100–116. https://doi.org/10.1080/10286608.2020.1808888
- Skullestad, J. L., Bohne, R. A., & Lohne, J. (2016). High-rise timber buildings as a climate change mitigation measure - A comparative LCA of structural system alternatives. *Energy Procedia*, 96(1876), 112–123. https://doi.org/10.1016/j.egypro.2016.09.112
- Stern, B. G. (2018). *Minimizing embodied carbon in multi-material structural optimization of planar trusses*. Massachusetts Institute of Technology.
- WoodWorks Wood Products Council. (2021). U.S. Mass Timber Floor Vibration Design Guide. WoodWorks Wood Products Council.

Structural Design of a Cross-Laminated Timber (CLT) Single-Family Home Anthony C. Jellen P.E.¹ and Ali M. Memari PhD, P.E.²

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Abstract: Cross-Laminated Timber (CLT) as a structural material has attracted the attention of many in the Architectural/Engineering/Construction (AEC) community. Although CLT is used in multi-family residential structures, it has not been used extensively for the construction of single-family residences. In this paper, a CLT structural system alternative design is presented for a previously light-framed, traditional style, single-family residence.

Introduction

CLT panels are most often utilized by U.S. designers as an attractive construction material alternative for low-to-mid-rise multi-story residential and commercial buildings. However, while CLT panels can also be utilized for the construction of single-family residential buildings, they tend to be expensive in comparison to conventional construction alternatives. Often, manufacturers will find it difficult to profitably produce the minimal material required for the construction of a single-family residence, rendering the use of the material unfeasible in many instances.

In addition to cost disadvantages, the limited available CLT design guidance makes single-family home design time consuming and risk prone in comparison to conventional light-framing methods which are well established and somewhat prescriptive in nature. Budgets for design are often small and significant engineering effort cannot be justified in most instances. Although building/design codes and production standards have been established for CLT, the design is currently largely conducted according to the principles of engineering mechanics and structural engineering practice. The lack of standardized details, pertinent residential design examples, and prescriptive design aids makes it time-consuming to design smaller structures without the aid of expensive specialized software.

Introduction to Design

Currently, CLT is utilized in more modern avant-garde designs, where designers leverage the long-spanning, plate-like nature of the wooden slab element. Some modern examples of single-family dwellings constructed using CLT are presented in both the U.S. edition (Karacabeyli and Douglas 2013) and the Swedish edition (Borgstrom and Frobel 2019) of the CLT Handbook.

In this paper, the design of a traditional style $2-\frac{1}{2}$ -story single-family home using CLT elements and current design resources is discussed. The residence has 8 feet ceiling heights for both the 1st and 2nd story, a basement, attic floor space and bonus floor space above the attached garage. Previously, the design of the same home was undertaken using conventional wooden light-framing methods. The light-frame design was published in 2009 as a chapter in the book titled, "Timber Buildings and Sustainability" (Jellen and Memari 2019). This alternative CLT design was intended as a follow-up to the original design. The intention is to identify benefits and challenges associated with the use of the alternative system. The structural shell of the residence, adapted from the light-framed design is shown in Figure 1.



Figure 1. Rendering of CLT Panelized Home Design.

In this design the CLT panels are utilized as load-carrying plate elements, which transfer both conventional gravity loads and lateral wind loads to the concrete foundation. To be consistent with the initial light-frame design, the conventional gravity and wind loads were computed based on a project location of State College, PA. As with the original design, seismic loads are assumed not to govern the design of the lateral load resisting system. The dwelling utilizes a platform framing system, similar to that described in The CLT Handbook (Karacabeyli and Douglas 2013), in which the floor and roof panels bear directly on the exterior and interior bearing walls. Floor and roof panels transmit gravity loads such as dead, floor live and snow loading through wall panels to foundation. The floor panels also serve as diaphragms that transfer wind loading to designated CLT shear resisting wall panels. The 2021 Special Design Provisions for Wind and Seismic (SDPWS) (American Wood Council 2020) is the standard that provides engineering design guidance on the design of these lateral force resisting components.

Preliminary Design

The panelized model shown in Figure 1 was created in Autodesk Revit. According to the Wood Products Council, creation of a 3D model of the building system is necessary to realize the benefits of a prefabricated mass timber system (Woodworks 2019). For the purposes of this design, it was decided to use CLT panels for the roof, floors and walls. The structure of the home, in the original design, consisted of a light-platform-framed system which utilized thin structural panels as diaphragm and shear wall elements to provide lateral stability.

The platform framing style of the original design was maintained; however, CLT panels were essentially substituted for the light-framed floor, roof, and wall assemblies. This one-to-one substitution allowed the CLT alternate design to proceed with only minor floor plan modifications. Platform framed CLT methods are likely not the most economical solution for this design; however, by using this method it is possible to demonstrate not only design of the floor systems, but also the walls. In an actual design situation, all the building system options should be evaluated.



Figure 2. First floor plan.

The main exterior dimensions of the building are shown in Figure 2. As shown in Figure 3, CLT panels are used for both interior and exterior load bearing walls. The exterior walls not only transmit axial gravity load, but also transmit in-plane and out-of-plane wind forces. The interior bearing walls transmit gravity load only. Upon reviewing the geometry of the building, an 8 foot primary panel module (width) was selected as the basis for panelization. According to the Engineered Wood Association (APA), typical panel widths for CLT are 2-feet, 4-feet, 8-feet and 10-feet (APA 2019) having lengths up to 60 feet. It was necessary to consider both the geometry of the main building and the garage when determining the primary panel module. The factors that influenced the selection of the 8-foot module are as follows:

- 1. Light-framed construction is typically designed using a 4-foot or 8-foot module, because most of the construction materials such as structural sheathing are produced with these dimensions. An 8 foot module is a logical choice for adapting a light-framed structure for use with CLT panels.
- 2. Ceiling height for both the 1st and 2nd stories are both 8 feet, therefore, it was logical to select the 8-foot module for the interior and exterior wall panels.
- 3. The length of the main building is 36 feet; therefore, 4-1/2 panels per floor are required. There's no real benefit of selecting another module dimension and the remaining half-section could potentially be utilized on another floor.
- 4. Three 8-foot panels equal to 24 feet can be placed spanning the short 22 feet direction for the garage floor/ceiling structure.
- 5. The 30-foot width of the building is a convenient and efficient dimension for considering 60 feet long master billets.

Upon completion of the preliminary design evaluation, structural design was conducted to determine actual member and connection specification. Although preliminary panel design properties can be obtained from PRG 320 (APA 2020), it was decided to use manufacturer specific properties since they are readily available. To demonstrate similarities and differences between CLT manufacturers terminology and offerings, products from two CLT manufacturers were specified; Nordic X-LAM panels were specified for the walls and Katerra panels were specified for the floors and roof.

As mentioned previously, conventional external loads were calculated based on State College, PA. Tekla Tedds (Tedds) software was then used to determine the Main Wind Force Resisting (MWFR) and Components and Cladding (C&C) wall and roof wind loads for both the main building and the garage. Tedds was also used to determine balanced, unbalanced and drifted snow loading for the sloped roofs.



Figure 3. Building section.

The structural design was partitioned into sections. The sections include, CLT Wall Panel Design, CLT Floor Panel Design, CLT lateral System Design, and lastly the Foundation System design. Connections were designed; however, will not be discussed in this paper.

CLT Wall Panel Design

In this section, the initial design and specification of the CLT wall panels is discussed. Final wall verification occurs in the CLT lateral System Design section. The wall panels are initially specified based on their capacity to resist the internal axial forces resulting from the application of the prescribed gravity loads and the internal bending forces resulting from the application of out-of-plane wind forces on the wall panel. The primary method of design for the walls was hand calculations. The 2018 NDS (AWC 2017) was utilized as the design basis and the Nordic X-lam Technical Guide (Nordic 2020) was consulted to obtain panel options and design properties.

With minimization of the material use in mind, the X-LAM 89-3S, 3.5-inch thick panel was initially selected for consideration. The 89-3s is a 3-layer, 3-½-inch thick panel. The panel is certified according PRG 320 as an E1 stress grade panel. Initially, the controlling 2nd story wall panel was selected for design. It was decided

to orient the strong-axis vertical. Typically wall panels are oriented in this fashion to provide greater bending resistance to out-of-plane wind forces.

Design limit states are the axial capacity, the out-of-plane bending capacity and also the lintel requirement. The axial capacity and demand were first determined. An axial demand of 1,213 plf was calculated based on controlling ASD load combination Dead (D) + 0.75 Live (L) + 0.75 Snow (S) + (0.75) 0.6 Wind (W). The 2018 NDS design equations located in Section 3.7 and those in the associated commentary section C3.7 were utilized to develop the capacity. Design capacity was calculated on a per foot basis. The column buckling resistance (P_{cE}) was calculated using the minimum apparent bending stiffness (EI_{app-min}) = 0.5184 EI_{app} as recommended by the CLT handbook section 2.2.2. The apparent bending stiffness, defined by 2018 NDS Section 10.4.1, was calculated using a shear deformation factor (K_s) of 11.8 (pinned support conditions). The axial capacity of the 89-3s was calculated to be 29,726 plf, which far exceeds the demand of 1,214 plf.

The unadjusted panel bending capacity for the panel was provided in the Nordic technical guide. Adjusting per 2018 NDS Table 10.3.1 resulted in a design moment capacity of 5,360 lbf/ft. C&C magnitude wind loading was applied and a bending demand of 108 lbf-ft was calculated based on ASD load combination 0.6 D + 0.6 W. Once again the capacity far exceeded the demand. Considering the interaction between axial and bending force, a demand/capacity ratio of 0.023 was calculated using NDS interaction equation C3.9.2-3. The resulting ratio of 0.023 shows that the capacity of the thinnest panel far exceeds the demands. By engineering judgement no additional strength checks were required.

Initially, the lintels were checked oriented with the strong-axis vertical. This orientation is beneficial for resisting out-of-plane wind forces; however, only the center lamination is available to resist bending forces. The lintel bending capacity was calculated per the provisions of NDS Section 3 considering only the center horizontal ply. Because the lintel is actually part of the wall, the boundary conditions will be fixed. Due to the fixed boundary condition, a portion of the bottom of the lintel will be in compression; therefore, the beam stability factor (C_L) will not equal 1.0. The slenderness ratio, based on an effective length of 2.06 $l_u = 2.06 \times 6$ -feet = 12.36-feet, and an effective width of 0.75-inch was calculated. The calculated slenderness ratio of 60 was greater than the limit of 50 prescribed in NDS Section 3.3.3.6; therefore, it is not possible to utilize the 89-3s panel for an integral lintel in the strong-axis vertical position.

Slenderness continued to be a concern during the initial evaluation of the lintels. Upon discovering that the 89-3s were inadequate, it was decided to check the wider 4.125 inch, 105-3s panel. The 105-3s did meet the bending slenderness criteria; however, the bending strength of the single layer was not adequate. Next, the possibility of utilizing the panels oriented with the strong-axis horizontal was investigated. The lintel bending slenderness concerns were resolved; however, in this new orientation, the compression member slenderness limit set forth in NDS Section 3.7.1.4 was not satisfied. In order to satisfy the slenderness limit, with the strong-axis in the horizontal position, a 5-layer, 5.625-inch 143-5s panel was required.

The addition of the extra two layers was unacceptable, therefore, it was decided to add joints at the larger openings and utilize independent lintels rather than

the continuous panel on the 1st floor . It was determined that 105-3S lintels installed with the strong-axis horizontal were adequate for all 1st floor lintels. The panels were upsized to match the new lintel size. Because of the lighter loads on the 2nd story lintels, the 105-3S lintels were able to be utilized in the vertical position. This allowed for jointless 2nd story panels.

Floor and Roof Panel Design

A combination of hand calculations and software based solutions were utilized for analysis and specification of the floor/roof panels. As with the wall panels, the floor and roof panels were sized on a per-foot basis. When required, RISA 3D software was used to calculate internal forces and estimate deflections. Material properties were estimated based on the outer layer wood species properties. An equivalent thickness was calculated based on equations 1 and 2, where \mathbf{d}_{equiv} is the thickness of the beam and \mathbf{b} is the width of the beam (12 inches in this case). Apparent stiffness was considered to include the effects of shear deformations, as recommended in the 2018 NDS.

$$I_{app} = EI_{app} \div E$$
^[1]

$$d_{equiv} = \sqrt[3]{\frac{12 I_{app}}{b}}$$
[2]

In addition to hand calculation and RISA 3D, WoodWorks Sizer program was utilized to analyze the floor panels.

Preliminary panel sizes were selected from Katerra CLT Pre-Analysis Span Tables (Katerra 2020b). The strength of the floor panels was checked first. Floor panels were assumed to be continuous over intermediate bearing locations and span one-way. A representative 1st floor panel was first checked using Sizer and the results compared to hand calculations. Analysis results from RISA 3D and Sizer compared closely and therefore Sizer was used to check the remaining floor panels.

Upon completion of the floor panel design, the preliminary roof panel sizes were verified. As can be seen in Figure 3, the roof is designed to function without the need for interior bearing. The decision to detail the roof in this manner was made to largely eliminate obstruction in the most usable central portion of the attic and to avoid loading the interior span of the attic floor below. In order to analyze the roof panels, RISA 3D models were created for both the main roof and the garage roof. The analytical models not only provided the internal forces and deflections required to determine adequate panel sizes, but also provided joint forces which were used to determine connection requirements at the peak and base of the panels.

The Garage panels were checked first. Based on the pre-analysis tables, a 3.54-inch K3-0350 panel was selected for analysis. Upon review of the design loads, it was clear that due to the adjacent higher main portion of the building, the drifted snow load would control the design. Neither the K3-0350 panel nor the 3.84-inch K3-0380 panel satisfied the L/240 live load and L/180 total load deflection criterias; however, the wider 4.14-inch K3-0410 panel was able to satisfy all strength and service criteria.

The same process was followed for the selection of the main roof panel. Like the Garage panel, the initial pre-analysis table panel selection (K3-0380) did not pass the deflection criteria. There was no snow drift possible on the main roof, but due to the roof slope, an unbalanced snow loading was required to be investigated. In order to satisfy deflection criteria, the thicker K3-0410 was also required for the main roof.

Lateral Force-Resistance System (LFRS) Design

Figure 4 identifies the main LFRS components. The CLT floor and roof panels act as rigid diaphragms transferring wind loads to designated shear panels located within the walls. The shear wall boundaries, outlined in Figure 4, are fictitious and defined by the anchorage to the floor panels. A segmental approach, based on the mandatory requirements set forth in Appendix B of the 2021 SDPWS was utilized to apportion the shear wall segments. Appendix B does not permit shear walls to be designed using Force-Transfer Around Opening (FTAO) or Perforated Shear Wall methods. The horizontal diaphragm, connections and chords/struts were all fully designed; however, for brevity, analysis, calculations, and details are not discussed in this paper.



Figure 4. LFRS components, southern building elevation.

Initially, the design of the horizontal diaphragms was considered. In order to determine whether the panels possessed adequate internal shear strength, the panel edgewise shear stress (F_v) was required. The allowable design value for edgewise shear stress was obtained from Katerra guidance (Katerra 2020a). The CLT panels' in-plane stiffness and strength were large and far exceeded the diaphragm demands. Based on the large calculated roof panel shear capacity, it was assumed that subsequent diaphragm and shear wall panels were adequate to resist in-plane shear loading; therefore no further strength checks were performed. A rigid diaphragm analysis was conducted to determine both the diaphragm demands and shear distribution to resisting wall segments.

After determining the shear load distribution to the adjoining shear wall segments, the segments were checked for overturning resistance. Both the compressive pressure (f_c) and tensile force (T), resulting from the propensity of the panel to overturn when subjected to shear loading, were calculated. Figure 5a shows the panel forces.

Conservatively, considering the self-weight of the CLT panels only and ASD load combination 0.6 D + 0.6 W, the tensile forces were calculated for each shear wall segment. Along Wall Line 2, only SW1 required tensile anchorage. No anchorage was required for those segments along Wall Line 1. To resist the tensile

forces, Simpson Strong-Tie MSTC28 straps were specified. The ST6224 straps, depicted in Figure 5b, would have been adequate to resist the calculated tensile force; however, for continuity of load path, the force had to be directly transferred to the panel below. The intersecting 2nd floor panel created a separation between the two panels preventing installation of the required number of nails. The longer strap was required to bridge this distance. Because the MSTC28 had excess capacity, calculations were performed and the required number of nails reduced from 18 to 10 per side. Even with this reduction and consideration of the overstrength factor prescribed in 2021 SDPWS Section B.3.4.3 the MSTC28 capacity of 1966 lbf was more than adequate to resist the calculation demand of 279 lbf.

The bearing capacity of the CLT floor panel below the compressive leg of the overturning CLT panel was also checked. It was assumed that a perpendicular to the grain failure would occur from the vertically oriented laminations of the shear panel. For the bearing check, the overturning analysis was repeated considering ASD load combination D + 0.75(0.6 W) + 0.75 S and adding the collateral roof and floor dead load to the self-weight. Based on equation 6.11 in the Swedish CLT Handbook, bearing area was estimated considering the two strong axis wall laminations widths and 25% of the segment length. A maximum bearing pressure of 82 psi was calculated which was less than the allowable floor capacity of 425 psi.



Figure 5. a.) Shear panel overturning free-body diagram b.) Shear panel tension resistance strap.

Foundation Design

Foundation design was relatively simple and resulting foundation elements were similar in size to those required for the light-framed wood structure previously designed (Jellen and Memari 2019). The W8x18 girder utilized for the light-framed structure was adequate for midspan support of the CLT floor system. Concentrated load checks were conducted according to the Steel Construction Manual (SCM) (American Institute of Steel Construction (AISC) 2011) Specification Section J10 at the column bearings. All checks passed; however, a maximum LRFD factored reaction of 48.2 Kips did approach the limit of 51.1 kips calculated for web

compression buckling. The columns were also sized at the same time the girder was checked. Due to the heavier column loads, a thicker-wall 3.5-inch diameter (0.216 inch thick) adjustable column was required, in lieu of the thinner 11 gauge column utilized for the light framed design.

The foundation wall specification was similar to that of its light-framed counterpart; however, the footing sizes increased slightly. The increased weight of the CLT structure required a 24 inch wide plain concrete wall footing in lieu of the 18 inch wide footing utilized for the light-framed structure. Interior column pad footings increased in size from the 4 ft - 0 in x 4 ft - 0 in x 10 in thick pads utilized for the light framed structure to two 4 ft - 6 in x 4 ft - 6 in x 12 in pads and a 4 ft - 0 in x 4 ft - 0 in x 12 in pads and a 4 ft - 0 in x 4 ft - 0 in x 12 in pad. In general, there was a need for larger foundation elements due to the increased weight of the structure; however, the increases were minimal and not likely to affect the foundation costs significantly.

Conclusions

In general, certain aspects of this single-family residence CLT design were time consuming. Additionally, CLT is typically less cost effective than competing building materials for single-family residences. Also, when using CLT for small projects such as single-family homes, the manufacturer is likely to require the complete design, including panelization, to be delivered by the design team. This increases the front-end design time as well as the design fee. It is difficult to justify the increase in design effort given the minimal design budgets available for most single-family projects.

If CLT is to be considered for use in single-family projects, then the efficiency of the workflow should be maximized. During the course of this design, valuable lessons were learned regarding efficient workflow. The following is a list of some of those lessons:

- 1. Adapting an existing building plan for use with CLT panels can be difficult if the geometry of the structure does not match typical CLT panel dimensions.
- 2. Interior Bearing walls, not stacked with the wall or beam below, will be applied to the floor panel as a line load, which could result in increased floor panel thickness.
- 3. To improve efficiency hand calculations should be minimized. Consider 2021 SDPWS Section 4.1.2.2 for lateral system design, which allows, "approved alternate procedures that are in accordance with the principles of engineering mechanics". FEA software like Dlubal's RFEM could be utilized.
- 4. During wall design, recommend designing lintels first.
- 5. For wall and lintel design, always check the slenderness prior to performing further structural checks.
- 6. Due to the geometry of the floor plan, various floor thicknesses were required for this design. This could increase cost.
- 7. Examples of the application of the overstrength and reduction factors required for diaphragm and shear wall design by the 2021 SDPWS would be helpful to designers.

Light-framed construction is still the most economical construction system for traditional style single-family homes. The system is familiar to most contractors and

the material is readily available. The units of construction are modular and construction using this method can be accomplished by the homeowner if required. There are many benefits to using this system; however, there are also many inefficiencies in the construction system. Most revolve around inefficient workflow.

Currently the inefficiencies inherent in light-framed construction methods do not outweigh the economic savings of the system; however, if economic conditions change, the demands of homeowners shift toward more complex structures or an increased number of manufacturers come online, then the economy of alternative construction systems, such as CLT, could improve. Additionally, as CLT research continues and more domestic resources become available, both workflow and economy of the system will improve as well.

References

- American Institute of Steel Construction (AISC). (2011). *Steel Construction Manual*. American Institute of Steel Construction.
- American Wood Council. (2020). Special Design Provisions for Wind and Seismic (SDPWS). American Wood Council.
- APA. (2019). *Cross-Laminated Timber Selection and Specification*. The Engineered Wood Association.
- APA. (2020). ANSI/APA PRG 320: 2018: Standard for performance-rated cross-laminated timber. APA The Engineered Wood Association.
- AWC. (2017). 2018 National Design Specification for Wood Construction. American Wood Council Leesburg, VA, USA.
- Borgstrom, E., and Frobel, J. (Eds.). (2019). *The CLT Handbook, CLT Structures Facts and Planning*. Swedish Wood.
- Jellen, A., and Memari, A. (2019). "Structural Design of a Typical American Wood-Framed Single-Family Home." *Timber Buildings and Sustainability*, G. Concu, ed., InTechOpen, 27–54.
- Karacabeyli, E., and Douglas, B. (2013). "CLT handbook." US Edition, FPInnovations and Binational Softwood Lumber Council, Point-Claire, Quebec.
- Katerra. (2020a). Katerra CLT Product Definition.
- Katerra. (2020b). Katerra CLT Pre-Analysis Span Tables.
- Nordic. (2020). Nordic X-LAM Technical Guide. Nordic Structures.
- Woodworks. (2019). *Mass Timber Cost and Design Optimization Checklists*. Woodworks.

Resilience and Social Justice as a Framework for Architectural Education, Research and Practice – The Design+Build Kunga ADU

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1. <u>INTRODUCTION TO DESIGN + BUILD SALT LAKE</u>

The Design+Build Salt Lake (D+BSL) program at the University of Utah's School of Architecture (SOA) is a newly implemented regional, academic led design build program and immersive experience where students develop, design and construct affordable, 40-60% more energy efficient than code-standard small residential buildings (D+BSL, 2020). It teaches students about physical design and construction and offers a test bed for applied research in the field of residential design, systems and performance for faculty and students. It also tries to meet critical affordable housing needs for people in underserved areas in the region, evident through helping to create affordable homes for Habitat for Humanity (low-income) and Salt Lake City Assist (wheelchair bound former refuge) clients to date.

Similar to the Design Build Bluff program at the SOA, D+BSL focuses on the practical component of actual construction in the student's education, immersing them "into the realties and exigencies of the construction industry", which "encourages a more lateral relationship between ideas on paper and nuts and bolts on site" (Yusaf, Galarza 2015), at the same time integrating the conceptual and research through modeling software and digital fabrication.

In addition, regional communities are supported through engagement, co-design and building activities, raising awareness of careers in the build environment by providing opportunities for students to engage in community service and creative projects as a way to promote cultural diversity and sustainability.

Offering a comprehensive construction component, the inaugural Kunga ADU project allowed student leadership throughout all design, permitting and construction phases of a real-world, small-scale project (Fig. 01).

2. <u>STUDIO PHILOSOPHY</u>

Both design build programs at the SoA are positioned within the School's graduate degree program. Students join one of the programs after they are trained in research and design methods and the comprehensive application of technology and professional integration in the studio setting. The D+BSL coursework cluster includes a 5-credit design studio, a 3-credit sustainability technology seminar and a 6-credit build studio.

Learning objectives of the classes include a practice-oriented architectural education that exposes its participants to all stakeholders and actors in a realworld project, in which students experience the immediate impact of their architectural thinking, their communication and action in the broader context of building construction. They begin to express their own position of architecture and form and learn to cope with the challenges that come with the actual realization of a project from architectural sketches, plans, renderings and models to the built project. A holistic, integrated development process allows them to interact with the low-income minority group clients, the community, building officials, and the engineers that are part of the studio team.



Figure 01: The contemporary Kunga ADU after its finalization in fall 2020

Studio outcomes include the goal to design and build a small residential building, for which the students learn to work collaboratively in a team atmosphere while respecting the opinions of others. They gather, assess, record and comparatively evaluate relevant information and performance to support conclusions related to the project, and acquire skills to assess disparate information sources. Participants gather information about the site, precedents and determinants of design including but not limited to historic traditions and cultural issues, entitlement issues, sustainability, health safety and welfare restrictions, accessibility and the programmatic needs of a client. They further develop skills to represent ideas in a narrative form and translate them into abstract concepts that incorporate the essence of the project criteria. This includes the preparation of a comprehensive program as an assessment of the future building occupant's needs, an inventory of spaces and their requirements, a detailed analysis of the specific site condition design assessment criteria, a review of the relevant building codes, standards, applicable zoning and relevant sustainable requirements. Thereafter, they execute design development in a manner that demonstrates comprehensive competence in architectural design relevant to the specific topic, where they resolve the main issues within the project concerning architectural technologies so that they extend and amplify the original design concepts. At the end of the design process, students have developed fundamental design skills that reconcile conflicting agenda with an integrated overall and cohesive design outcome that balances the requirements of multiple building systems. Participants have also learned professional communication skills with an improved ability to write technical briefs, to listen and empathize with constituents and to present ideas effectively to a client or other stakeholders. They then present a comprehensive architectural project that is sophisticated in its architectural design and thoroughly developed in detail at the level of construction documents, which is used to obtain the building permit. This phase also includes a rigorous description with a critical, candid reflection upon its intends and results, represented through concise and clear technical documents that utilize the conventions of architectural communication. By the end of the construction skills necessary to build the project that they designed.

3. <u>DESIGN METHOD</u>

The Kunga ADU studio process required complex thinking and a strong collaborative group approach, in which students had to learn that the sum of all efforts is more important than an individual outcome. Simultaneously the success of the overall project heavily depended on each individual's reliable contribution. The class cluster was structured as a combination of iterative research, design, precedent and fabrication assignments of increasing complexity. Numerous participatory meetings and workshops with community partners, the wheelchair-bound former refugee client, members of the jurisdiction, neighborhood citizens and manufacturers exposed students to challenges of urban planning and zoning, architectural design and project research. This integrated and holistic design team approach allowed at all project stages that a cross section of architecture students, faculty, practitioners, stakeholders and engineers engaged in meaningful ways. The classes' setup experimented with new modes of optimized living, seeking to develop a clienttailored small living unit that had to consider all aspects of code requirements, and had to be optimized in its passive energy performance at a limited budget. The initial design studio and technology seminar method began with researching suitable small-scale residential and high performance precedent case studies, among which Sobek's B-10 in Stuttgart, Germany (Archdaily.com 2021), Maddison Architects' RCCV in Victoria, Australia (Maddison Architects 2021), Propel Studio's Wedge ADU in Portland (Propel Studio 2021), and Yale's School of Architecture Homeless Home in New Haven (Dezeen.com 2021) were explored and critically reflected on. In parallel, studio participants explored, analyzed and mapped the given site with regard to the precedent research outcome, by critically questioning assumptions about standard design solutions and constructing methodologies predominate along the Wasatch Front, specific siting, passive energy and building orientation, climate and code requirements. Methods of choice were journalistic, including case studies, design and construction methodologies, structural studies, a thorough code review and material identification. They were also data driven, incorporating climate, building orientation, cost and system research, Volatile Organic Compounds (VOC) free components, iterative Sefaira energy simulations and Passive-to-Active design strategies (Ruegemer, 2011). The process required a close collaboration with the structural and mechanical engineers, who were consulting the team frequently. Students gathered and analyzed information from a variety of sources including recent literature, the Internet, local municipality and utility providers and manufacturers, did field explorations on site and visited local trades and a prefab component manufacturer. The outcome was a comprehensive catalog of site, design and functional requirements, existing plants and trees, 'healthy' materials and lowimpact construction methods, preliminary performance and component assembly simulations, all of which were superimposed onto the given context of the actual project site within its (legal) boundaries.

After another feedback loop with the client, students substantiated and finalized the initial design towards a project that was agreed on by all stakeholders, was buildable and also high performing. As an important part of the resilient approach present in this method, research and quantitative optimization methods were continuously utilized to explored specific Passive House (PH) envelope components and detailing (Corner, D., Fillinger, J., Kwok, A., 2018; Lückemann, 2009), which was complemented by real time Sefaira and Passive House Planning Package (PHPP) energy simulations for all iterations that the team explored. With the PH approach being an established standard for energy efficient buildings in many parts of the developed world, the standard comes with systemic disadvantages that can be overcome by including Active House strategies (Hegger, Fafflok, Passig, 2013). This was specifically important for the Kunga project, where the combination of the two standards helped to reach the goals by carefully gauging requirements of both systems against each other, to carefully move the dial towards either more passive or active systems, to fulfill the defined comfort and performance requirements for the client at a limited project budget

The design process was further driven by a new ADU guideline developed by Salt Lake City in parallel to the student's design work, as well as the building permit and structural requirements of the jurisdiction.

4. <u>DESIGN PHASE</u>

The Kunga ADU project was challenged by a very narrow and complex timeline that tried to align an academic semester schedule with the realities of an 8-months permitting process that consisted of a required conditional use permit (CUP) and the actual building permit. As a result, the team worked in parallel to still outstanding permits, hoping that those would finally be granted without requiring larger changes. To bridge the gap between the fall semester start in late August and the attainment of the building permit in November of 2019, the team decided to prefabricate most building components. The visit at the local prefab manufacturer led to a simple solution for stick-framed interlocking wall components manufactured for temporary assembly in the

school's shop yard that would later be disassembled and transported to the site for final assembly.

4.1 Site Considerations

The integration of the project into the restrictive environment of cumbersome code requirements left only a small area on the existing property to locate the building. Key considerations for placement included accessibility and visual connection to the main house and access to daylight and passive solar winter heat gain, which was used for careful building orientation and the vigilant placement of window openings in the building's envelope. The flat site allowed for a thermal-bridge free, fully insulated shallow slab foundation (Corner, Fillinger, Kwok, 2018) that was easily constructed by the students.

4.2 Program and interior

Design and programming of the 830 sq.ft. ADU followed the client's functional requirements and daily routines, with each space specifically designed around daylight access, functionality and wheelchair accessibility. The main space includes the kitchen and living/working area along the building's south side, with a bedroom and bathroom tucked behind towards the north façade. A small gallery above the bedroom constitutes a space for a future caregiver. The ideal performative building mass of a simple cube was developed towards an external surface area (2,840 ft²) to internal TFA (the net conditioned floor area of 735 ft^2) ratio of 3.8, which is suboptimal since the ideal PH performance value is at or below 3.0. The discrepancy is due to the building's small size - it is much more challenging to optimize a small building's A/V (area to volume) and form factor (Lewis, 2014). Except for the kitchen furniture, for which the client requested a regular layout to work on the counter top with the wheelchair parked in parallel, the building was designed for full ADA accessibility. The students designed and build all furniture as part of the overall design process, using CNC-milled and clear-coated Baltic birch plywood in combination with simple base cabinets purchased from a global furniture manufacturer chain.

4.3 Material choice and indoor environment

The most important, highly dynamic 'material' applied throughout the small building is daylight, which has been carefully orchestrated for each space, providing an every-changing vibrancy in the south-facing spaces of the ADU. The interior design focuses on the utilization of very few materials: a neutral, daylight-reflective VOC-free white paint for all walls and ceilings, and a sealed concrete floor. Furniture and window frames are made from Baltic birch, to add warmth to the palette of reduced materials (Fig. 02). This conscious reduction in materials allows the client to define her lifestyle through the elements and components that she brings into the building. Using a chemicals of concern list, all materials were carefully selected for a minimized environmental impact and to ensure highest indoor environmental and air quality by avoiding VOCs and off-gassing materials, focusing on natural and long-lasting supplies and applications.



Figure 02: Living room with the wheelchair-optimized working sofa

5. <u>SUSTAINABILITY AND RESILIENCE</u>

The passive-to active design strategies applied in the Kunga ADU range from a site-specific design with south-facing orientation, daylight studies to enhance passive solar heat gain and light comfort, integrated fixed sun blades above the south facing windows to control summer heat gain, and a concrete floor that is exposed to the winter sun for additional heat gain during the cold months of the year. Envelope components are as close to PH requirements as the budget allowed. As per PHPP (PHIUS 2021), and Ubakus U-value, moisture and heat protection calculator (Ubakus 2021), the building's envelope components are rated R-32 for walls, R-50 for roof, and R-32 for its floor slab respectively. Windows have a performative U-value of 0.26. Final certified PH air infiltration rate was at 0.6 ACH₅₀ (US DOE, 2019), using the novel AeroBarrier technology (Yost, 2019). An optimized Active Building Compact Core and Post Occupancy Monitoring system (POM) developed by the author as part of his research provides performance data, allowing interpretation of performance measures implemented for their feasibility/ROI.

5.1 HVAC systems and system performance

The electric-only building is heated through a combination of a 3-zone radiant floor heating in the 4" insulated shallow-slab concrete floor (thermal mass

activation in addition to solar heat gain) and a heat-pump Mini Split system, which also provides cooling during the hot summer months. The radiant system is run by an on-demand electric water heater that also provides Domestic Hot Water (DHW) in the building, with the system controlled and remotely accessible through smart thermostats.

As part of the PH approach, a small whole-house Energy Recovery Ventilation (ERV) system with MERV 7 filters (EPA, 2021), provides a continuous stream of pre-conditioned, clean and healthy air into the ADU, simultaneously recovering about 88% of the exhaust flow's thermal energy (Kwok, Grondzik 2007, Lechner 2009).

5.2 Simulation results

Iterative Sefaira energy simulations and physical model studies led to an EUI performance increase of 44% over the comparable code standard building, which was mainly achieved through a 71% heating demand reduction in Salt Lake's heating-dominated climate, and a 40% cooling demand reduction (Fig. 03). The projected EUI is 20 kBTU/sq.ft./yr, and projected annual energy consumption is 3,696 kWh, compared to 8,811 kWh for the same building constructed to code standard (Fig. 04). The actual monetary savings is only 12-16% compared to a natural gas-heated building, due to the four times higher cost of electricity for an equal amount of (heating) energy. Being constructed as a solar-ready building, the Sefaira energy model suggests that nine, 315 W standard residential roof PV panels would offset the building's simulated energy requirements.

			EUI 👻	Annual Energy Cost 👻	Annual Net CO _{2e} Em •	Annual Energy Cost 👻
	AS BUILT	PTHP / Split System	20 🗸 44%	\$0.5 ¥16%	8,845 ¥40%	\$400 ¥12%
CODE STANDARD 829 ft ² Clone Del <u>1</u> , Export Jof	HVAC System Type			14 007		
	829 ft*	Fan Coil Units and Central Plant	30 kBTU/ft ² /yr	\$0.6 /ft ²	14,987 lbCO _{2e} /yr	\$456
NET ZER 829 ft ²	NET ZERO PV	HVAC System Type	O kBTU/ft²/yr		15 lbCO _{2e} /yr	\$1
	829 ft*	PTHP / Split System (System 2)		\$0.0 /ft ²		



As part of the project's ongoing research component, a custom-built EKM push-monitoring POM system was installed and went into operation on March 15, 2021, to be described in detail in future publications. After 8 months of data collection it is still too early to allow for an objective and quantitative proposition, but a first data interpolation averaged onto the monthly consumption shows the following tendency:

Between March 16, 2021 and November 22, 2021, occupants consumed an average electricity of 493 kWh/month. Thereof, 191 kWh were used for radiant floor heating, 70 kWh for the production of DHW (1,817 gal.), 9.33 kWh operated the Zehnder ERV, and 7.71 kWh were utilized for the radiant pumps and the monitoring system. 76.28 kWh were used to operate the Mini Split heat

pump system. The remaining 138.52 kWh were utilized for lighting, cooking, appliances and other electric household devices. To summarize, 275 kWh/month were used on average for heating, cooling and fresh air in the building (HVAC side), which interpolates to 3,300 kWh/year. Comparing this to the Sefaira numbers for HVAC energy segments alone (Fig. 04, left), the sum for heating in KBT/yr (6,211), cooling (704), fans (498) and pumps (335) is 7,748, which equals 2,271 kWh/year and is 1,029 kWh/year lower than the actual energy consumption. Furthermore, compared to the simulated total energy consumption of 3,696 kWh/year, occupants would use an annually interpolated 5,916 kWh/year, which is about 62% more than predicted), but still 33% lower than foreseen code standard performance (Fig. 04). It needs to be noted that the building, original modeled for occupancy of one senior adult in a wheelchair, was occupied from the onset by a young family of 2 adults and 2 small children.



Figure 04: Energy segments in kBTU/year (left) and Sefaira simulated Total Energy comparison of the code-standard version (center) and the asbuilt ADU (right)

The ongoing, two-year POM phase will show how precise these assumptions are. Besides, the bi-weekly POM data analysis already led to the client's education towards better performance, when the author discussed these first results and recommended operational behavior changes that led to increased efficiency.

6. <u>CONCLUSION</u>

Despite the many challenges within an 'impossible time frame' and a global pandemic, the Kunga experience has been successful in delivering a beautiful and already AIA award-wining small-scale project to the client. The author is confident in stating that the Kunga experience overall has been a success in its original intention to serve as an outreach, community service, teaching and research initiative, linking faculty and students in architecture with stakeholders, practitioners, jurisdictions and industry partners, to create strong learning opportunities about architecture through sustainable, resilient and affordable building design and construction projects, extending design education beyond the classroom into the community, thus offering a truly transformative experience to all involved and especially to the program's participating students. The project has a significant impact on:

- The client family's life by providing additional space urgently needed;
- The general public by leading the way towards future ADU designs for an urban densification in the region;
- The academic community of participating students and faculty;
- The professional community who engaged in mentoring architecture students by sharing their expertise; and
- The future development of the new D+BSL program.

This impact includes a strong sustainable focus as it relates to the project design, and a social and just focus as it relates to the scope of work and responsibilities for architects.

REFERENCES

Design + Build Salt Lake (2021). "*The Kunga ADU*," <u>https://www.designbuildsaltlake.org/kun</u>. Accessed June 25, 2021

Yusaf, S., Galarza, J. (2015). "*Taking the Pulse of Bluff*," Dialectic III. Oro Editions. ISBN 978-1-941806-93-7. Pg. 73-79

- Archdaily.com (2021). "Aktivhaus B 10 / Werner Sobek Group." <u>https://www.archdaily.com/596695/house-b10-werner-sobek-group</u>. Accessed December 04, 2021
- Maddison Architects (2021). "RACV Tiny Home." https://www.maddisonarchitects.com.au/projects/racv-tiny-home Accessed December 04, 2021
- Propel Studio (2021). "*The Wedge ADU*." <u>https://www.propelstudio.com/the-wedge-adu-portland-or</u>. Accessed December 04, 2021
- Dezeen.com (2021). "Yale architecture studentscreate dwelling in Connecticut for the homeless." <u>https://www.dezeen.com/2017/11/06/yale-</u> <u>university-architecture-students-create-dwelling-homeless-new-haven-</u> <u>connecticut/?ct=t(gb_d_newsletter_6_15_17_greater_than_3_6_14_20</u> <u>17</u>). Accessed December 04, 2021
- Rügemer, J. (2011). "Design Strategies Towards High Performance Market Rate Housing: the 125 Haus in Utah," The International Journal of Design Principles and Practices, Volume 5, Issue 5. Common Ground Publishing, Champaign, Illinois, USA. ISSN 1833-1874. Pp. 253-276
- Corner, D., Fillinger, J., Kwok, A (2018). "Passive House Details Solutions for High-Performance Design," Routledge, New York. Pp. 24-27, 42-45 and 80-81
- Lückmann, R. (2009). "Passivhäuser Energieeffiziente Baudetails." WEKA MEDIA GmbH & Co. KG, Leinfeld-Echterdingen

Hegger, M., Fafflok, C., Hegger, J., Passig, I. (2013). "Aktiv Haus – Das Grundlagenwerk," Callwey, Munich, Germany. Pp. 15-17

- Lewis, S. (2014). "PHPP Illustrated A Designers Companion to the Passive House Planning Package," RIBA Publishing, Newcastle Upon Tyne, England. Pp. 12-13, 22-24 and 30-35
- United States Passive House Institute PHIUS (2021). "Passive House Planning Package PHPP," <u>https://passivehouse.com/04_phpp/04_phpp.htm</u>. Accessed April 5, 2021
- Ubakus U-value, moisture and heat protection calculator (2021). <u>https://www.ubakus.com/en/r-value-calculator/</u> Accessed November 22, 2021
- U.S. DOE (2019). "Air Leakage Guide. Building Technologies Program." https://www.energycodes.gov/sites/default/files/documents/BECP_Bui dling%20Energy%20Code%20Resource%20Guide%20Air%20Leakag e%20Guide Sept2011 v00 lores.pdf. Accessed May 23, 2021
- Yost, P. (2019). "The Promise of AeroBarrier for Air Sealing Homes," https://www.greenbuildingadvisor.com/article/aerobarrier-for-existinghomes. Accessed June 30, 2021
- Unites States Environmental Protection Agency (2021). "What is a MERV rating?," <u>https://www.epa.gov/indoor-air-quality-iaq/what-merv-</u>rating-1. Accessed June 23, 2021
- Kwok, A., Grondzik, W. (2009). "The Green Studio Handbook." Elsevier, Oxford, UK. ISBN 978-0-7506-8022-6. Pp. 193-196
- Lechner, N. (2009). "Heating, Cooling Lighting." John Wiley & Sons, New Jersey. ISBN 978-0-470-04809-2. Pp. 544-545

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Facilitating Real-World Project-Based Service-Learning Opportunities by Participating in Department of Energy Race to Zero and Solar Decathlon Competitions

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ABSTRACT

The Department of Energy (DOE) Race to Zero and Solar Decathlon student competitions facilitate project-based service-learning opportunities for students majoring in Architecture, Interior Design, and Construction Management. The department of Construction & Building Sciences (CBS) supports annual interdisciplinary student-led design-build teams to engage with local non-profit organizations to design and build net zero ready and net positive homes. Two net-zero ready competition homes were constructed in partnership with Habitat For Humanity, which led to to participation in the 2020 Solar Decathlon local build challenge to design and build a net-positive home in collaboration with Ogden City. The home won first place in *Energy Performance*, second place in **Presentation**, and third place in **Engineering**. The home is outperforming the energy model and is a verified net positive home after a year of operation. As a result of the media attention, the local housing authority is now partnering on projects to address the housing shortage and affordability issues in Utah. These real-world experiential project-based service-learning experiences are often the highlight of students' undergraduate experience and have resulted in an influx of positive exposure for the CBS department and University that included increased enrollment, student satisfaction, and support from our administration.

INTRODUCTION

The faculty within the department of Construction & Building Sciences, representing Architecture, Interior Design, and Construction Management programs, have supported student-led design teams since 2017 to participate in the Department of Energy's (DOE) *Race to Zero* competition and the 2020 *Solar Decathlon Local Build Challenge* (SDLBC). Undergraduate students are required to design/build affordable, marketable homes that meet the DOE *Zero Energy Ready Home* (ZERH) guidelines incorporating current building science principles and practices.

This paper outlines how participation in these student competitions has provided project-based service learning opportunities, resulting in greater exposure and enrollment in Architecture, Interior Design, and Construction Management programs. It also explores the opportunities that exist to improve building design and construction practices using the ZERH guidelines.

2017-2019 RACE TO ZERO COMPETITIONS

Each year, students have gone above and beyond the baseline Race to Zero student competition requirements to partner with the local chapter of Habitat for Humanity to design and construct affordable, high-performance, single-family homes. Each home had a real site, design criterion, and unique design/budget constraints imposed on the students' submission. These design solutions resulted in greater community impact and industry partnerships.

The first five-bedroom, two-bathroom 2,160 square foot ZERH was designed for a single mother of 6 children in 2017 for the Race to Zero student competition and was constructed in 2018. The home was featured in the National Association of Home Builders local "Parade of Homes," highlighting affordable net zero construction strategies to the builder and Parade visitor communities. The home garnered a lot of media attention and led to a video being produced by the local utility natural gas company, Dominion Energy with their spokesman "Therm," which presented the ZERH strategies implemented in the project, such as a hybrid furnace/water heater, heat pump Heating Ventilation & Air Conditioning (HVAC), Energy Recovery Ventilator (ERV), air sealing, and passive solar design strategies. The video highlighting the net zero design strategies implemented can be viewed at the following link. https://www.youtube.com/watch?v=KPLILKD0eUo

The 2018 Race to Zero student competition three-bedroom, two-bathroom, 1040 square foot ZERH home was designed for a family of four to meet all standards outlined in the U.S. Sustainable Habitat for Humanity Construction Standards (HFH 2017), as well as 2018 Race to Zero Student Design Competition Guidelines (NREL 2018). This was the students' first all-electric home and introduced mini-split HVAC technology. The home introduced insulated shallow foundation design/build techniques to the local building department, whose representatives partnered with students to oversee the implementation was completed properly, avoiding unnecessary costs and environmental impacts typically associated with traditional frost depth footings and foundation for a slab on grade home in a cold climate.

2020 SOLAR DECATHLON COMPETITION

The culminating 2020 Solar Decathlon local build challenge experience was to build a net positive, five-bedroom, three-bathroom, 2450 square foot single family home with a detached two-car garage. The property was provided by the city in which the University is located (Ogden). The University funded the project with the intent to create a revolving fund that could be used to design and build affordable net zero homes in the local community. The three main objectives of the revolving fund include: provide a project-based student service learning experience; promote high performance net zero energy home design/build strategies; and serve the community by providing affordable housing solutions.

Teams competing in the Solar Decathlon Build Challenge worked during a two-year period to design (2019), build (2020), and operate (2021) their houses in their own respective regions, with student work culminating in the presentation of their work at the Solar Decathlon Competition Event held at the National Renewable Energy Laboratory in Golden, Colorado. (DOE 2020) Participants were required to demonstrate creative solutions for real-world issues in the building industry.

Highlights of the Department of Energy Solar Decathlon Competition include:

- Teams compete to earn points by operating their house successfully, and by showcasing the excellence of their solutions to industry expert jurors. (DOE 2020)
- Through local exhibitions, teams are able to explain the importance of their innovations and solutions to a broad public audience.
- The competition and winners are promoted through a variety of media outreach efforts, which provide participants and their collegiate institutions an opportunity for national exposure. (DOE 2020)
- Collegiate institutions that participate in the challenge are recognized as leaders in cultivating career-ready, young professionals with cutting-edge skills. Industry partners who collaborate with teams gain national and local recognition and have the opportunity to interact with knowledgeable future design and construction professionals. (DOE 2020)

The 2020 SDLBC included ten contests: Energy Performance; Engineering; Financial Feasibility & Affordability; Resilience; Architecture; Operations; Market Potential; Comfort & Environmental Quality; Innovation; and Presentation. (DOESD, 2020) The following sections of the paper are excerpts from the final deliverable and presentations to the juries in each of the three contests the team placed in the top three.

ENERGY PERFORMANCE CONTEST-FIRST PLACE FINISH

According to the DOE, "Superior energy performance is at the heart of the Solar Decathlon. This Contest evaluates the building's energy use and production, as well as its capability to provide energy services—whether connected to the electricity grid or operating with on-site and/or stored power." This contest scored five sub contests including Energy Efficiency, Energy Production, Net-Zero Plus Energy, Demand Response, and Off-Grid Functionality.

Our home scored 95.2 points of the total 100 points possible. Energy Efficiency was addressed by specifying high levels of insulation [R29 Structural Insulated Panel (SIP) exterior walls, R49 Insulated Concrete Form (ICF) foundation walls, and raised heel energy trusses to allow full depth R49 blown in fiberglass insulation] which provided superior resistance to heat transfer or high R values.

The home was air sealed to under 1 Air Change per Hour (ACH) using Aerobarrier. Aerobarrier fills gaps as small as a human hair and up to $\frac{1}{2}$ wide. All sorts of gaps left

by tradesmen get filled like drywall or sheathing overcuts, gaps between boards, and unsealed penetrations. It sealed the home to .6 Air Changes per Hour (ACH) at drywall stage to 50 pascals of pressure. Windows were specified as fixed windows unless required to meet egress to minimize air leakage and used triple surface coated double pane low e glass with argon between the panes to provide a U factor of .29 or better.

This home not only met all requirements for the 2020 SDLBC, but also the 2020 SDLBC code requirements (DOE 2019). Students used the DOE Zero Energy Ready Home National Program Requirements (Rev. 07) that built upon the comprehensive building science requirements of Energy Star for Homes Version 3, along with proven Building America innovations and best practices (DOEZERH 2020).

DOE Zero Energy Ready Homes are verified by a qualified third-party and are at least 40-50% more energy efficient than a typical new home. This generally corresponds to a Home Energy Rating System (HERS) index score in the low to mid 50's, depending on the size and region in which it is built (DOEZERH, 2020). Our home earned a HERS of 44 without the solar array and -8 with the solar array to compensate for the electric vehicle charging capabilities. This translates into the home being 56% more energy efficient than a 2006 energy code compliant home with a HERS score of 100.

ENGINEERING CONTEST- THIRD PLACE FINISH

This contest expects the effective integration of high-performance engineering systems, including heating, cooling, water, and ventilating systems. Solar Decathlon houses reflect different technology and integration options, providing an analysis of design implications for energy and environmental performance, up-front and long-term costs, and reliability. (DOESD 2020) We received 78 of the total 100 points possible in this category.

Because the home was so air tight and super insulated, mechanical ventilation was required by code to provide fresh air. An innovative approach to maximizing our investment in conditioned air was undertaken. All bathroom fans were replaced with exhaust ports tied to the ERV where the conditioned air preheated or cooled the incoming fresh air via a heat exchanger. The now "pre-conditioned and filtered" fresh outdoor air was introduced into the common spaces of the home to balance the ventilation system. Energy monitoring of the home via Emporia Vue Gen. 2 circuit level monitoring allows us to track the energy consumption of individual circuits. The ERV is on one of these circuits and has used 319 KWh of energy over the entirety of 2021. This equates to approximately \$.06 per day to continuously exchange fresh air at 75 Cubic Feet per minute. This provides a complete fresh air change in the home every 4.5 hours at approximately 95% efficiency.

Coupled with the innovative ventilation system is the Mitsubishi cold climate ductless mini split heating and cooling heat pumps. These heat pumps have individual room programmable thermostats, which allows for meeting room specific needs. The homeowners have reported that they are currently only using two of the 5 units provided on the main level because the solar heat gain through the windows in the winter is so great and the home stays at a consistent temperature without having all of the units on. So far in 2021, the heating and air conditioning of the whole home has cost on average \$2.94 per day in electricity and they have used 7597 KWh of electricity to maintain a temperature of 70 degrees Fahrenheit year-round. Not needing to bring natural gas into the home helped offset the cost of an all-electric HVAC system with a COP of 3.2, as opposed to installing gas furnace with a highest efficiency of 96-98%.

Another innovative approach was to maximize the self-consumption of site generated solar energy. A 50-gallon Rheem Prestige hybrid hot water heater, with a Wi-Fi enabled programmable thermostat, was implemented to load shift when the solar electricity generated on site could be used to super heat the domestic hot water. It was programmed to heat the hot water to 140 degrees Fahrenheit between the hours of 10:00 A.M and 2:00 P.M. when the homeowners typically were producing more solar energy than they could consume; thus, using the energy they are producing instead of putting it back on the grid. The plumbing system was designed specifically to minimize the amount of pipe run between the water heater and faucets, reducing material and labor costs.

The home incorporated Goal Zero Yeti 2500-Watt Hour portable battery backup technology to allow the home to maintain critical loads for up to 72 hours if the electrical grid were to be down in a natural disaster or other unforeseen event. One of the 39 solar panels is continuously trickle charging the battery so it is always at full capacity. An additional 8 add on 1500-Watt Hour battery units would provide enough battery backup to run all critical loads (lights and outlets in main living space, microwave, and smoke detectors) for more than a week. The solar array generates enough energy to offset the energy usage of the all-electric home annually, and it also generates enough electricity to charge an electric car enabling it to drive up to 20 miles per day.

So far this year (2021), the home's solar array produced 14.87 MWh of electricity and the home consumed 13.77 MWh of electricity making the home net positive by 1.1 MWh. This over production is partially due to the homeowner not charging an electric car and the battery back-up system not needing to be used.

Several builders and homeowners have used our website to duplicate systems or strategies in their own homes. (<u>https://www.weber.edu/solardecathlon/default.html</u>) All materials used on this project were selected with affordability in mind. For instance, SIPs minimize thermal bridging with 6" of polystyrene, high density, foam between two sheets of 7/16" OSB. This also allows a nearly airtight exterior building envelope. By using SIPs, we reduced framing labor and material costs by 17% when compared to traditional framing.

Large overhangs were designed to nearly eliminate solar heat gain in the summer with appropriate shade angles, yet to allow maximum solar heat gain in the winter. There

are limited windows on the west side of the home to minimize solar heat gain, and also in respect to the privacy of the neighboring house. The only window on the south side is in the door and is only a quarter light window to allow daylighting into the laundry/mud room area.

The land was donated by the city Ogden, Utah to show their commitment to revitalizing neighborhoods and breathing new life into historic districts. This particular lot sat empty for nearly 10 years after a dilapidated four plex was torn down. The debris from the old fourplex had been buried on site and the students discovered an underground aquifer that ran through the site. This discovery determined that the project had to provide a perimeter drain as well as a French drain under the monolithic basement slab.

The Craftsman Architectural Style home was intentionally designed to nestle in with existing homes on this historic avenue and showcase how a period style home can provide a net-zero energy lifestyle. Students worked with city planners to design a home that would fit in on the narrow, deep lot. The home is 24' wide by 58' deep with a detached two car garage. Students were provided a set of schematic plans and ideas that city planners had designed using SketchUp, and were allowed to alter to fit within the guidelines of the 2020 SDLBC. The design was dictated by the 20' front and side setbacks on the corner lot. A 6' side setback on the west side required that windows be strategically placed so they didn't look directly into the windows of the neighbor.

Aside from visible solar panels, there is no distinct differentiation between this home and it's neighbors, other than the knowledge that this home is a net positive, all-electric home capable of producing all of its own energy annually, maintaining all of its critical loads in excess of a week's duration, plus charging an electric car to drive up to 20 miles per day. The design team wanted to prove that it is possible to build a net zero home that fits into the neighborhood, and appeals to a large audience, not just those that are energy conscious.

The home is long and narrow, therefore long sight lines were designed to allow the feeling of a more open floor plan. All upstairs hallways are eliminated to provide for a spacious feel of the floor plan, while accommodating ADA guidelines. As a result, potential buyers who walked through the home frequently commented on how much bigger it felt than it appeared from the exterior. All of the living space is intentionally placed on the east side of the home, provided with large windows to introduce ample daylight and allow the home's occupants to enjoy the view of the picturesque Rocky Mountains. In fact, during construction, daylight was so prevalent that no artificial light was required to work on the interior during the day.

The home is designed to make the "True Cost of Ownership" affordable to occupants of the east bench sector of Ogden by nearly eliminating energy bills. The home is outperforming the most widely accepted measuring stick for how energy efficient a home is using the Home Energy Rating Score (HERS) energy model predictions; The homeowners are experiencing electrical energy bills of only ~\$9 per month, which is the unavoidable charge for the required connection to the utility company's electrical

grid. This equates to an annual energy bill of around \$108. The grid is essentially acting like a battery to store excess energy that is being produced in the spring and fall. This can subsequently be used in winter and the hottest part of the summer when usage is greater than production.

The building envelope of the home showcases off the shelf solutions to reduce utility costs. The combination of Aerobarrier and a super-efficient HVAC, requires conditioning the air only once an hour; whereas, most new homes today require the air to be conditioned 4-7 times an hour.

The foundation is built with Insulated Concrete Forms (ICFs) that have an effective R value of 45-55. The main floor's exterior walls are panelized Structural Insulated Panels (SIPs) that have an effective R value of 29. The roof utilizes 16" raised heel energy trusses to allow full depth R 49 blown in fiberglass insulation in the attic to be extended all the way out to the exterior edge of the exterior walls, thus eliminating the leading cause of ice damming. The windows are triple low-e coated glass filled with Argon gas and have a U factor of .27 or lower depending on the operation of the window. All appliances are Energy Star and Water Sense certified. The home uses 100% LED fixtures or bulbs.

PRESENTATION CONTEST- SECOND PLACE FINISH

Presentation quality can dramatically affect market perception and the likelihood of innovation adoption. This contest evaluates the team's ability to accurately and effectively convey its design and energy performance strategy to relevant audiences. (DOESD 2020) We scored 85 out of 100 in this contest.

In order to showcase our home and how net zero design and construction is possible, our interior design department designed a kiosk to showcase the new and innovative building materials used in the home. It included media displays, videos, a 3D printed model as well as sponsor information. Several open house events were held both virtually and in person.

Our online presence was focused on making information available to the public regarding our Net Zero build. An organized website was key as we shared plans, project manuals, sub-contractor and supplier information to allow future homeowners to duplicate our efforts. Instagram was the preferred platform for content because it specifically targeted our followers demographics, and ability to quickly load content. The website had over 4,000-page views since launching the website in January of 2020. Visitors spent close to 3 minutes on the website, while 50% came back for a second look. Many stayed on our main page, with 1/3 viewing student profiles. The website is https://www.weber.edu/solardecathlon/default.html, with links to our social media platforms included.

Our heaviest traffic occurred shortly after the local newspaper articles were published. Students received a lot of media attention in the form of multiple press releases, an article in *Utah Construction & Design* magazine, three different live news station interviews and highlights in the evening news, with all major print news writing stories, including follow up stories.

The overarching goals of the project were to create a sustainable revolving fund, support community builds, fostering student education and advance green building concepts from academia research into common industry practices. This home has been a teaching tool for high school concurrent enrollment classes and technical college students who completed the entire plumbing scope and assisted in the framing and electrical scopes as part of their apprenticeship programs. University and technical college students worked alongside sub-contractors, used new methods and materials, fundamentally changing the future of residential construction. Work has already begun on the next two projects that include off-site manufacturing or pre-fabrication.

Upon completion, the home was sold on a lottery system. We listed the home, giving prospective homebuyers 2 weeks to submit full price offers. We received 13 full price offers on the home at \$350,000. The home was appraised at \$425,000. Each potential buyer's name was placed on a paper in a tumbler, from which the University's President drew the name of the "winning" buyer. The home was built for \$147.51 per square foot, while the local going rate was \$175 per square foot. The value per square foot based on the appraisal was \$173.47 per square foot.

CONCLUSION

Participation in the Department of Energy *Race to Zero* Student Design Competitions and 2020 *Solar Decathlon* Build Challenge greatly enhanced the college experience for students majoring in Architecture, Interior Design, and Construction Management. One of the videos on the website created for the Solar Decathlon is the team lead reflecting on her excitement to show to her kids and family what she did for her senior project. She says, "I didn't write a paper for my capstone experience, I designed and built a net-positive home I can be proud of for years to come, and I drive by I can say, I built that!"

These projects have allowed conversations surround the "true cost of ownership" to provide context for the case to invest in long term energy savings. Students have commented that their opinion on what they will invest in has shifted from granite countertops to items no one will ever see such as air sealing and insulation. Building Science became something that was fun and exciting instead of just another lab with pre-defined outcomes.

The needle of progress and long-term change is moving in the right direction. The number of homeowners, builders and developers, who have reached out wanting more information and consultation on how they can achieve net zero on their projects is astounding. The Covid-19 pandemic forced the team to develop a lot of engaging material on the website for remote tours and public displays. This ended up being a great resource to be able to send potential adopters of our systems on their own projects.

The website contains all information needed to duplicate the systems to nearly eliminate thermal bridges, air seal the home, mechanically ventilate the space very efficiently, and provide comfort in all seasons.

The home continues to outperform the HERS energy modeling. As predicted, the HVAC is the largest electricity consumer using 13,392 KWh of energy to maintain a temperature in the home of 70 degrees year-round. The Water Heater is the second highest consumer at 7598 KWh of energy, and the ERV used just 319 KWh of energy in 2021. The total electrical consumption of the home in 2021 was 13.85 MWh and the production of the solar array was 14.87 MWh substantiating that the home is a net positive home. The Emporia Vue circuit level energy monitoring system helped identify an issue and further investigation proved that the compressor on the hybrid heat pump water heater was not working properly and is currently being repaired. Despite the water heater using six to seven times more electricity than normal to rely solely on resistance heat to provide all of the domestic hot water, the home is still netpositive. The synergies of super insulation, air tight, and nearly no thermal bridges make for an exciting case study of just how efficient a building envelope can be. These experiences will undoubtedly propel students into the industry as emerging professionals. It provides an interdisciplinary capstone project that students will be proud of for many years.

REFERENCES

- 2019-2021 Weber State University Solar Decathlon Local Build Challenge Team. (2021). 2019-2021 Weber State University Solar Decathlon Local Build Challenge Submission.
- DOE. (2020). DOE Solar Decathlon 2020 Build Challenge Competition Guide.
- DOESD. (2020). *DOE Solar Decathlon Build Challenge Rules (June 2020)*. U.S. Department of Energy. Retrieved from: https://www.solardecathlon.gov/2020/assets/pdfs/build-challenge-rules.pdf
- DOESD. (2019) DOE Solar Decathlon Build Challenge Building Code (July 2019) U.S. Department of Energy. Retrieved from: <u>https://www.solardecathlon.gov/2020/assets/pdfs/build-challenge-code.pdf</u>
- DOEZERH. (2020) *DOE Zero Energy Ready Home National Program Requirements* (*Rev. 07*). Retrieved from: <u>https://www.energy.gov/eere/buildings/guidelines-</u>participating-doe-zero-energy-ready-home-program
- HFH. (2017) 2017 U.S. Sustainable Construction Standards. Retrieved from: https://www.habitat.org/lc/env/pdf/US_Construction_Standards.pdf
- NREL. (2018) 2018 U.S. Department of Energy Race to Zero Student Design Competition Guide. National Renewable Energy Laboratory. Golden, CO.
- SDOE. (2017-2019) Race to Zero History. Office of Energy Efficiency and Renewable Energy, US Department of Energy. Retrieved from: <u>https://energy.gov/eere/buildings/race-zero-history</u>

Continued Experiences with the Solar Decathlon Design Challenge

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ABSTRACT

Ball State University has participated in five Race to Zero (RTZ)/Solar Decathlon Design Challenge (SDDC) competitions since 2017. During this time, we have worked with twenty student teams of over 100 students, seen fourteen teams advance as finalists, and celebrated five award prizes—four in housing divisions.

The driver for our continued participation in SDDC is the rigorous integrated design framework provided for teams. This design integration involves the expansion of boundaries beyond traditional "architectural" design considerations into technical systems, performance modeling, environmental impacts, etc. Although some SDDC teams involve students in other disciplines to address technical integration requirements outside of architectural design, we have achieved these expectations mostly within the architecture teams themselves by expanding horizons and harnessing technical assistance from industry partners and other resources. In doing so, we have been able to keep the teams efficient as well as to encourage the students to learn more about buildings than they would in an architectural design studio with a less diverse range of systems engagement. Institutional recognition of the value of SDDC has resulted in a scaling-up of our involvement in the program. What began with graduate students and a single studio advisor now includes undergraduate teams and multiple advisors, which offers benefits for collaboration and challenges with coordination.

This paper will describe the structure of our SDDC studios; the infusion of building science into the design studio setting; working with external partners; and observations on successes and challenges. The focus will be on how the experience is different from conventional architecture studios and the positive impact that the competition has on encouraging, guiding, and demanding better comprehensive design solutions.

SOLAR DECATHLON DESIGN CHALLENGE (SDDC)

The US Department of Energy (DOE) created the Race to Zero (RTZ) in 2014 as an annual design competition for university students. Two goals of the competition were to "integrate high performance with design in degree programs" and to "inspire students to enter into sustainable building careers." Early on, RTZ focused on housing typologies, required compliance with the DOE's Zero Energy Ready Home requirements (USDOE 2, 2019), and provided building science training sessions.

RTZ was renamed the Solar Decathlon Design Challenge (SDDC) in 2018 to combine DOE competition efforts and to distinguish RTZ from the Solar Decathlon design/build

competition begun in 2002. From competing teams, there were relatively few changes to the structure of the design competition other than the name change. (USDOE 3)

From 2014-2017, the competition focused on four residential building typologies as divisions: attached housing, suburban single-family detached, urban single-family detached, and multi-family. For the 2017/2018 competition, a small elementary school commercial building type was added as a division. For the 2018/2019 competition, a small office building typology was added as a division and the multi-family type was changed to a mixed-use multi-family type. For the 2020-21 competition, a small retail type was added to the two other commercial types. More changes are expected for the next SDDC cycle. These regular changes to the competition divisions are evidence that the organizers strive to respond to team feedback, to track emerging interests/issues in the building industry, and to provide sufficient options for student team involvement.

SDDC requires that students develop collaborative teams to design proposals for one of the building typology divisions. The proposals are evaluated by a jury according to how well they respond to ten contest areas (hence the "decathlon" name). These contests change year-to-year in response to industry trends and/or feedback from teams and juries. See Table 1.

2016/17 RTZ	2020/21 SDDC
1. Architectural Design	1. Architecture
2. Interior Design, Lighting, and Appliances	2. Engineering
3. Energy Analysis	3. Market Analysis
4. Constructability	4. Durability & Resilience
5. Financial Analysis	5. Embodied Environmental Impact
6. MEP Systems Design	6. Integrated Performance
7. Envelope Performance and Durability	7. Occupant Experience
8. Indoor Air Quality (IAQ) and Ventilation	8. Comfort & Environmental Quality
9. Innovation	9. Energy Performance
10. Presentation and Documentation Quality	10. Presentation

Table 1. RTZ/SDDC contest areas

DOE develops a new competition guide each year that describes the requirements for team structure, competition deadlines, parameters for the divisions, and details related to the contests. These guides establish expectations for the submitted proposals to: address technical considerations, comply with industry standards, and integrate enclosure and HVAC systems. While the NAAB accreditation requirements that govern US schools of architecture require that students demonstrate abilities related to integrated design, the high level of design development required by SDDC—including verifying predicted performance against industry benchmarks—is not the norm and may contribute to the appeal for participating architecture schools.

SDDC AT BALL STATE

The Ball State University Department of Architecture is part of the R. Wayne Estopinal College of Architecture and Planning (CAP). CAP includes programs in architecture, landscape architecture, urban planning, urban design, historic preservation,

construction management, and interior design. Ball State does not have a college or department of engineering. The Department of Architecture has an enrollment of 374 students, which is the largest department in the college and represents 36% of CAP enrollment. The department has accredited undergraduate and graduate programs Instruction primarily occurs at the Muncie, Indiana campus but we also have a satellite location in Indianapolis that houses one year of our Master of Architecture program.

Under the newly revised National Architectural Accrediting Board (NAAB) requirements, architecture programs must provide evidence of student ability and understanding in a range of considerations including those that relate to building technology and construction methods; design synthesis; building systems integration; health, safety, and welfare concerns; and regulatory considerations. In the Department of Architecture, these student learning objectives are satisfied in our ARCH 602 (previously ARCH 501) graduate-level and ARCH 400 undergraduate-level comprehensive architecture design studio courses.

A significant challenge of the Arch 602 and Arch 400 studios is creating a project through which students can attain a high level of technical detail over the course of a single 16-week semester. In 2017, the graduate comprehensive design studio began using the RTZ as the design project for the course. In 2020, the undergraduate comprehensive design studios joined the graduate course in using SDDC as the design project for the course, two courses taught simultaneously.

SDDC allows our comprehensive design studio to meet and exceed departmental and accreditation student learning objectives for at least four reasons.

- It includes smaller building types that are an appropriate scale and are manageable for students in small teams to develop and complete in a short period of time. In recent competition cycles, the addition of larger building types such as the school and office building pose challenges to teams.
- It focuses on collaboration and teamwork, which means that students contribute individual expertise to the projects and that members learn from one another for help and skills development. Indeed, the competition challenges architecture students to develop schemes to a level of complexity uncommon in architecture studio courses, which encourages and necessitates assistance from other courses and disciplines with technical expertise.
- The schedule and the typical spring semester schedule align relatively well (albeit not perfectly). Because some SDDC teams begin their design development in the fall semester, teams that do the projects over one semester only appear to be at somewhat of a disadvantage. However, the flexibility of the competition requirements allows teams to participate within the constraints of their own departmental and curricular constraints.
- It encourages involvement of community partners and industry professionals to further assist students with limited technical skills or knowledge develop more detailed and technically sophisticated proposals.

Team Structure. The typical Ball State SDDC team structure is illustrated in Figure 1. The basic structure was developed in 2017 and the arrangement has been sufficiently robust and accommodates modifications over time. For example, in 2020 the scale of the endeavor increased when we added a 2nd course to the annual competition cycle.



Figure 1. Diagram illustrating the course and collaborative structure of the Ball State SDDC teams

The centerpiece of the team collaboration structure is the core design team situated in the design studio. Originally taught by one design studio faculty member, there are now two lead faculty in two studios with part-time design adjuncts in the graduate course. The enrollment of the studios and the student preferences for team size determine the number of core teams each year. See Table 2.

Year	Faculty	Courses	Teams	Team Sizes
2017	1	Grad only	3	2-3 Students
2018	1	Grad Only	2	4 Students
2019	1	Grad Only	2	5 Students
2020	3	Grad & Ugrad	5	5-7 Students
2021	3	Grad & Ugrad	3-5	4-9 Students

Table 2. SDDC team statistics by year

Each core team works collaboratively with students in architecture elective courses designed to support the studio. The mainstay elective course has been Arch 632 High-Performance Buildings, a course focused on energy simulation. Over the years we experimented with other support courses with limited success in terms of improving our standing with the competition juries. In 2017, we offered a LEED for Homes course that ran the proposals through the LEED for Homes framework and developed a LEED score as a way of distinguishing the proposals. In 2018, we offered a course on embodied energy/carbon that ran the proposals through Tally software to determine the carbon footprint of the materials used. These courses have been useful to some extent, but not as essential as the simulation course. We now integrate the embodied energy/carbon analysis into the energy modeling course. The design core teams

sometimes work with an independent study course on cost estimating led by faculty in our construction management program, which has been an easier way for faculty in that program to be involved in the competition given their curricular constraints.

The competition encourages teams to work with industry partners "who can provide a market-ready perspective for proposed design solutions." (USDOE 3) Internally, we divide these "outside the university" partners into two categories: community partners and industry partners. Community partners are organizations that are in the business of building the kinds of buildings the student teams are proposing and can act as clients for our student teams. Ball State SDDC teams have worked with a variety of community partners including custom homebuilders, non-profit homebuilding entities including Habitat for Humanity, and community development corporations (CDCs). Typically, partners assign a liaison that works directly with the student teams. Interactions include video conferences (particularly useful during Covid-19), in-person critiques, workshops, presentations, site visits, etc. The involvement varies depending on the partner and the liaison availability. Ideally the partner interfaces with the teams at least once per month throughout the semester. Finding a partner who is willing to work with all the teams is easier than having multiple during a semester.

Industry partners are professionals and/or academics working in specialty areas. For our teams, these partners have included mechanical engineers, the local ASHRAE chapter, a PV systems installer, housing designers, real-estate professionals, community development or services organizations, etc. Typically, the industry partners interface with the teams once per semester through a workshop. We have also had industry partners review student reports and provide feedback. See Figure 2.



Figure 2. HVAC Workshop with engineers from the ASHRAE CIC in 2020 (by authors)

Design Studio Courses. For the 2017-2019 SDDC, the core design teams were situated in a single 6-credit graduate-level comprehensive design studio taught by a single faculty advisor. These studios had approximately 8-10 students enrolled. This arrangement resulted in an excellent teacher/student ratio for a college course (and even for an architecture studio course where there are typically 12-15 students). The students in these small studio classes were divided into 2-3 student teams each taking on one of the housing typologies. Department leadership recognized quickly that SDDC was an

excellent experience for students and a rigorous way of satisfying curricular needs, and they have supported the expansion of our involvement. The basic idea is to use SDDC to give all students in our programs a net-zero design experience.

We dramatically scaled-up our involvement in SDDC in 2020. The graduate-level studio core teams were joined by a 6-credit undergraduate-level core teams. Each studio had a faculty advisor. The effort was complicated by the fact that the graduate-level course had moved off-site to our Indianapolis center while the undergraduate group remained at the Muncie campus. In addition, the class days and times were different with some overlap. For example, the undergraduate group met Monday, Wednesdays, and Fridays from 1-5pm while the graduate group met Mondays and Thursdays from 12:30-5:30pm. Between the two courses, the number of students involved increased to over 30 and the number of teams also increased to 5. Despite the size changes and logistical challenges, the studio faculty advisors decided that it was important for the two courses to share resources and have opportunities meet.

Since Mondays were a shared class day for both courses, topical workshops and design reviews for both groups were scheduled for those days. Mondays become the day the two studios met together virtually. For example, if an industry partner was visiting the Indianapolis center to give a presentation to the graduate-level group, the undergraduate studio would meet in a classroom and join the presentation using a web conference. Also, the groups would physically meet for site visits or workshops when possible. During Covid-19, web conferencing became an indispensable tool to connect. In 2021, the local ASHRAE chapter successfully conducted an HVAC workshop via Zoom using the Breakout Room feature, which limited the amount of partner involvement by consolidating meetings with groups. Another benefit for the advisors was shared coordination of activities. Finally, having design reviews online allowed guests who would otherwise not be able to travel to meet with the teams in person. There were some Mondays when there was not a group activity especially around the SDDC submittal deadlines.

In 2021, after one cycle of fine-tuning the scheduling across the classes, the advisors decided to have three milestone design review presentations aligned with the SDDC schedule: the first a week in advance of the first Project Proposal submission, the second two weeks in advance of the large Project Portfolio submission, and the last a week in advance of the juried competition event. These reviews allowed teams to receive one last round of feedback from advisors and invited guests on their materials in advance of submitting them to SDDC. After the competition event at the end of the semester, the classes met for one last time to recap the experience and share work.

Finally, the two courses used a common weekly report template for teams to document what each team member had worked on over the past week, how much time (as a %) was spent addressing the SDDC contest areas, and what goals/questions the team had for the upcoming week.

Elective Seminar Courses. A variety of 3-credit architecture elective seminar courses have been offered over the years intended to provide support to the core studio teams. The instructor for these courses coordinates the class schedule with the studio schedule, is involved in the studio curricular planning, and regularly attends studio reviews to

stay abreast of developments with the competition teams. Assignments in the elective classes are intended to provide useful research, information, or analysis for the core teams at strategic points throughout the process. The most successful elective focuses on high-performance buildings and conducts a building and energy code review for the teams in the initial weeks of the semester. As the core team designs progress, digital models are shared with students in the elective classes to perform energy analysis using a variety of tools including REM/Rate to obtain a HERS score (for residential building types), using BEopt to provide comparisons of systems selections, etc. Teams across the courses coordinate materials with each other directly.

The information from these analyses is then shared with the core teams to inform their process. The idea is that the elective class removes some of the technical burden from the design teams and provides an extra "set of eyes" focused on details. The elective classes appear to be most useful to teams when they address competition requirements (e.g. energy modeling to obtain a HERS rating) rather than considerations that go beyond the competition requirements (e.g. demonstrating how a project could achieve a LEED or a WELL certification), which was a surprising outcome over the years since the advising team believed that an important role for the support courses would be these "extra" considerations that would distinguish projects at the competition.

Independent Study Courses. When necessary, we have engaged students in the SDDC process through independent study courses, which are more flexible and adaptable than scheduled classes. SDDC encourages teams to work in interdisciplinary and cross-disciplinary ways within their institutions. This can be challenging given the constraints of curricula in different departments. The Ball State Construction Management program's curriculum does not allow much room for elective courses to accommodate involvement. The best option for them has been for a small handful of students in their program to work with an advisor on SDDC as an independent study. For departments interested in being involved in SDDC, but who are unwilling or unable to use independent studies and cannot accommodate the competition in existing or new courses, we have had to forgo collaborations.

Within the Department of Architecture, there have been students over the years who are interested in doing an independent study related to SDDC as part of a graduate thesis. We have had one excellent experience with this arrangement, but in general it is exceptionally challenging for a single student to manage a large complex project like SDDC without a larger collaborative team as we have in the studios.

CONCLUSIONS

Outcomes. Since 2017, Ball State has engaged 20 student teams and over 100 individual students in the SDDC. Of these 20 teams, 14 have advanced to the finalist round after the first Project Proposal (formerly Progress Report) submission resulting in a 70% success rate in getting teams to the final jury presentations. Of these 14 finalist teams, 5 have been awarded prizes by the competition juries resulting in a 36% success rate for the finalists and a 25% success rate overall. One trend we are tracking internally is that it appears to be more difficult to advance to the finalist round now than before. Anecdotally, this may be the result of more teams registering for the competition. To

address this issue, DOE invited 10 finalist teams per building typology in 2021 compared with 8 previously. We have seen our success in getting to the finalist round decrease over time. However, the number of awards given per division has increased to now include first, second, and third place winners as well as separate Grand Prize winners for the residential and commercial divisions.

Departmental, college, and university leadership have taken increased interest in our SDDC involvement and successes, which has allowed us to integrate the competition into our curriculum, expose more students to the SDDC program, and expand our efforts. One example of these benefits has been support for a 2023 Solar Decathlon Build project on a local site in Indianapolis that we are currently working on with Englewood CDC, the community partner we have used for the past two SDDC cycles.

Challenges. While the competition registration fees have decreased over time (a positive), it is expensive to travel to the competition event held at NREL in Denver each April. DOE requires that a member of the team present in person and encourages up to five team members to attend. Some travel funding through the university has helped to subsidize the travel costs for the students, but the team members typically still pay a percentage of the expenses. Due to Covid-19, the in-person event was shifted to a virtual event for the 2020 and 2021 cycles, which was a missed opportunity for the student teams but eliminated the burden of the travel costs. However, the NREL event is always a highlight and we anticipate a return to the in-person event in 2022.

One challenge with the competition event is that DOE limits how many faculty advisors and student team members can attend. This limitation is due to space available to host the event at NREL, but it can be difficult to determine who attends and who stays behind. A colleague at another university has taken larger groups than NREL allows to Denver and then some of the team members do not attend the event to give everyone on the teams the opportunity to travel.

SDDC officially begins in the fall-semester but our curriculum only allows us to begin the projects in the spring semester. Some competing teams at. Other schools have upwards of 7-8 months to develop their proposals while we are typically constrained to approximately 11-12 weeks. It is hard to compete with teams who have had more time to develop their projects. This is an issue that has been raised with DOE in faculty feedback sessions but that has not been adequately addressed to date.

SDDC requires that all student team members complete a building science training program organized through DOE. The goal is to establish a level playing field for the teams who may come from very different disciplinary backgrounds and who may or may not have experience or knowledge with high performance or net-zero energy building design. Initially, the training was run through RDL with Joe Lstiburek and John Straube as the instructors— undisputedly building science experts. However, the videos were too long, somewhat rambling, and difficult for the students to get through. In 2021, DOE released a new set of training modules through Heat Spring and the instructors are primarily DOE and NREL staff. The videos are shorter, more concise,

and easier for students to get through. However, there are two challenges we have experienced with the building science training. First, our teams sometimes have students who are only involved in limited aspects of the design process and who may be from majors outside those that deal with buildings. It is difficult to justify that these students complete a lengthy training process when they have limited involvement. Second, in our courses we find that the students usually do the training with minimal complaints but that it can be difficult to see the knowledge gained in that training applied directly in the projects. There appears to be a disconnect here—doing the training doesn't guarantee that the students will use the training to inform their project.

Scaling-up our involvement in SDDC by adding more courses, students, faculty advisors, etc. has complicated our involvement in the competition. There is more coordination necessary between different faculty advisors; less consistency with the technical details and solutions that the teams propose; and less awareness of what the various teams are developing. In short, more teams are harder to manage. Our approach has been to use the schedule to provide some structure for all teams.

Lessons learned. Ball State's participation in SDDC has been an overwhelmingly positive experience for faculty, students, and associated partners. Each year, we closely track the strengths and weaknesses of our process, schedule, and outcomes, and we use this information to inform our process in subsequent years. Below are a few lessons we have learned over the past 5-years of SDDC involvement:

- It is best to let student self-select to take a course or studio that is engaged with the SDDC. This isn't always possible but improves student engagement.
- SDDC technical requirements place pressure on teams to quickly develop a building that can be detailed, which can result in schemes that do not fully benefit from the iterative architectural design process. In short, teams can end up with well-detailed but generic or mundane architectural solutions.
- Determining the perfect size SDDC team challenging. Too few students and every member has to do a lot of different things. Too many members and there. Is a risk of members becoming too specialized (and perhaps not satisfying the broad objectives of the course) and also some members not being as engaged.
- The DOE juries are still not releasing the scores for the 10 contest areas for each team, which would be very helpful for repeat advisors.
- The competition requires them to learn a lot simply because they "need to know" things to submit strong materials that are competitive with other teams. DOE provides many, perhaps too many, resources to help students, but the short timeline for many teams seems to mean that many of the resources go underutilized—especially the building science training modules.
- SDDC asks teams to design a net-zero building that addresses a set of contest area criteria, but teams quickly learn that the proposals need to go far beyond these basic requirements to be competitive. Every team shows up with a net-zero building that, is basically the minimum requirement for admission to the competition.

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REFERENCES

- National Architectural Accrediting Board (NAAB). (2020). *Conditions for Accreditation: 2020 Edition*, National Architectural Accrediting Board, Inc., https://www.naab.org/wp-content/uploads/2020-NAAB-Conditions-for-Accreditation.pdf
- US Department of Energy (USDOE 1). (2021). *Solar Decathlon Design Challenge Rules*, US Department of Energy, Washington, D.C.
- US Department of Energy (USDOE 2). (2019). *DOE Zero Energy Ready Home National Program Requirements (Rev. 07)*, US Department of Energy, https://www.energy.gov/sites/default/files/2019/04/f62/DOE%20ZERH%20S pecs%20Rev07.pdf, Visited site on 8/26/2021
- US Department of Energy (USDOE 3). (2019). Solar Decathlon Competition Guide 2018-2019, US Department of Energy, Washington, D.C.

Frame House: An Open-Source Housing Design and Construction System

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ABSTRACT

Frame House is a conceptual design experiment which aims to simplify the housing design and construction process and empower occupants to participate in the creation of their home through a user-fabricated modular component system. Frame House builds on concepts from the traditional balloon framing system but introduces a modular, component-based aspect to this structural framing system to ease the customizability, transportability, and the assembly and disassembly processes. The modularity of the structural system theoretically allows Frame House to be user-fabricated, encouraging homeowners to participate in the design and construction of their homes. In this paper, we present our preliminary research on housing market issues, existing precedents for modular, customizable housing systems, conceptual development process of the Frame House system, future potentials, ongoing research plans, and possible use cases in the residential housing industry.

INTRODUCTION

Overview

Frame House is a conceptual design experiment which aims to simplify the housing design and construction process and empower occupants to participate in the creation of their home through a user-fabricated modular component system. Frame House builds on concepts from traditional balloon framing, but introduces a modular component- based aspect to this system. In doing so, this system gains the potential to be easily customizable, transportable, and demountable. Additionally, the modularity of the components can allow Frame House to be user-fabricated, encouraging homeowners to participate in the design and construction of their homes. With these potential benefits, Frame House has the possibility to reduce the strain of housing market issues such as the lack of affordable housing and lack of skilled labor, among others. While Frame House does not claim to solve every challenge relating to this complex issue, the team sees the potential to bring new opportunities into the market.

The conceptual development of the Frame House took place in the Spring of 2021 during one of Penn State's Directed Research Studios, *Open-Source Housing Systems*, offered by Benay Gürsoy in the Department of Architecture. Frame House's research process began with an analysis of the current housing market issues and several existing systems. Using

this research, the team established project goals and developed the preliminary design system which was explored through a series of scaled prototypes. Our current goal is to develop a working structural frame construction system. The team plans to run a digital structural analysis on the structural frames and create a series of structural tests which will be done in collaboration with the Pennsylvania Housing Research Center (PHRC), using their lab and equipment. In the future, the team hopes to make the system more affordable, expedient, customizable, expandable, and demountable.

Analysis of Housing Market Issues

In his book, *The Architecture of Affordable Housing*, Sam Davis notes that the fact that "the United States is suffering from an acute housing shortage is indisputable. In 1989, the shortage of housing for those in need stood at over five million dwellings" (Davis, 1995). This shortage has only increased. "By 2030, UN-Habitat estimates that 3 billion people, about 40 percent of the world's population, will need access to adequate housing. This translates into a demand for 96,000 new affordable and accessible housing units every day" (UN Habitat, 2021). This is further exacerbated by the fact that many families' housing costs are increasing to upwards of 50-70% of their income (Davis, 1995). Since "seventy percent of the cost of a new dwelling is affected by planning and design", it is imperative to create a new system of designing and building that can reduce housing costs and restore the affordability of homes (Davis, 1995). While building truly sufficient affordable houses does not necessarily cost less than building market-rate houses, the main cost savings can come from two main strategies: material and space efficiency and creative home financing (Davis, 1995).

Lack of skilled labor creates an additional bottleneck toward increasing housing stock. A study conducted by Freddie Mac reveals that the housing shortage is partly caused by the deficit of skilled construction labor (Freddie Mac, 2021). This shortage is only getting worse during the recent COVID-19 pandemic, seen in the 2020 survey by the National Association of Home Builders (NAHB), where the deficit of skilled labor topped the list of the problems builders faced in 2020 (Chaluvadi, 2020). These labor and housing shortages are even anticipated to increase after the COVID-19 pandemic ends, since emergency situations like this one increasingly displace many people who live in the affected areas, creating acute spikes in housing needs (Metraux et.al., 2020).

The COVID-19 pandemic revealed additional issues in the housing market as well. The rise of remote work during this time showed an increase in desire for more livable square footage and the need for more flexibility. Existing houses are unable to adapt to these changes, making homeowners unhappy with their living spaces. Beyond that, those who want to build their own home to meet their unique needs have difficulties designing and constructing a home by themselves. More specifically, the safety, serviceability, permit and inspection requirements needed to comply with codes, make it difficult for prospective homeowners with no construction background to build the homes that they will occupy. As a result, homeowners have few avenues to affordably build a new home that can meet their everchanging needs.

These issues are complex in nature and do not stem from isolated causes. Modular, self-built housing systems, such as the Frame House, can reduce the strain on the housing market by

lowering the design and construction costs, and reducing the need for skilled labor, while increasing flexibility in living spaces.

Analysis of Existing Systems

PREVI Low-Cost Housing Development: Atelier 5 Submission

PREVI, *Proyecto Experimental de Vivienda*, is an experimental social housing project developed during the 1960s in Lima, Peru which was collectively designed by a group of international architects who aimed to reconcile the conflicting forces of informal growth and top-down planning through low-cost, modular housing designs (Stirling, 2021). The Atelier 5 team from Switzerland designed one portion of this complex. Their housing system has been assigned as a guiding precedent in the *Open-Source Housing Design Systems Studio* to Puja Bhagat and Celina Deng, two students from this studio who are among the authors of this paper. Atelier 5's system was of particular importance due to its goals of affordability, easy constructability, light-weight components, expandability, and self-built kit-of-parts. While Atelier 5 used precast concrete components to achieve these goals, in the design for the Frame House as the studio project, the system is updated to integrate contemporary digital fabrication technologies for ease and flexibility of fabrication, as well as open-source access.

Although Atelier 5's design had many virtues, there were some issues as well. Because of the limited footprint, it was an inflexible system to expand upon. The rigidity of the concrete panels meant that expanding or reconfiguring the spaces in a home was particularly difficult. Additionally, the mandatory split-level design of the home made it incompatible with the needs of mobility-restricted occupants. Using Atelier 5's system as a precedent, the students explored ways to update the existing design for more flexibility in expansion, and accessibility.

Wikihouse: Open Source Digital Construction System by Alastair Parvin

Wikihouse was created in 2011 by Alastair Parvin as an open-source, DIY housing system (Wikihouse, 2021). Users can download the cut sheets for specific models of Wikihouse structures and fabricate them using CNC machines. Because of their kit-of-parts nature, Wikihouses are easy to assemble with a small group of people, though they require additional envelope development and finish work that are not modularized within the Wikihouse system. While Wikihouse system includes well-designed components that are freely available for anyone to download and fabricate, these elements are not easily adaptable, as the different building models are discrete, and parts are not standardized or interchangeable from one to the other. With the Frame House system, the students similarly intended to design modular components and connection systems. However, their goal was to make a standard, interchangeable system of components with envelope and HVAC as embedded elements within the design.

Designing for Modularity

Many designers have experimented with modular housing, creating affordable and easily constructible modular housing systems. *U-Build* by Studio Bark in the United Kingdom features simple modular boxes that can be easily connected to create a unique home design. This system aims to enable users to participate in the construction process by focusing on easy fabrication, construction, and disassembly (Studio Bark, 2021). *The New Makers* also

have a series of similar modular housing systems. Their goal is to design an affordable "plug & play" set of modules that are flexible in nature (The New Makers, 2021). Each system of parts addresses a unique living condition and is designed to fit the needs of each occupant type. These types of modular systems are relevant to Frame House's kit-of-parts design.

Designing for Adaptability

Other designers have tackled the challenge of designing adaptable structures. *The Open Building* by John Habraken is an adaptable building system that focuses on building flexibility, resilience, and a circular construction economy. The core principle behind this system is to separate a building's components by their specific lifespans and allow those elements to be interchanged independently of others. With this logic, the structure is kept permanent while the interior can change more freely, allowing the building to adapt to future needs of homeowners, new regulations, and new innovations and still maintain all core building functions (Habraken, 1961). *The Open Building* system and other adaptable buildings have been thoroughly analyzed by Renee Y. Chow (2017) and Stephen Kendall (2017).

Avi Friedman further details the flexible house concept through his *Adaptable House* scheme. This concept focuses on making homes to be both spatially and structurally flexible, allowing them to adapt more completely to changing homeowner needs. His book details specific design techniques for changing interior layouts, upgrading systems, and altering building layouts. The last section of the book even discusses real-world applications of this concept (Friedman, 2002). While both of these systems are not modular, they do address many of the challenges around interchangeable components in housing which are applicable to the Frame House's adaptability goals.

Designing for Disassembly

Designing for disassembly pushes the life cycle of buildings one step further, where the structure is intended to be broken down and potentially reused at the end of the building's lifespan. While these types of systems require a significant amount of prior planning, they have the potential to reduce environmental impacts of structures, particularly in terms of material waste and carbon footprint. ARUP, along with Frener & Reifer have explored the potential for disassembly in their report, "Design Innovation for the Circular Economy" (ARUP, 2016). Their report details studies done on the disassembly of facades, reuse of materials, ability to track material end of life, and more. In the conceptual development of the Frame House, the students aimed to utilize the concepts behind the design for disassembly movement to create components that have the potential to be broken down, exchanged, and rebuilt.

Main Goals for the Frame House System

The main goals in the *Open-Source Housing Systems* design studio was to design houses that the users can affordably, quickly, and easily customize, fabricate, build, and adapt. Along these lines, Frame House system is designed to allow users to generate housing variations based on their needs, which they can potentially construct themselves with a standard kit-of-parts and modify based on their changing needs. Although it is in its conceptual design stage, the precedents reviewed in this paper are a testimony that Frame House system has the potential to be affordable, expedient, customizable, expandable and reusable. It can simplify

the housing design and construction process and empower occupants to participate in their home creation.

Development of the Modular System

The authors designed a preliminary Frame House system using the established project goals, the identified issues in the housing market, and lessons learned from existing affordable modular housing projects as drivers. The team used traditional balloon framing techniques as a basis for the structure of Frame House and introduced a modular aspect to the frame construction. They focused on making the kit-of-parts of the Frame House system easily demountable, transportable, exchangeable, reusable, and recyclable. Additionally, any number of unique homes could be constructed using the same components, different than the traditional lumber framed houses which are less flexible in nature. With the kit-of-parts, users would be able to construct a Frame House through a series of individual frames connected by infill components. This frame-style design allows the users to customize the shape and size of the home by simply adding or removing components, and creates a repetitive construction process that can be quickly comprehensible for individuals who lack construction skills. Additionally, the individual components introduce human-scale elements into the design which are light-weight and easy to work with, as opposed to a cut lumber construction. Frame House's linear format, based on the design of the Atelier 5 houses, also creates the potential for this system to be utilized as both an urban infill housing, as well as a rural row or detached homes.

After establishing this preliminary system, the team conducted a series of small-scale prototype tests, ranging from connection explorations to understand the structural frames of Frame House at a detail level, up to large half scale tests which investigated Frame House's user constructability and component functionality (Figure 1). Throughout the prototyping process, the team discovered several issues with the preliminary design, including obstacles with structural stability and the potential for incorrectly assembled components. The team found that prototyping was an effective way to test design intentions and troubleshoot areas of difficulty in the system.



Figure 1: Frame House Prototypes

Alongside the system design and physical prototyping, the team also developed a digital design interface to facilitate an easy transition from design to construction. This interface allows occupants to easily create unique Frame Houses using the standard kit-of-parts. The user can explore and generate homes until they are satisfied with the final result. From here, the program automatically generates the home's component cut sheets which have been nested in order to utilize the minimum amount of material. In doing so, the user has a direct connection from design to construction, which will in turn simplify the home creation process. Sample floor plans and models can be seen in Figure 2.



Figure 2: Frame House Variations

FRAME HOUSE: CONCEPTUAL POTENTIALS

Through the team's literature studies and initial conceptual development from the design studio, several potentials for the Frame House system have been discovered which can be further explored in future research.

<u>Affordable</u>: Theoretically, Frame House's modular component-based frames can make building a house cheaper than building with standard balloon frame construction methods due to the elimination of labor costs, optimization of material cut sheets to reduce waste, utilization of a thickened edge slab, and integration of casework into the kit-of-parts. As can be seen in Figure 3, a 2,300 sqft home can potentially cost up to \$90,000 less than a standard construction home based on the National Association of Home Builder's 2019 Residential Home Construction Cost Breakdowns for Single- Family Homes (Ford, 2020). While this data requires additional research and testing to solidify the actual cost of Frame House, the initial estimates are promising.

<u>Expedient</u>: Frame House system can also be faster to construct than a typical balloon framed, owner-built home due to the ease of assembly and repetitive nature of the components (Figure 3). Since the components are modular and easy to connect, unskilled homeowners may assemble frames more easily. While production-built homes would still be much faster to construct, according to Berks Home Production Builders (Berks Homes, 2020), Frame House does have the potential to improve upon the timeline of occupant constructed homes (Agadoni, 2021). Therefore, with the Frame House system, more houses can be built in a

shorter period of time with more flexibility in design. Additionally, the modular components and frame structure design bring the potential to design in HVAC pathways, envelope connections, and casework in the kit- of-parts. Plumbing and electrical systems can be wired through the frame and wall cavity, and the HVAC duct systems can be inserted inside the floor cavity. While the team has not conducted research on this aspect of Frame House yet, there are many modular housing precedents which have integrated systems successfully, such as the WikiHouse.

COST ANALYSIS

Based on a 2,300 sqft home (16'-0" x 72'-0", 2 stories) ** Data Approximated from NAHB 2019 Residential Home Construction**



** Standard Home considered to be built by a production builder and have a basement

** Frame House considered to be built by occupants and have a slab on grade foundation

TIMELINE ANALYSIS

Based on a 2,300 sqft home (16'-0" x 72'-0", 2 stories) ** Data Approximated from Berks Home Production Builders**



Figure 3: Frame House Cost and Timeline Analysis

<u>Customizable</u>: Frame House's digital design interface has the potential for users to create unique homes using the standard kit-of-parts quickly and easily. Users can design any number of unique Frame Houses with many frame configurations. In doing so, users can have incredible flexibility in customizing a Frame House to their specific needs, all while designing within the kit-of-parts dimensions and assembly requirements. Generated Frame Houses are constructible through the standard kit-of- parts and come with optimized cut sheets for fabrication.

<u>User-Friendly Construction</u>: Frame House's digital design interface would allow users to seamlessly transition from design to construction through the digital interface's ability to generate optimized cut sheets. Frame House system's modular components can make building a home simpler, particularly with the *mistake-proof* principles added to each piece which make it difficult to assemble a Frame House incorrectly. Each piece type is labeled with a unique identifier and directional marker which inform the users on how and where the pieces should be assembled. During the component prototyping phase in the design studio, the team found that two partial frames and one infill set at $6^{\circ} = 1^{\circ}-0^{\circ}$ scale could be constructed by two individuals in about 34 minutes. Moving forward, the team plans to add identifiers for the placement of envelope and HVAC components into the kit-of-parts design as well, as a way to potentially simplify the system further. In doing so, user error can be minimized and construction simplified. Frame House's user-friendly construction can, thus, minimize the need for skilled labor, which in turn may help reduce the strain on the housing market.

<u>Ready for Occupancy</u>: Frame House has the potential to be a complete system ready for occupancy once constructed. Further research is needed to integrate envelope control layers and HVAC system pathways, to make the system comply with the United State's Residential Building Codes (RBC). Existing modular systems that are code-compliant and ready for occupancy once built, specifically the WikiHouse by Alastair Parvin and the UBuild system by Studio Bark, are used as precedents and guiding forces. The team sees potential in Frame House adapting similar code compliance strategies, specifically starting with Pennsylvania based codes.

<u>Expandable/Downsizable</u>: Once constructed, Frame House is designed to be expandable and downsizable. Frames can be removed, added, or rearranged in order to adapt to the occupants' changing needs. This conceptual feature of Frame House is particularly applicable to any unforeseen circumstances that may require adaptations to homes. This would make Frame Houses more flexible than houses built using standard construction methods. The interior of Frame Houses is designed to be adaptable since it is separated from the structure. However, more research needs to be conducted to enable the envelope and frames to be similarly adaptable. While full envelope deconstruction can be challenging in terms of maintaining proper airtightness and environmental comfort, there is potential for a partially demountable system, similar to *The Open Building* system by John Habraken.

<u>Reusable</u>: Because of Frame House's standard modular components, there is a potential to disassemble and reuse pieces for another house or donate pieces to support a community member's house. This can lengthen the lifespan of a Frame House and reduce its total waste production over time since parts can be repurposed. This aspect of Frame House can reduce

the strain on the housing market's resources since new homes may not necessarily require completely new parts. While the interior of the home can be easily demountable and reusable, the reuse of structural components in Frame House requires additional testing to understand the extents and limitations for deconstructing and reconstructing components.

CONCLUSIONS AND FUTURE RESEARCH

The Frame House system presented in this paper has been developed during Spring 2021, as part of the *Open-Source Housing Systems* design research studio at Penn State University, Department of Architecture. The team is currently working on developing the Frame House system further through structural simulations, load tests and full-scale prototypes in collaboration with the Pennsylvania Housing Research Center (PHRC). In doing so, the team aims to deepen their understanding of Frame House's structural capacity and buildability. The team also plans to integrate envelope design into the modular system, coordinate system pathways into the kit-of-parts, and align the structural system with the Residential Building Code and Pennsylvania-based codes.

Frame House has the potential for many different uses in the residential industry through various building typology applications and organizational structure adaptations. One possible application of the Frame House system is for disaster response housing. Disasters often displace a large number of individuals in a short amount of time. Frame House System can be suitable for this circumstance due to its potential for reduced cost and construction time, easy deployment and deconstructability, and minimal wasted space using flat-packed transportation. Additionally, Frame House's reusable nature can theoretically allow each temporary home to be rebuilt many times over. Another application for the Frame House System can be an accessory dwelling unit (ADU) for families who would like to extend their home using an external structure.

The Frame House System can be further optimized when particular organizational strategies are applied. The team realizes that it is impractical for a single Frame House user to obtain a CNC machine. Rather, it may be more efficient to create centralized CNC factories which could cut all parts that users may need. These factories could optimize the fabrication process by mass producing many Frame House parts at once, reaping all the benefits of community building without the need for homes to be constructed in the same location. Since Frame House parts can be flat-packed and transported, this system could be effective across a wide variety of locations. Frame pieces can also be more efficiently nested on CNC beds over a larger number of homes, which would reduce material waste and save additional cost. Through these organizational changes, the Frame House system can be efficiently scaled-up to reduce time, cost, and material waste. With the more optimized system, Frame House can potentially address the needs of the housing market with its ability to design and construct more houses in a shorter period of time without the need for skilled labor. In doing so, Frame House can contribute to a more balanced housing market in the future.

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REFERENCES

Agadoni, L. (2021, August 17). Building a Home: Step-By-Step Guide.

- Million Acres. https://www.millionacres.com/real-estate-investing/house-flipping/the-building-a-house-timeline-its-more-important-than-you-think/
- ARUP. (2016). The Circular Economy in the Built Environment. ARUP, London.

Berks Homes. (2020). Berks Homes Youtube Channel. https://www.youtube.com/user/BerksHomes/videos

- Chaluvadi, A. (2020, February 07). Top Challenges for Builders: Cost/Availability of Labor in 2019 & 2020. National Association of Home Builders: Eye On Housing. https://eyeonhousing.org/2020/02/top-challenges-for-builders-cost-availability-0f-labor-in-2019-2020/?ga=2.119945676.591436676.1622079280-233554895.1622079280
- Chow, Renee, edited by Alex Lifshutz. (2017). Loose Fitting Architecture. Architectural Design. Volume 87. https://download.e- bookshelf.de/download/0010/7620/32/L-G-0010762032-0026007433.
- Davis, Sam. (1995). The Architecture of Affordable Housing. University of California Press. ISBN: 978-0-520-20885-8.
- Ford, C. (2020, February 03). Cost of Constructing a Home. National Association of Home Builders Classic.https://www.nahbclassic.org/generic.aspx?genericContentID=271883&channelID=311
- Freddie Mac. (2021, May 07). Housing Supply: A Growing Deficit. Freddie Mac Home Builders. http://www.freddiemac.com/research/insight/20210507_housing_supply.page?
- Friedman, Avi. (2002). The Adaptable House. McGraw Hill, New York. ISBN: 0071377468
- Habraken, John. (1961) Open Building System. https://www.openbuilding.co/
- Hermann, A, & Wu, D. (2021, February 18). The Pandemic Reveals the Need for Space, but Building Smaller Units Remains Essential. Joint Center for Housing Studies of Harvard University. https://www.jchs.harvard.edu/blog/pandemic-reveals-need-space-building-smaller-units- remainsessential
- Kendall, Stephen. (2017). Open Building Studies, Lectures, and Reports. Design Factory. https://drstephenkendall.com/open-building-studies-reports-and-lectures/
- Lerner, M. (2020, September 17). How the Pandemic Has Put Flexibility Front and Center in Home Design. The Washington Post. https://www.washingtonpost.com/realestate/how-the-pandemic-has-put-flexibility-front-and-center-in-home-design/2020/09/16/a85cb08a-e3e5-11ea-b69b-64f7b0477ed4_story.html

Metraux, S, Rayl, M., O'Hanlon, J., & O'Neill, S. (2020, March 30). Addressing the Threat of COVID-

- 19-Related Housing Instability and Displacement in Delaware. University of Deleware. http://udspace.udel.edu/ handle/19716/25186
- Stirling, J, & Kurokawa, K. (2021). PREVI. Architectuul. http://architectuul.com/architecture/previ
- The New Makers. (2021). Product. The New Makers. https://thenewmakers.com/producten/
- UN Habitat. (2021). Housing. UN Habitat For a Better Future. https://unhabitat.org/topic/housing Wikihouse. (2021). About. https://www.wikihouse.cc/About
- Studio Bark. (2021). Designed By Architects, Approved by Engineers, Built by You. U-Build. https://u-build.org/about-us/

Discussion of Tiny Home Inclusion as a Concentric Diversification Strategy in Production Home Building to Address Housing Crisis

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<u>Abstract</u>

In a world of bigger is better, the Tiny Home Counter-Movement is seemingly a fad in the residential construction industry. However, sales of tiny homes continue to endure. New builders that specialize in various types of tiny homes continue to sprout up in high deficient housing stock markets, especially market areas like California. Large developers tend to rely on strategies that involve a mix of small enough lots to enable the correct number of houses to produce a profitable development. What if the paradigm was to shift? The impacts of the COVD-19 pandemic further exacerbated construction costs and schedules, furthering the housing affordability and shortage issues while allowing society to reevaluate their housing situations. By remembering housing types and mixes from the past, integrating them with low-risk opportunities could provide the ability to fill a missing gap in the current housing industry in California. Including the option of tiny homes into residential development through concentric diversification, residential builders can protect themselves from the impact of our cyclical industry while also expanding their business. This position paper seeks to connect the issues related to the housing crisis with concentric diversification through tiny home integration. The arguments and discussion contained herein will illustrate that concentric diversification is the lowest risk growth strategy for residential construction firms. In addition, this discussion demonstrates how tiny home development is the potential vehicle to integrate increased sustainability while reestablishing the option of the "starter home" and the easily manageable downsized "empty-nester home." An introduction to an achievable pathway with incremental steps to testing this diversification method will support further research.

Introduction

Construction is a cyclical industry (Berman & Pfleeger, 1997). Residential construction is particularly susceptible to business cycles (Sloate, 2012), with periods of growth followed by periods of recession. If a builder does not plan adequately, keeping an eye on the market trends, a severe slowdown may decimate their business. Therefore, some companies will incorporate expansion methods of acquisitions or

diversification. These entrepreneurial methods vary based on the business's strategic planning process (Ahuja & Lampert, 2001). Diversification is a standard method for a company to increase effectiveness and economic stability, reduce cost and production risks, optimize project delivery, and increase economic competitiveness (Kalinichuk & Tomek, 2013). Therefore, it is wise to incorporate diversified growth strategies to ensure cash flow (Ehrlich, 2001).

Concentric diversification is a method of business expansion that focuses on growth in related industries (Figure 1). As defined by Wheelen et al. (2018), it is "an appropriate corporate strategy when a firm has a strong competitive position, but industry attractiveness is low." In construction, there are numerous methods for growing a company. However, home builder growth is more successful when crafted in a careful strategy sensitive to the industry's peculiarities (Markides, 1997). Constantinos Markides (1997) outlines six steps to successful strategic growth in his article on diversification. Initially published in 1997, these following steps endure providing a well-reasoned process: knowing the company's strengths and weaknesses, what assets are necessary for the new venture, are we competitive, will the diversification cause more harm than benefit, and will this growth strategy improve the company or are we unable or not in the position to benefit?



Figure 1: Framework of concentric diversification, adapted from Wheelen et al., (2018)

Carefully implemented diversification in residential construction provides reliable means to protect a firm from the impacts of the industry's cyclical nature (Rijamampianina et al., 2003). Sustainability in the current global climate change discussion is shifting the paradigm of housing options (Shearer & Burton, 2019). Noticeably, tiny homes are developing into a more viable alternative to fulfill the movement towards responsible development in this emerging political and cultural shift (Schenk, 2015). Therefore, this paper aims to correlate tiny homes to affordable, sustainable, permanent transitional home design through responsible concentric diversification. A proposed framework for continuing research in tiny home incorporation is provided.

Background

Concentric Diversification Opportunities for Residential Construction

Residential builders grow through various forms of diversification (Ehrlich, 2001). Custom builders will strategically position themselves to keep their trade craftsmen busy and under contract until interest rates are lower. Production home builders will implement concentric diversification to retain profits by having real estate agents and mortgage brokers as additional services. Incorporating these necessary services into their business model can capitalize on further gains within the firm. With the changing regulations in California that now encourage construction of Accessory Dwelling Units (ADUs) (California Department of Housing and Community Development, 2021), integration of this type of housing option provides residential developers a related diversification option. ADUs are offered as an add-on to existing development or a new opportunity in a potential housing development. An established home builder could expand into managing residential rental properties of communities that have been completed but not purchased.

Since the 1960s, single-family starts have been an indicator of an economic recession (Blythe, 2019). As interest rates rise, household income thresholds for mortgages rise, resulting in fewer qualifying for new home loans (Zhao, 2021b). Rentals' market rates increase as fewer people qualify for home loans (Boykin, 2021), thus lowering the demand for new construction. The preparation and weathering of the cyclical nature of residential building is a topic of the National Association of Home Builders (NAHB). In an article from 2010 entitled, "Business Diversification is Key to Home Builder Growth," the NAHB contends that their course will examine more than twenty-five different construction industry opportunities for expansion. The NAHB claims that diversifying clients' options can grow a business and increase profitability (NAHB, 2020). Another aspect that is gaining the attention of the NAHB is the integration and development of tiny homes as a new avenue for home builders (Quint, 2018a). Classes, seminars, and other informational outlets are available for assisting and promoting diversification.

Is Concentric Diversification Worth the Risk to Strengthen the Core Business?

Does this type of diversification strategy ultimately lead to successful growth? Suppose a company diversifies into a related industry that closely aligns with its core competencies. The result may include new revenue streams, enhancing the business's portfolio, acquiring new capabilities, or securing a competitive advantage (Nordmeyer, n.d.). For example, Walt Disney is a well-known company that successfully diversified from an animation business into resorts, theme parks, live entertainment, cruise lines, planned residential communities, television broadcasting, and retailing (Markides, 1997). The related expansions of Walt Disney link to their core business of entertaining illustrate a very successful pattern of concentric diversification. First Call Construction provides a relevant example of this type of related expansion. First Call has implemented concentric diversification by expanding from residential remodeling and insurance restoration to minor commercial improvements that larger contractors do not want to do, thus insulating themselves from the fickleness of the residential construction industry (Zuckerman, 2007). Be warned, no growth strategy is without risk, not guaranteed, and is not easy (Vance, 2015a). In a Harvard Business Review survey, 62% of sampled businesses damaged their bottom lines by diversification (Despain, 2015). A study from McKinsey & Company showed 33% of respondents reporting increased company value of at least 10% of their business efforts (Nordmeyer, n.d.). In comparing the different methods of growth strategy, concentric diversification tends to embody the least amount of risk (Neffke & Henning, 2013).

Concentric diversification is less risky when the growth stems from the strength of the firm's core competencies. It broadens the distribution network of the business without requiring a new target audience (Quain, 2018). A company with solid core competencies has a strategic advantage against its competition by expanding into a related industry than expanding into an unrelated market. It allows the company to achieve significant goals with fewer working parts and financial costs (Quain, 2018). Their competitive advantage will provide a secure foundation for growing their market share, widening their client base, and achieving synergy. Concentric diversification stemming from a competitive advantage supported by core competencies will further strengthen the competitive advantage (Rijamampianina et al., 2003). For example, a successful home builder incorporating tiny homes or ADUs into their offerings poses a viable and lower-risk business expansion.

Businesses can implement concentric diversification to increase shareholder value through synergy (Wright, n.d.). When a company experiences better results as a whole rather than the sum of its parts, the company achieves synergy. For example, a residential builder incorporates real estate agents, property management, and a mortgage broker. By transferring knowledge and market intelligence, sharing resources, and combining operations, these companies' synergy strengthens as their core competencies expand. Thus, if real estate agents share feedback from their clients after visiting various properties, it may provide information on emerging preferences or a new trend for future developments or home designs. Similarly, a builder that includes ADUs in their development plans has the opportunity to remodel or build ADUs to remain resilient when new construction slows.

Diversification Based upon Capitalizing on Core Competencies.

Intriguingly, tiny home construction firms are springing up while current home builders have not expanded into this niche market. Three identified core competencies are *creating customer benefit*, the *difficulty of imitation*, and its *applicability across markets* (Vance, 2015b). When implementing a growth strategy, a company must capitalize on these identified strengths of its core competencies. Diversification based on core competencies that are easy to imitate or do not provide a customer benefit will not provide a long-term strategy (Vance, 2015b). Thus, a deeper understanding of the complexity of a corporation's core competencies will facilitate the proper analysis necessary to discern the best direction of sustainable corporate growth.

Diversification is not always the best option for a company, primarily if they have already found an ideal application of their skills (Vance, 2015a). Therefore, when looking at different markets to diversify, the firm must verify that the market is one that it can acquire all necessary assets, where its core competency is a synergistic fit. A firm's core competencies will only improve (Vance, 2015b). Tiny home inclusion is a

market available to existing and established home builders with an entrepreneurial spirit. The owner of First Call Construction, Scott Cierzan, states it well, "I hope I'm in the middle of the road — entrepreneurial enough to take advantage of opportunities but cautious enough not to chase everything. Finding the balance is the hardest part," (Zuckerman, 2007).

Tiny Homes as an Alternative Sustainable Residential Development Approach.

Tiny homes gained notoriety in the late 2000's post-recession recovery. However, the first tiny house company in the US started building mobile units in Sonoma, California, in 1999 (Nonko, 2017). The tiny house movement embodied response to living more with less, reducing household carbon footprint, refocusing on simple needs, options of off-grid living, and a lower cost option for those outpriced in current markets (Whitford, n.d.). The tiny houses first developed integrated a traditional home on top of a vehicular pull trailer. These are typically defined as 100 to 400 square feet (SF), producing about 2,000 pounds of CO2 emissions each year compared to the 28,000 pounds produced by an average-sized home (James Hardie Building Products, 2017). This paper focuses on tiny houses with permanent foundations, a type of ADU per regulations, as large as 500 SF (California Department of Housing and Community Development, 2021).

Senator Tina Smith in 2019 stated that housing costs are growing faster than wage growth, increasing housing price points above what people can afford (NAHB, 2019). A common argument against the tiny home trend is the high cost of a single tiny house build, the lack of a flexible living environment. Still, most importantly, it does not resolve the issue of rising land costs (D'Amico, 2020). One problem is rising costs affecting affordability in purchasing new homes (Thompson, 2021a). The share of prospective newly built homebuyers peaked at 42% at the end of 2020 before falling to 33% (Quint, 2021). The reduction is related to the double-digit cost increases of building materials, particularly lumber prices (Thompson, 2021b). Currently, 21.1 million US households have insufficient funds for a \$100,000 home (Zhao, 2021a).

A second issue with tiny home development is the cost of land and using it efficiently. A recent NAHB article states home lots have risen in price by a record 18% (Siniavskaia, 2021). In the article, Siniavskaia (2021) denotes that the Pacific division has the smallest lots across the US through the median lot value rates at the second most expensive. California is the least affordable place to live, regardless of community size (Thompson, 2021). Coupled with the average single-family house is 2,261 SF, with the majority having four or more bedrooms and three or more bathrooms (US Census Bureau, n.d.).

Exploring a Framework to Concentric Diversification with Tiny Home Pathway. Tiny Homes are a Sustainable Housing Option

To utilize land more efficiently in California, the combination of two lots in a home development would accommodate six to eight tiny homes, compared to one house per lot. These tiny home groupings or bungalow courts (currently referred to as cottage plans) would have a communal outdoor area with a smaller personal area to assist cost-efficiency and flexibility. Including cottage plans in production housing
would provide more opportunities for first-time homebuyers and downsizers, thus increasing interest in this type of housing option (Quint, 2018b).

Tiny homes are not the only solution to housing affordability (Shearer, 2018), through the integration of new construction methods could further lower costs and shorten timelines (Schenk, 2015). For example, utilizing modular construction would reduce the cost of construction and scheduling timelines, with the majority of the homes being prefabricated to be assembled on-site (<u>Trambley, 2021</u>). Thus, leaving only those decorative or architectural accents added on-site to provide homeowners with a sense of personalization. Currently, tiny homes (SF limited to 400 SF or less) are estimated to cost between \$40,000 and \$100,0000 to build (HomeAdvisor, n.d.).

Favorable Financial and Regulatory Changes to Support Tiny Home Inclusion.

From the debut of the tiny house, there are obstacles in their path to inclusion in residential communities (Evans, 2017). The first is the reluctance of banking institutions to support traditional home loans to purchase a tiny home (Evans, 2021). As the first generation of tiny homes was mobile, they did not meet the requirements for a standardized home loan, though some institutions supported personal loans (Luthi, 2021). One distinction in this proposal is the cost of a permanent foundation, depending on the size and location, would be higher than a mobile tiny house trailer frame (HomeAdvisor, n.d.). A permanent foundation will provide stability needed to allow banks to endorse a mortgage loan for a purchase or to build a tiny house. Though the options are still limited, tiny home financial support is becoming more available with personal loans and lines of credit. (Luthi, 2021).

Another significant issue is the tiny home prohibitive government regulations (Evans, 2021). Depending upon local jurisdictions, most regulations regarding zoning, property setbacks, and minimum land sizes are currently evolving to integrate tiny and small homes into urban planning (Evans, 2017). In California, the tiny home climate is changing in a favorable light, as seen in adopting inclusive ADU regulations (California Department of Housing and Community Development, 2021) and major cities particularly encouraging tiny home infills (Trambley, 2021). In addition to the governmental challenge is the negative perception some established communities have regarding tiny home inclusion (Carbone, 2019). The idea of Not in My Back Yard (NIMBY) is still prevalent in some residential communities (Trambley, 2021). Perceptions are changing through proliferate media coverage and television shows regarding the tiny house movement with these changing regulations (Evans, 2019, 2021, Shearer, 2018).

Exploring Tiny Home Viability for Residential Construction Firm Growth.

Though the pandemic culminated in the issues of labor shortages, housing affordability, and sky-rocketing costs (Thompson, 2021a, 2021b), it could be the breaking of dawn for a new era of housing (Shearer, 2018). The previous framework presented in the basic principles of concentric diversification is adapted to demonstrate the opportunity for tiny home inclusivity. Figure 3 shows the new pathway with tiny homes as the overall goal with ADUs as the market test for demand.



Figure 2. Concentric diversification framework for tiny home inclusion, adapted from Wheelen et al., 2018).

As illustrated above, a firm looking to diversify would first grow into a minor business expansion, testing the market for the larger goal. For example, provide a tiny house as a type of ADUs within their existing home development. The cost and materials of this tiny home become a portion of the building plan for each participating lot. Including an ADU would provide the future homeowner with a tiny house for various uses (Shearer, 2018), such as a mother-in-law suite, man cave, she-shed, or a small rental property for a college student or caregiver to an elderly owner. A smaller primary house footprint with a tiny home ADU would suit an average California building lot of 5,000 to 7,500 SF (Garcia & Tucker, 2021).

Providing a smaller, lower-cost starter home than the current single-family starter home, which is currently four bedrooms, three baths, and a total of 2,200 SF (Shearer & Burton, 2019), would be a desirable option in the face of housing affordability (Evans, 2021). A small 400 to 800 SF with one or two bedrooms and one-bath starter homes would appeal to a vast majority of housing cost-burdened renters who cannot afford the housing market (NLIHC, 2021). If buyers demonstrate favorably towards the ADU inclusion, the construction firm would then have a case for adapting and integrating tiny home cottage collections into mainstream home developments (Evans, 2017) as a further related expansion option.

The impact of this proposition has a greater significance for California home builders. A more diverse product line will provide a means of advantage (Wheelen et al., 2018). If a large portion of the population is unable to afford a modest two-bedroom rental home or even a modest one-bedroom apartment in 93% of US counties (NLIHC, 2021), then how will US home sales be sustained when an average home is twice the size? By providing a smaller footprint for a starter home, millions of Americans will have the opportunity towards homeownership, which will give a sustainable additional product line for residential construction companies (Shearer, 2018).

Concluding Remarks and Future Research

Concentric diversification is a robust and viable growth strategy for residential construction firms if implemented consciously and carefully. After careful analysis and deliberation, each company must pursue a related growth service or product line specialization that aligns with the existing structure and culture. Residential home builders are poised to take advantage of an emerging niche market. As the proposed framework demonstrates, careful concentric diversification will provide an entry for established home builders to include ADU's. To be successful, a company should grow from the strength of its core competencies, those aspects, and characteristics that your company exceeds over your competition. By ensuring diversification from a position of core competency strength, risks will not be eliminated but minimized.

Residential home builders have demonstrated critical strengths in building single-family homes; however, the slowing of the industry today is related to affordability and post-pandemic cost increases in materials and land values, not only cyclical impacts. Concentric diversification into ADUs and, more importantly, tiny home developments provide a substantial, viable, low-risk growth opportunity to take advantage of current economic and cultural trends. With the ramifications of sustainable innovations in construction materials, methods, and design, tiny home developments could hold the key to affordability. Incorporating them into existing and new home construction provides options for increasing density, lowering the carbon footprint while being responsive to the changing needs of the residential market, economic, societal, and industry issues. Tiny homes as a permanent housing model require further research, and concentric diversification can viably provide the opportunity to study it further.

References

- Ahuja, G., & Lampert, C. M. (2001). Entrepreneurship in the Large Corporation: A Longitudinal Study of How Established Firms Create Breakthrough Inventions. Strategic Management Journal, 22(6/7,), 521–543.
- Berman, J., & Pfleeger, J. (1997). Which Industries Are Sensitive to Business Cycles. Monthly Labor Review, 120(2), 19–25.
- Blythe, B. (2019, February 4). *Why Housing Is a Leading Economic Indicator* [Economic News]. TheStreet. <u>https://www.thestreet.com/markets/14853734</u>
- Boykin, R. (2021, March 16). *Explaining Rising Interest Rates and Real Estate to Clients*. Investopedia. https://www.investopedia.com/explaining-interest-rates/
- California Department of Housing and Community Development. (2021). Accessory Dwelling Units (ADUs) [State of California]. Accessory Dwelling Unit. https://www.hcd.ca.gov/policy-research/accessorydwellingunits.shtml
- Carbone, R. (2019, September). Could TINY HOMES Help NH's Big Housing Shortage? *Business NH Magazine*, *36*(9), 31-33.
- D'Amico, C. (2020, November 25). Tiny Homes Won't Fix the Housing Crisis | The Walrus [Nonprofit Online News]. *The Walrus: Living Room*. <u>https://thewalrus.ca/tiny-wont-fix-crisis/</u>
- Despain, M. (2015, June 19). Diversification vs Di-worse-ification. *Preferred CFO*. https://www.preferredcfo.com/diversification-vs-di-worse-ification/
- Ehrlich, S. (2001, July 31). Opportunities for Diversification. Custom Builder.

https://www.custombuilderonline.com/opportunities-diversification

- Evans, K. (2017). Integrating Tiny Houses into the American Urban Fabric: A Comparative Case Study of Land Use Policy Change in the Carolinas [Ph.D., Clemson University]. <u>http://www.proquest.com/861AAD53EC3E45F3PQ/1</u>
- Evans, K. (2019). Exploring the relationship between visual preferences for tiny and small houses and land use policy in the Southeastern United States. *Land Use Policy*, *81*, 209-218. <u>https://doi.org/10.1016/j.landusepol.2018.10.051</u>
- Evans, K. (2021). Overcoming Barriers to Tiny and Small Home Urban Integration: A Comparative Case Study in the Carolinas. *Journal of Planning Education and Research*, 41(3), 270-281. <u>https://doi.org/10.1177/0739456X18788938</u>
- Garcia, D., & Tucker, J. (2021, April 5). Potential Impact of SB 478 on Local FAR and Minimum Lot Size Requirements. *Terner Center for Housing Innovation:* U.C. Berkley. <u>https://ternercenter.berkeley.edu/research-and-policy/</u>
- HomeAdvisor. (n.d.). *Learn how much it costs to Build a Tiny House*. True Cost Guide. <u>https://www.homeadvisor.com/cost/tiny-house/</u>
- Kalinichuk, S., & Tomek, A. (2013). Construction Industry Products Diversification by Implementation of BIM. 3(4), 8.
- Markides, C. C. (1997, November 1). To Diversify or Not To Diversify. *Harvard Business Review*. https://hbr.org/1997/11/to-diversify-or-not-to-diversify
- NAHB. (2019, July 11). Fed Chair: Home Builders Feel Like They've Been Hit by a "Perfect Storm." NAHB Now. https://nahbnow.com/fed-chair-home-builders/
- NAHB. (2020, November 11). *Business Diversification is Key to Home Builder Growth*. NAHB Now. <u>https://nahbnow.com/diversification-key-growth/</u>
- Neffke, F., & Henning, M. (2013). Skill relatedness and firm diversification. *Strategic Management Journal*, *34*(3), 297–316. https://doi.org/10.1002/smj.2014
- NLIHC. (2021, July 14). *NLIHC Released Today "Out of Reach 2021: The High Cost of Housing" Report*. National Low Income Housing Coalition (NLIHC). <u>https://nlihc.org/news/2021-high-cost-housing-report</u>
- Nonko, E. (2017, July 19). *A tiny house movement timeline*. Curbed. https://archive.curbed.com/tiny-house-timeline
- Nordmeyer, B. (n.d.). *Tangible Vs. Intangible Resources*. AZCentral. https://yourbusiness.azcentral.com/organizations-used-concentric.html
- Quain, S. (2018, October 29). *What Are the Benefits of Concentric Diversification?* Chron: Small Business. <u>https://smallbusiness.chron.com/diversification.html</u>
- Quint, R. (2018, January 12). *Potential Home Buyers Sidelined by Availability, Affordability – and Seek Home Improvements*. NAHB Now. https://nahbnow.com/buyers-sidelined-by-availability-affordability/
- Quint, R. (2018, February 7). *Tiny Homes Might Have Potential Buyers*. NAHB Eye On Housing. <u>https://eyeonhousing.org/tiny-potential-buyers/</u>
- Quint, R. (2021, July 23). *Have High Prices Reduced New Construction Interest?* NAHB Eye On Housing. <u>https://eyeonhousing.org/prices-reduced-interest/</u>
- Rijamampianina, R., Abratt, R., & February, Y. (2003). A framework for concentric diversification through sustainable competitive advantage. *Management Decision*, 41(4), 362–371. https://doi.org/10.1108/00251740310468031
- Schenk, K. (2015). *Flex House: Prefabricating the Tiny House Movement* [M.Arch., University of Cincinnati]. <u>https://etd.ohiolink.edu/ucin1428652984</u>

- Shearer, H. (2018). Tiny Houses: Planning for Affordability and Inclusions. *Session 1-A Housing and Urban Regeneration,* Joint Asia-Pacific Network for Housing Research and Australasian Housing Researchers Conference, Griffith University, Gold Coast, Australia. <u>https://www.griffith.edu.au/2018-joint-apnhr-and-ahrc-conference</u>
- Shearer, H., & Burton, P. (2019). Towards a Typology of Tiny Houses. *Housing, Theory & Society, 36*(3), 298-318. https://doi.org/10.1080/14036096.2018.1487879
- Siniavskaia, N. (2021, August 10). *Lot Values Surge at Record Breaking Pace*. NAHB Eye On Housing. <u>https://eyeonhousing.org/lot-values-surge/</u>
- Sloate, P. L. (2012, January 1). *The Construction Industry: Focus on Forecasting*. Contracting Business. <u>https://www.contractingbusiness.com/const-forecasting</u>
- Thompson, E. (2021, February 12). *Record-High Lumber Prices are Hammering Housing Affordability*. NAHB Industry News. <u>https://www.nahb.org/record-high-lumber-hammering-affordability</u>
- Thompson, E. (2021, November 11). *Housing Affordability Holds Steady but Supply-Side Challenges Persist*. NAHB Industry News. https://www.nahb.org/affordability-holds-steady-challenges-persist
- Trambley, L. (2021). The Affordable Housing Crisis: Tiny Homes & Single-Family Zoning. University of California Hastings Law Journal, 72(3), 919-958.
- US Census Bureau, M. C. D. (n.d.). *Characteristics of New Housing*. https://www.census.gov/construction/highlights.html
- Vance, J. (2015a, August 3). Diversification Part 2: 5 Ways to Diversify your Revenue Base. *Preferred CFO*. <u>https://www.preferredcfo.com/ways-to-diversify/</u>
- Vance, J. (2015b, September 18). Achieving True Diversification Through Core Competency. *Preferred CFO*. <u>https://www.preferredcfo.com/diversification-product-markets/</u>
- Wheelen, T. L., Hunger, J. D., Hoffman, A. N., & Bamford, C. E. (2018). *Strategic* management and business policy: Globalization, innovation, and sustainability (Fifteenth edition). Pearson.
- Whitford, B. (n.d.). Full History of The Tiny House Movement [Online Publication]. *Coze Living Tiny Homes*. https://cozeliving.com/tiny-house-movement/
- Wright, T. C. (n.d.). Organizations That Have Used Concentric Diversification. AZCentral. https://yourbusiness.azcentral.com/orgs-cncntrc-divers.html
- Zhao, N. (2021, March 10). *Housing Affordability Explained in One Pyramid*. NAHB Now. <u>https://nahbnow.com/housing-affordability-pyramid/</u>
- Zhao, N. (2021, March 18). *Households Priced Out by Higher Interest Rates*. NAHB - Eye on Housing. <u>https://eyeonhousing.org/priced-out-by-interest-rates/</u>
- Zuckerman, D. (2007, July 9). *Companies find success in diversification*. Remodeling. <u>https://www.remodeling.hw.net/success-in-diversification</u>

Case Study: The Effect of Homeowner Behavior on Energy-Efficiency in a High-Performance Home

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ABSTRACT

A case study was performed on a high-performance home from August 2020 through January 2021 to determine the effect of homeowner behavior on the energy consumption of the home. Overall, there is a significant lack of research into the intersection of human behavior and high-performance homes, and this study aims to provide an additional set of data to further industry knowledge in this crucial area. The builder was consulted to aid in the creation of an accurate energy model using the BEOpt software, and his guidance to the occupants was incorporated into an expected set of behaviors. A whole-home energy monitor and smart thermostat were used to gather data, and the occupants provided survey responses throughout the study detailing their behavior. The final analysis compared the predicted to the actual energy usage, finding that the model predicted the overall electrical use of the house to within 0.12%. However, further analysis of the data revealed unexpected behaviors and home conditions. The occupants generally did not conform to the builder's expectations of behavior, the builder's thermostat guidance or the expectations set out in the BEOpt program. The results were provided back to the builder so that he can incorporate the results into his future guidance to occupants and future construction methods.

INTRODUCTION

The energy-efficient remodeling market is growing significantly as homeowners and home builders realize that energy resources as currently utilized are finite and must be conserved. There is a marked trend over the past decade towards providing "green" features and products in remodeling or new builds. In 2018, NAHB reported that 58% of single-family builders and 69% of multi-family builders and remodelers performed at least some green projects, and one-third of all respondents in those categories said that at least half of their projects were "green" (*Dodge Data & Analytics, 2020*). Oftentimes, there is no proof of coherence between the energy efficiency of what a builder promises and what homeowners experience. Design energy models are valuable for providing a proof of concept, but unless a homeowner adheres to the original builder's intent and lives in the home in an energy-conscious manner, there may not be significant energy savings, despite the high-performance materials. Previous studies have found that there may be significant variation on the

as-modeled results, some noting up to a 50% difference, based on occupant behavior (Fabi et al., 2012). For example, a family may keep windows open on pleasant days, thereby significantly reducing the thermal retention of the home envelope (Davis et al., 2020). This study examines one example of a high-performance remodel to determine how closely the results hew to the original intention.

For this study, the target property is a two-story single-family home in rural New Jersey. The home is a 2019 rebuild of a mid-1800s farm house. It has three bedrooms and two bathrooms and approximately 1700 square feet of living space with a front and back porch. The remodel utilized the latest building products, techniques, and appliances, creating a tight envelope and a potential for very low energy usage and bills and greater influence of occupant behavior on overall performance. The study property was selected due to a relationship with the builder and ability to access the home for monitoring performance. A mixed-methods study was performed to determine the effects of homeowner behavior on the as-built energy performance of the home. The study was conducted from August 2020 through January 2021, setting baselines for performance in summer and winter, and focusing on the fall "shoulder months" when homeowner behavior is most variable as the temperature changes. The results of the study contribute to a greater understanding of the after-construction effects of an energy-efficient remodel, providing homeowners and builders with an expanded understanding of how to actually achieve their resource-reduction goals.

BACKGROUND

When homeowners, builders, and remodelers look to design an energy-efficient whole-home build or remodel, the majority of the data available to aid in their decision-making is theoretical and materials-based, not empirical and accounting for homeowner behavior. Many studies have been performed that delve into technological solutions for energy reduction, including renovations of existing homes to reduce energy costs without getting to zero and net-zero-energy demonstration remodels (Jackson et al., 2012; Ascione et al., 2017; Aldrich et al., 2010; Cattano et al., 2013). However, none of these projects evaluated the specific effects of homeowner behavior and instead focused on technological or system upgrades. Studies have shown that aspects such as air-tightness are crucially linked to homeowner behavior, because if air-tightness increases past a certain level, homeowners will open a window. Remodelers have been found to increase the airtightness past code, even, because their knowledge of the interrelated concepts is limited (Fabi et al., 2012). Few whole-home studies have been conducted; most address a single factor, such as window-opening and window-closing; the wholehome studies that exist in the literature do not tease out the effect of specific behaviors (Branco et al., 2004; Fabi et al., 2012; Schakib-Ekbatan et al., 2015). Many energy models exist, although most are highly complex and mathematical, and not well-suited for the average construction industry practitioner (Karmellos et al., 2015; Russell et al., 2014; Hong et al., 2014; Ascione et al., 2017). These models do not account for homeowner behavior. Thus, the as-built models are simply a "best

guess," and there is no general guidance for how to adapt it to an "as-lived-in" model. This study examines how resident actions and behaviors affect the as-built energy efficiency of a high performance residential building.

METHODS

In order to determine the potential impact of resident behaviors, the following research objectives were undertaken in this study:

- 1. Determining deviation between actual and predicted energy usage to assess accuracy of a current modeling software to identify deviation.
- 2. Compare seasonal recorded temperatures to the average temperatures used by the model to determine potential deviation to attribute to non-standard temperatures during study period.
- 3. Determine percentage of deviation that may be attributed to homeowner actions in order to assess the potential impact of specific occupant behavior on energy usage in the home.

A mixed methods approach was used to meet these objectives. The first two objectives were addressed quantitatively, while the third objective was addressed through a mixed-methods study. The quantitative section was accomplished through the creation of an as-built energy model for a specific residential high-performance home and the comparison of that model to the results of installing a whole-home energy monitor on the home's electrical panel. The energy monitor remained on the home from August 11th, 2020, through January 12th, 2021, encompassing five months of data collection. During the "shoulder months" in the spring and fall, the homeowner is more likely to violate some of the builder's original assumptions for keeping heating/cooling to an absolute minimum and instead open windows and turn on fans to keep airflow high, sometimes while still mechanically heating and cooling the air. These transition months provide a valuable insight into homeowner behavior as seasons are turning. The as-built energy model was compared to the results of the whole-home energy monitor to determine areas of deviation, thereby achieving objective 1. The resulting data was parsed through multiple avenues of inquiry, both quantitative and qualitative, to understand any possible homeowner-behavior-related causes of deviation, as per objective 3.

Energy Model

Data collection began with the building of a detailed, as-built energy model. The model was created in the BEOpt software, developed by the National Renewable Energy Laboratory, and run using the EnergyPlus simulation engine from the U.S. Department of Energy. All assumptions in the simulation are derived from the Building America Housing Simulation Protocols (*BEopt: Building Energy Optimization Tool.*). The first draft of the model was created based on the original plans generated by the architect. These plans served as the basis for the model floor plan and elevations. The builder was then brought in to help complete the model by

providing details of building techniques, systems, and actual materials used to ensure parameters of the energy model were as close to what was built.

Data Analysis

The first step in analysis was to determine the overall deviation between modeled energy usage and actual energy usage. Using August 8th, 2020, at 10 pm through January 12th, 2021 at 12 pm, the model predicted 2,539 kWh of energy usage, and the Sense monitor calculated 2,542 kWh of energy usage. Representing a 0.12% difference. At surface values, this may appear to be negligible, however, expanding into daily and hourly totals shows deviations between the modeled and actual energy usage. In the Sense data, there are significantly more spikes and troughs when viewed daily, as in Figure 1. This reflects how the occupants actually use electricity, instead of a flattened modeled curve. The model can generally predict the average overall usage given a long enough period of time.



Figure 1. Modeled and actual energy usage, viewed daily

With a basic trend line added to the data set, the daily energy usage appears lower than the modeled energy for the first half of the study, then by the end of the study, the homeowners appear to be using more energy, on average. This is verified by dividing the data set into two subsets and taking the totals for each (Table 1). Prior to November 1st at noon, the model predicted 1,406 kWh of usage, while Sense only recorded 1,342 kWh of usage. From November 1st at 12:00:59 pm through the completion of the study, the model predicted 1,133 kWh of usage, while Sense recorded 1,200 kWh of usage.

Dates	Modeled Energy	Actual Energy
	Usage	Usage
Aug 8 th – Jan 12 th	2,539 kWh	2,542 kWh
Aug 8^{th} – Nov 1^{st} (12:00:00 pm)	1,406 kWh	1,342 kWh
Nov 1 st (12:00:59 pm) – Jan	1,133 kWh	1,200 kWh
12 th		

Table 1.	Modeled	and	actual	energy	usage.	split on	Nov	1 st
Labic 1.	moucicu	anu	actual	churgy	usage,	spineon	1101	1

Additionally, if daily usage by device is graphed, the "always on" number recorded by Sense spikes around November 18th and remains high throughout the completion of the study (Figure 2).



Figure 2. Usage by device by day, with Always On highlighted for clarity

Combined with a homeowner interview, these pieces of data point to the possible effect of employment. The homeowners had employment outside the home through approximately November 1st, then transitioned to working from home. Their fall employment consisted of 12-hour days on weekends for both of them, and about 8-10 hours on weekdays for at least one and sometimes both. After the fall season, they worked from home nearly exclusively, so it follows that their energy usage was higher than the model predicted.

Temperature and Thermostat Analysis

The Ecobee average temperature was recorded as 52.28°F, while the predicted average according to the model was 53.56°F. Overall, the time period of the study appeared to be slightly colder overall, by 1.8%, than the weather data set. Although

this difference could potentially have affected their heating usage by causing an increase in heating requirements, their heat source is propane and is not reflected in the data. However, the colder-than-average temperatures could have affected their air conditioning usage, leading to an overall decrease in requirements during the cooling months. The model expected 270 kWh of cooling energy requirements, and the Sense monitor only recorded 184 kWh. A portion of this difference could be attributed to the cooler-than-average temperatures, although not likely the entire difference.

A major premise in the builder's theory of occupant behavior involved setting the thermostat at 68°F during the heating months and 78°F during the cooling months. The assumptions on which BEOpt is based provide for a 65°F thermostat during the heating months and a 75°F thermostat during the cooling months. The occupants adhered to neither set of guidance, and instead had an average cool set temperature of 71.20°F, which was 5.33% below the recommended model temperature and 8.72% below the builder's guidance temperature (Table 2). During the heating months, the occupants set their thermostat at an average of 68.04°F which matched closely with the builder's guidance, only deviating by 0.05%, but was 4.62% above the model recommended temperature.

Season	Guidance Authority	Reference Setting	Actual Setting	Deviation
			(Average)	
Cooling	BEOpt model	75°F	71.20°F	-5.33%
Cooling	Builder	78°F	71.20°F	-8.72%
Heating	BEOpt model	65°F	68.04°F	+4.62%
Heating	Builder	68°F	68.04°F	+0.05%

 Table 2. Deviation between recommended and actual thermostat settings

The occupants demonstrated a strong preference for a cooling setting of 72°F in the summer and a heating setting of 68°F in the winter. During interviews with the homeowner, this arose as a point of contention, as one occupant was very strongly set on a cooling thermostat setting of 72°F, and the other would have preferred 75°F. The thermostat was sometimes set to 75°F overnight, from approximately 10 pm to 6 am; otherwise, it was set around 72°F. There were a few occasions when they would also set the heat to 72°F during the cooling season, such as September 15th through 21st, and September 28th through October 1st. There was a clear, strong preference for that temperature.

Despite the deviation between recommended thermostat settings and actual thermostat settings, the average indoor temperature across the entire study hewed closely to that which the model predicted. The average indoor temperature, according to the BEOpt model, should have been 69.68°F, and the average indoor air temperature, as recorded by the Ecobee, was 69.52°F. Although the model had higher swings in temperatures when the thermostat was set to higher temperatures during the cooling season and lower temperatures during the heating season, overall, the indoor temperature was, on average, very similar.

Device Usage

In order to determine the efficiency of appliance usage, the Sense whole-home energy monitor uses machine learning to parse out various devices using electricity in a home, relying on the principle that nearly every device uses electricity in a different manner. Overall, the device with the largest quantity of electricity used over the course of the study was the dehumidifier. Since Sense was using machine learning, it is possible that because the dehumidifier was found first, the total amount of electricity used was highest. However, it is more likely that it was found first because it was using the most electricity and therefore had the easiest-to-identify signature. The dehumidifier also remained among the highest individual daily usages throughout the study. The air conditioner, which was detected only the day after the dehumidifier, used only half the total electricity of the dehumidifier. The dryer, which was found two days later, used one-fifth the electricity of the dehumidifier.

When comparing this usage to the BEOpt model, it appears that the large appliances in the case study home used less electricity than projected, but the furnace used significantly more than projected. Lights and cooling were very different between the model and the energy monitor (Table 3).

Device	Actual Usage	Predicted Usage	Deviation
Large appliances	505.7 kWh	573 kWh	-12%
(refrigerator,			
washer, dryer,			
dehumidifier)			
Cooling (air	184.1 kWh	340 kWh	-45.9%
conditioner)			
Heating (furnace)	161.8 kWh	47 kWh	+244.3%
Lights (bedroom,	16.7 kWh	517 kWh	-96.7%
living room, guest			
room)			
Miscellaneous	1601.8 kWh	1,063 kWh	+50.7%
(total minus all			
other categories)			

Table 3. Actual and predicted usage of various device categories

It is possible that Sense did not detect all components of the air conditioner, such as the "cooling fan/pump" detailed in the BEOpt model, but instead was providing data for only one portion of the air conditioning system. Lights could potentially have fallen in the same Sense challenge, that the machine learning could not parse each individual light bulb. Because the miscellaneous category is so much higher in the case study home, it is likely that Sense was unable to find individual smaller users of electricity and instead lumped them in an "always on" or miscellaneous category.

Reported Behavior

A survey was requested from the occupants of the case study home daily throughout the course of the study. The entire study encompassed 154 days, and survey responses were received for 75 of those days, which represented a 48% survey response rate. The survey was set up with a smartphone-compatible layout, a calendar event and a reminder to their phone at 8 pm daily. Overall, the system for garnering survey responses was only moderately effective.

When analyzing occupant behaviors such as opening windows, only days with survey data were analyzed for the effects of behavioral changes. Without a survey response, there was not adequate information on the daily routine of the residents to draw conclusions. Overall, on survey response days, Sense totaled 1214 kWh and the model totaled 1176 kWh, representing a 3.2% overage. During an interview conducted after the conclusion of the case study, the occupants noted that they were more likely to remember to complete a survey when an event occurred that was out of the ordinary, which may potentially have contributed to the increase in energy usage on days when they completed a survey. During the same interview, the occupants were asked for further data regarding their presence or absence in the home, and their work schedules throughout the case study period. Overall, their energy usage based on occupant status followed a predictable pattern. When there were no occupants in the house, the home used significantly less electricity than when there were one or more occupants, as demonstrated in Table 4.

Occupancy	Actual Electricity Usage	Predicted Electricity Usage (Same Dates in BEOpt Model)	Deviation
No occupants	0.5092 kWh	0.6899 kWh	-26.2%
Single occupant	0.6541 kWh	0.6186 kWh	+5.7%
Two occupants	0.7405 kWh	0.6949 kWh	+6.6%
More than two	0.6530 kWh	0.6240 kWh	+4.6%
occupants			

The time periods with additional guests were during the dates wherein both occupants of the house were working long days and full weeks outside the home, up to 14 hours per day on weekend days, and 8 hours per day during the week. This may have mitigated the effect of the additional bodies on the electricity usage of the case study home.

One notable insight from the study was that their window opening behavior had almost nothing to do with the temperature either inside or outside the home. Instead, they only opened windows when they wanted to deal with interior odors, when their cooking smoked up the kitchen area, or for COVID mitigations, either to ensure airflow when guests were present or for a short period of time in late December when one occupant was suspected to have COVID. The provided air movement solutions, including the hood vent and one indoor fan per bedroom, were inadequate, so instead, they opened multiple windows to allow for air movement.

An insight from the data that supports their conclusion that temperatures were not the cause of their window-opening behavior is that on days when they opened windows, they did not change their thermostat or turn off their heating or cooling systems. The data demonstrates that their thermostat was set lower on cooling days and higher on heating days when they professed to have opened the windows (Table 5). However, the deviation was relatively small, indicating that, as they noted during the interview, they likely did not change the thermostat when their windows were open.

	Cool Set Temperature	Heat Set Temperature
Days with Windows Open	70.30°F	68.13°F
All Days	71.20°F	68.04°F
Deviation	-1.3%	0.1%

CONCLUSIONS

This study provides insights into the behavioral aspects of life in a high-performance home. In order to ensure that these insights would be incorporated in a useful manner, the results were discussed with the builder to incorporate into future builds and modify their assumptions. Recommendations were made to the builder based on detailed analysis of the data in which desired heating and cooling temperature assumptions be revised. Additionally, the use of a higher efficiency HVAC system would help offset the efficiency issues seen, some of which were caused by a higher level of leakage than what was assumed in the existing construction.

This case study also provided insight into the behavioral tendencies of a set of occupants in a high-performance home, thereby enhancing the overall industry understanding of how residents interact with high-performance buildings. Future research is still required, however, as this case study was a single instance of a set of residents in one building during only a few seasons. An initial step will be the continuance of data gathering. The Ecobee thermostat and Sense monitor have remained installed on the home, and although the residents are no longer completing the survey, the data will be collected throughout an entire year, and beyond. Future analyses can be performed to see how the conclusions herein apply throughout the year, and multiple instances of a given season can be compared to each other to normalize temperature or behavioral deviations. Also, in order to gain a broader understanding of this data, additional, similar case studies should be performed. The builder who constructed this house has constructed other, similar homes in the area, and studying those in particular could provide additional insight into how different occupants live in homes constructed with similar techniques.

A final improvement would be a data model with additional options, to allow for the entry of various construction techniques that do not fit into the standard options

provided for in BEOpt. Although the results of the energy model were very close to the actual energy consumed, there was a lot of approximation that went into the production of the model. The options chosen did not represent the actual condition of the house, but were a "closest fit." If the model were able to be tweaked to allow for a more diverse set of entries, the builder would be more confident in its ability to predict the energy usage of additional homes.

REFERENCES

- Aldrich, R., Arena, L., Griffiths, D., Puttagunta, S., & Springer, D. (2010). The Consortium of Advanced Residential Buildings (CARB) - A Building America Energy Efficient Housing Partnership. https://doi.org/10.2172/1031549
- Ascione, F., Bianco, N., De Masi, R. F., Mauro, G. M., & Vanoli, G. P. (2017). Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance. *Energy & Buildings*, 144, 303-319. https://doi.org/10.1016/j.enbuild.2017.03.056
- Branco, G., Lachal, B., Gallinelli, P., & Weber, W. (2004). Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data. *Energy & Buildings*, 36(6), 543-555. https://doi.org/10.1016/i.enbuild.2004.01.028
- Cattano, C., Valdes-Vasquez, R., Plumblee, J. M., & Klotz, L. (2013). Potential Solutions to Common Barriers Experienced during the Delivery of Building Renovations for Improved Energy Performance: Literature Review and Case Study. *Journal of Architectural Engineering*, 19(3), 164-167. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000126
- Davis, L. W., Martinez, S., & Taboada, B. (2020). How effective is energy-efficient housing? Evidence from a field trial in Mexico. *Journal of Development Economics*, 143. https://doi.org/10.1016/j.jdeveco.2019.102390
- Dodge Data & Analytics. (2020). *Green Single Family and Multifamily Homes 2020*. National Association of Home Builders.
- Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58, 188-198. https://doi.org/10.1016/j.buildenv.2012.07.009
- Hong, T., Koo, C., Kim, H., & Seon Park, H. (2014). Decision support model for establishing the optimal energy retrofit strategy for existing multi-family housing complexes. *Energy Policy*, 66, 157-169. https://doi.org/10.1016/j.enpol.2013.10.057
- Jackson, R. K., Boudreaux, P. R., Kim, E., & Roberts, S. (Jan 1, 2012). Advancing residential energy retrofits. https://www.osti.gov/biblio/1050351
- Karmellos, M., Kiprakis, A., & Mavrotas, G. (2015). A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: Model, software and case studies. *Applied Energy*, 139, 131-150. https://doi.org/10.1016/j.apenergy.2014.11.023
- Russell, M., Jafari, A., & Valentin, V. (2014). Probabilistic life cycle cost model for sustainable housing retrofit decision-making. *Computing in Civil and Building Engineering (2014)* (pp. 1925-1933). https://doi.org/10.1061/9780784413616.239
- Schakib-Ekbatan, K., Çakici, F. Z., Schweiker, M., & Wagner, A. (2015). Does the occupant behavior match the energy concept of the building? *Building and Environment*, 84, 142-150. https://doi.org/10.1016/j.buildenv.2014.10.018

Impact of Occupant Characteristics on the Energy Performance of Multifamily Residential Building in the United States

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ABSTRACT

Occupant interactions with buildings significantly influence the overall energy consumption of building systems. In general, the impact of occupant behavior is most significant in residential buildings compared to other building sectors. In the United States, approximately 20% of all housing units are multifamily housing, consisting of 5 or more units. In current practice, most building energy simulation tools assume an identical 24-hour occupancy profile for all units in a multifamily building, however recent research suggests that such uniformity is not realistic. In this study, 12 years of American Time Use Survey data and the corresponding years of Residential Energy Consumption Survey data were used to evaluate the occupant characteristics of multifamily buildings and develop occupancy profiles for a typical multifamily building for use energy simulation applications. Two major classifiers, including (1) age of occupants, and (2) type of day, i.e., weekday or weekend, are used to characterize the occupancy profiles. Using these datasets, an energy simulation model for a multifamily building is created with updated occupancy schedules, to provide a more realistic prediction of the energy performance of multifamily building. This is then used to assess the energy savings potential of setback-based occupancy controls, as compared to a conventional multifamily building model. Overall, the results of this study provide a better understanding and more tailored prediction of the energy performance of multifamily residential buildings, which benefits both building energy modelers and researchers in sustainable residential building design.

INTRODUCTION

Energy consumption of residential buildings significantly depends on occupant behavior and their interaction with building systems (EIA, 2015, Hong et al., 2015). Accurate modeling of occupant behavior is thus needed for supporting the efficient design of building systems and targeted thermal comfort conditions (Saha et al., 2019). Occupant behavior was selected as an important parameter in improving the ability to assess the energy performance of buildings in International Energy Agency (IEA) Annex 53, 66 and 79 (Yoshino et al., 2017, Yan et al., 2018). Lo et al. (2010) discussed that accurate detection of occupants can reduce energy consumption in building by approximately 30%. Thus, it is important to understand and characterize the occupancy profiles in more detail to evaluate the energy performance of the buildings.

In the United States, more than 20% residential buildings are multi-family building (MFB). Multi-family is also the most dominant residential building type in dense urban areas (Jain et al., 2014). However, only few studies have focused on analyzing multi-family building occupancy scenarios and their impact on building performance. A data-driven method was applied using energy consumption data collected from 520 apartments in Seoul, South Korea to forecast next-day hourly electricity consumption

(Wahid et al., 2016). Jain et al. (2014) also developed a data-driven model to predict the electricity consumption for multi-family buildings in New York City (2014). These studies discuss the importance of treating all the units of a MFB individually based on their own characteristics, occupancy profile and interaction of occupants with the energy consuming appliances.

U.S. Department of Energy and the National Renewable Energy Laboratory created Residential Reference Building (Deru et al., 2011) and Prototype Building (Wilson et al., 2014) energy models for use in evaluating the energy consumption of "typical" MFBs in the U.S. The models include a combination of multiple units, each with the same assumed occupant schedule. The occupancy schedule used in these models are based on schedules published in ASHRAE Standard 90.1 published in 1989 (ASHRAE, 1989). These schedules represent occupancy as a fraction of the maximum number of people in the units and include a 24-hour hourly schedule ranging in value from 0 to 1, where 0 represents no occupants and 1 represents all the occupants are in home. However, this occupancy schedule does not represent the daily variation in occupancy profiles that are likely to exist across different households and over time. Assuming the same schedule for all days and household may thus misrepresent occupancy, also impacting the resulting predicted energy performance.

To work toward improving the representation of occupancy in MFBs, this study focuses the development and evaluation of the impact of updated occupancy profiles and associated occupant-based controls on the energy performance for MFBs. This is organized as follows. First the dataset and occupancy simulation methods are discussed, followed by the overall methodology. Next, characteristics of MFB occupants are studied to evaluate typical distributions. Based on the resulting characteristics, different occupancy profiles are then created. Finally, the energy consumption of MFBs using the developed occupancy profiles is evaluated and the impact of various occupant-based control strategies is analyzed.

OCCUPANCY DATA

Residential Energy Consumption Survey (RECS)

The RECS survey is conducted by Energy Information Administration (EIA) and focuses on residential buildings characteristics in the United States (EIA, 2015). This survey is a multi-year effort and published approximately once every 4 years. In this research, RECS data from 2005, 2009 and 2015 are used. This dataset contains a weightage factor used to statistically represent the U.S. residential building stock.

Residential Occupancy Simulator

This occupancy simulator (Occupancy Simulator; Mitra et al, 2020), developed based on American Time Use Survey (BLS, 2019), allows for the creation of stochastic occupancy schedules for U.S. households for each day of a year at a time granularity of 5 minutes. The simulator requires occupant characteristic input, including the number of occupants and their age and activity profiles. There are three possible options, "day-absence", where occupants normally not present in a home during the daytime; "stay-home" represents occupants stay at home throughout most of the day; "night-absence" represents an occupancy schedule where the occupant is not present in their home during nighttime. These profiles are used to study the energy performance of MFBs.

METHODOLOGY

The overall methodology is divided in two major components, as shown in Figure 1. The first is focused on studying the characteristics of occupants in multifamily buildings; the second uses those parameters to define typical schedules and implement occupant-based controls. RECS data is utilized to extract information on occupants' characteristics such as age, gender, education, and number of household members. Data analysis was completed using statistical software JMP and Excel.



Fig 1. Methodology used to evaluate the energy performance of a multi-family building using updated occupancy schedules and controls

Initially the information on occupants from MFBs with 5 or more units are filtered out and all characteristics are studied individually to detect which parameters can be used to represent and differentiate between different types of MFBs. The age of all occupants for different types of households is provided in the 2005 and 2009 RECS datasets, whereas in RECS 2015 only includes the number of adults and children. Therefore, for age distribution of occupants, RECS 2005 and RECS 2009 data are used. Similarly, the education level of occupants is collected from RECS 2009 and RECS 2015 data. Information on gender and number of members is collected from all three years of data. The significance of all parameters then evaluated, resulting in two scenarios designed to evaluate the maximum and minimum amount of time a a particular home type is unoccupied. The scenario for which the home is unoccupied for the maximum time represents the 'best case' scenario (note: it is considered "best" since this has the maximum opportunity for energy savings) the other, the 'worst case', where the home is occupied the largest amount of time. Next, the selected characteristics are used as inputs to the developed residential occupancy simulator to generate occupancy schedules to evaluate the impact of occupancy profiles and occupant-based controls on building energy consumption.

OCCUPANCY CHARACTERISTICS

Number of household members

Data on MFBs from the three years of RECS data are resulted in 3747 building information and they are classified based on the number of household members (Figure 2). The results show that the distribution of number of household members in MFBs is uniform across the three years of the survey. As shown that majority of the units have a smaller number of household members. More than 40% of the units are of 1-member whereas 2-member households represent approximately 30%. 3 and 4-member households represent approximately 15% and 10% of households, respectively, where 5 or more-member households make up less than 10%. Therefore, only 1-, 2-, 3- and 4-member households are considered in this study.



Fig 2. Percentage distribution of number of household member

Gender Characteristics

Gender is also considered (Figure 3). it is noted that there is not any clear and distinct trend in their distribution. Thus, gender is not used as a predictor in MFBs.



Fig 3. Gender distribution by number of household members

Educational Characteristics

Level of education is also extracted from the RECS 2009 and 2015 dataset and plotted by number of household members (Figure 4). This data is mapped to three categories, including those with '*no degree*', those with any '*degree from school*' but not with a college degree, and those who have a '*college degree*'. Some trends are noted. For 2member households, the majority have a '*college degree*' compared to '*no degree*'. However, for 4-member households more have '*no degree*' and a smaller number have a '*college degrees*'. For 3-member households, among these three levels of education, the distribution is quite even. However, there are no consistent trends across the years of data, thus this parameter is not considered in this study.



Fig 4. Educational qualification of householder in multifamily units

Age of occupants

Information on age of occupants is given in RECS 2005 and 2009, categorized in the ranges shown in Table 1. Based on this, all occupants ages are then classified and analyzed across the household sizes. In total this results in 36, 120 and 168 age group combinations for 2, 3 and 4-members households, respectively. The frequency of occurrence is calculated to determine the most typical age combination of occupants. **Table 1**: Age code of occupants

ble 1:	Age code of occupants			
	Age range of occupants	Code	Age range of occupants	Code
	Under 15	1	45-54	5
	15-24	2	55-64	6
	25-34	3	65-74	7
	35-44	4	75 and older	8

The age combinations of occupants for 1, 2, 3 and 4-member households are shown individually in Figure 5a-5d. In Figure 5b, 5c and 5d, the y-axis represents the age code of each of the occupants. As an example, in Figure 5c the value 133 implies in a 3-member household, 1 member is in age code 1 (under 15 years old), and 2-members are in age code 3 (25-34 years old). The x-axis represents the percentage of household members. For single member households, a larger number of people are in older age ranges. In 2-member households, the most dominant age groups is younger, where both are 25 to 34, or one is 25-34 and the other is under 25. For 3-member households, the most dominant age group is 133, where two occupants are 25-34 and the third is under 15. For 4-member households, more dominant occupant group have 2 occupants 25-34, and 2 under 15. These age combinations of occupants are used to create typical occupant distributions for all unit types in a typical MFB.



Fig 5. Age distribution in different households in multifamily buildings in (a) 1-member, (b) 2-member, (c) 3-member, (d) 4-member households

As mentioned previously, two extreme scenarios are analyzed, including the '*best case*' (least occupied time) and '*worst case*' (most occupied time) scenario. For 2-, 3- and 4member households, typical scenarios are the '*best case*' scenario. For 1-member households' typical scenario can be represented by the '*worst case*' scenario. All parameters are then used as the input to the occupancy simulator to generate occupancy profiles for each type of units. The percentage of total unoccupied time are calculated and given in Table 2.

Type of	Sconarios	٨٥٩	A	Activity		ctivity	Percentage time
household	Stellarios	Agu	(we	(weekday)		ekend)	absence
1 mombor	Best case	i. 25-34	i.	Work	i.	Stay	34.5
1-member	Worst case	ii. Over 75	ii.	Stay	ii.	Stay	8.1
	Best case	i. Under 25,	i.	Work	i.	Stay	10.5
2-member	Dest case	ii. 25-34	ii.	Work	ii.	Stay	19.5
	Worst ango	i. Under 65-74	i.	Stay	i.	Stay	1.1
	worst case	ii. Over 75	ii.	Stay	ii.	Stay	1.1
		i. 25-34	i.	Work	i.	Stay	
	Best case	ii. 25-34	ii.	Work	ii.	Stay	21.4
3-member		iii. Under 15	iii.	Work	iii.	Stay	
		i. 55-64	i.	Work	i.	Stay	
	Worst case	ii. 55-64	ii.	Stay	ii.	Stay	6.1
		iii. Under 15	iii.	Work	iii.	Stay	
		i. 25-34	i.	Work	i.	Stay	
	Post assa	ii. 25-34	ii.	Work	ii.	Stay	15.0
	Dest case	iii. Under 15	iii.	Work	iii.	Stay	15.0
4-member		iv. Under 15	iv.	Work	iv.	Stay	
		i. 15-24	i.	Work	i.	Stay	
	Worst ango	ii. 25-34	ii.	Work	ii.	Stay	2.4
	worst case	iii. 45 - 54	iii.	Work	iii.	Stay	2.4
		iv. 55-64	iv.	Stay	iv.	Stay	

Table 2: Typical occupancy scenarios for different member households

The results of this indicate the percentage of unoccupied time varies from 2.4% to 34.5%, depending on the number of household members. These occupancy schedules are then used as input to a building energy model to evaluate the energy performance of MFBs considering updated occupancy schedules and occupant-based controls.

BUILDING ENERGY MODEL

To study building energy consumption, the pre-1980 U.S. DOE Reference Building Model (USDOE) for a multi-family building was used as the baseline. This model is a three-story MFB with 8 units on each floor. Among the total 24 units, 1 unit is used as an office, and 23 are used for housing. The total area of building is $3,135 \text{ m}^2$ with each unit being approximately 88 m^2 . All units and the building are conditioned.

The heating and cooling setpoint for the units are 21.7 °C and 23.4 °C respectively. Gas is used for heating and electricity is used for cooling. The model are simulated in Lansing, MI, located in ASHRAE Climate Zone 5A, which is considered a cool and humid climate. EnergyPlus version 9.3 (EnergyPlus 9.3) was used for simulation.

In the updated building models, the number of household members are evaluated using the distribution obtained from household members distribution study (Mitra el al. 2020). It was determined that approximately 40% of units are 1-member, 30% are 2-member, 20% are 3-member households and 10% are 4-member households individually (Mitra el al. 2020).. Accordingly, of the 23 units, 9 are designated as 1-member, 7 are 2-member unit, and 5 and 2 units are 3 and 4-member households, respectively. For the 'best case' scenario, all the 'best case' scenarios for type of homes are considered and similarly for the overall worst-case scenario, worst-case of all individual units are considered.

OCCUPANT-BASED CONTROLS

Different occupant-based control strategies are implemented, as shown in Figure 7. In residential buildings the most common HVAC control methods used are temperature setbacks, where the system setpoint is reduce or increased when unoccupied, then switched back to the occupied building setpoint when occupants are present. Four different combinations of heating and cooling setback temperatures are used, including 1° C, 3° C and 7° C.



Fig 7. Occupant based control strategies, including setbacks of 1°C, 3°C, 5°C and 7 °C when unoccupied

RESULTS AND DISCUSSION

Total annual HVAC energy consumption for different scenarios using different occupant-based controls are shown in Figure 8. As the system runs at fixed setpoint temperature irrespective of occupant presence, baseline energy consumption is nearly identical for both the *best case* and *worst case* scenario. As the level of setback

increases, energy consumption decreases for both the scenarios, however the rate of reduction is higher for the *best case* scenario. This is because when a home is unoccupied for longer, the HVAC system thus also operates in setback mode longer, resulting in higher savings. In addition, it is noted that a larger setback creates a larger amount of energy savings.



Fig 8: Total annual HVAC energy consumption per household using occupant-based controls

In Figure 9 the percentage savings in electricity, gas and total energy used for HVAC systems is shown for the *best* and *worst case* scenarios and the varied control strategies. The savings in gas which is used for heating varies from 5% to 15% for the *worst case* scenario and from 7% to 21% in the *best case* scenario. Electricity consumption used for cooling purposes also reduced by 6% to 10% and 12% to 19% for the *best* and *worst cases* respectively. However, the electricity consumption does not reduce linearly. The maximum electricity savings is achieved at 5°C setback, which is reduced when this is increased to 7°C. Total energy consumption also reduced by 5-14% and 7-20% for worst- and best-case scenarios respectively. If the system runs at a higher setpoint temperature, it needs additional cooling energy to return to the occupied setpoint temperature. Thus, the benefit of higher savings during unoccupied times is reduced by consumption needed during the transitions from unoccupied to occupied states at very high setback temperatures.

The percent energy savings compared to the baseline model with no occupancy controls is shown in Figure 10 for different scenarios. For the *worst case* scenario (least amount of time unoccupied), a setback of 1 °C and higher resulted in savings in energy consumption, whereas for the *best case* scenario (most time unoccupied) all setback modes resulted in energy savings. Total estimated HVAC energy savings is estimated to be up to 14% to 20%.



Fig 9: Percentage annual energy savings in HVAC consumption for (a) the worst case (least amount of time unoccupied) and (b) the best case (most amount of time unoccupied) scenario

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Fig 10: Percentage variations in HVAC consumption compared to the baseline model with no occupancy controls

CONCLUSIONS

In this study typical occupant characteristics in MFBs in the United States were defined and used to evaluate the energy consumption due to different occupant-based controls. 2005, 2009 and 2015 RECS data were used to evaluate the characteristics of these occupants. Among gender, educational background, and occupant age range, age range of household members was found to best characterize households. To evaluate the maximum and minimum energy savings opportunities from occupant-based controls, the '*best case*' (most time unoccupied) and '*worst case*' (least time unoccupied) scenarios were calculated for each size household. These scenarios were used to generate a 1-year occupancy schedule for each household size. A range of degrees setback was considered, finding that, in general, as setback increases in amount, the energy savings potential increases. With a setback of 7°C, annual HVAC energy savings varied from 14-20% for homes in Lansing, MI (CZ 5A). Thus, the usage of the occupant-based controls has the potential to improve the overall performance of multifamily building HVAC systems.

This study represents the importance of considering occupancy schedules in MFBs to support an improved understanding of energy performance and the impacts of occupant-based control. As a future work, improved characterization of MFB households taking more parameter into account may help to expand our understand of MFB household occupant behavior. In addition, this study can be expanded to different climate conditions, as well as consider different control strategies to evaluate their impact on energy savings potential

REFERENCES

ASHRAE 90.1, (1989) "Energy Standard for Buildings Except Low-Rise Residential Buildings".

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., et al., (2011), U.S. Department of Energy commercial reference building models of the national building stock, Nrel/Tp-5500-46861, no.: 1–118. EnergyPlus 9.3, https://energyplus.net/ (Accessed on 10th April 2021)

- Hong T., D'Ocaa, S., Turnera, W.J.N., Taylor-Lange, S. C. (2015), An ontology to represent energy-related occupant behavior in buildings. Part I: introduction to the DNAs framework, Build. Environ., 92, pp. 764-777, 10.1016/j.buildenv.2015.02.019
- Jain, R.K., Smith, K.M., Culligan, P.J., Taylor, J.E., (2014), "Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy." Applied Energy 123: 168-178.
- JMP software https://www.jmp.com/en_us/home.html (Accessed 10th April 2021)
- Lo L.J., Novoselac, A., (2010), Localized air-conditioning with occupancy control in an open office, Energy Build., 42 (7), pp. 1120-1128
- Mitra, D., Steinmetz, N., Chu, Y., Cetin, K.S. (2020). "Typical occupancy profiles and behaviors in residential buildings in the United States." Energy and Buildings 210. https://www.sciencedirect.com/science/article/pii/S0378778819332530
- Mitra, D., Chu, Y., Cetin, K.S. (2020). "Cluster analysis of occupancy schedules in residential buildings in the United States." Energy and Buildings 236, 2021. https://www.sciencedirect.com/science/article/pii/S037877882100075X.

Occupancy Simulator, http://occsim.kristencetin.com/

- Saha,H.,Florita,A.R.,Henze,G.P.,Sarkar,S.,(2019),Occupancy sensing in buildings: A review of data analytics approaches, Energy & Buildings 188–189, 278–285
- U.S. Bureau of Labor Statistics, American Time Use Survey http://www.bls.gov/tus/#data (Accessed on 10th April 2021)
- U.S. Energy Information Administration (2015), A look at the U.S. Commercial Building Stock: results from EIA's 2012 Commercial Buildings Energy Consumption Survey,

https://www.eia.gov/consumption/commercial/reports/2012/buildstock/.

- U.S. Energy Information Administration, Residential energy consumption survey, (2015), https://www.eia.gov/consumption/residential/ (Accessed on 10th April 2021)
- United States, Department of Energy (USDOE), Commercial Reference Building, https://www.energy.gov/eere/buildings/existing-commercial-referencebuildings-constructed-1980, accessed on 10th April 2021)
- Wahid F., Kim, D., (2016), A prediction approach for demand analysis of energy consumption using k-nearest neighbor in residential buildings, International Journal of Smart Home, 10 (2), pp. 97-108, 10.14257/ijsh.2016.10.2.10.
- Wilson, E., Metzger, C.E., Hendron, R., Horowitz, S., (2014), Building america house simulation protocols, National. Renewable. Energy Lab., NREL/TP-55
- Yan, D., Hong, T., (2018), Definition and Simulation of Occupant Behavior in Buildings, International Energy Agency, EBC Annex, p. 66
- Yoshino, H., Hong, T., Nord, N., (2017), IEA EBC annex 53: total energy use in buildings—analysis and evaluation methods, Energy Build., 152, pp. 124-136

Development and validation of a post-occupancy evaluation model for LEED-certified residential projects

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ABSTRACT

Despite increasing interest toward sustainable housing and the rapid growth in the number of LEED-certified residential buildings and communities, little data is available about end users' feedback on these projects. This is partially due to the lack of post-occupancy evaluation tools available for this type of project. This study aims to develop and validate a post-occupancy evaluation model that could be useful for studies focusing on users' perspectives in LEED-certified residential projects. To develop this measurement instrument, a primary model for evaluation of residential satisfaction was developed based on Housing Needs Theory, Housing Adjustment Theory, and Psychological Construct Theory as well as the conceptual model of residential satisfaction developed by Weidemann and Anderson (1985). This model included cognitive, affective, and behavioral processes in evaluating satisfaction. The measures for the model constructs were adopted from LEED-ND, LEED-BD+C Multifamily Midrise, LEED-BD+C New Construction, and the UC Berkeley's Center for the Built Environment survey tool. The developed tool was employed in an online survey and the data collected from the survey was used for validating the model fit through Confirmatory Factor Analysis (CFA) (n=192). The model included five constructs, each of which included several measures: Perceived Infrastructure Performance (9 measures), Perceived Neighborhood Design (6 measures), Perceived Building Performance (8 measures), Perceived Economic Performance (4 measures), and Satisfaction and Behavioral responses (6 measures). Among the 33 initial measures initially considered in the CFA model, measures with a low factor loading on their corresponding construct (loading < .50) were removed, and their removal was theoretically supported. As a result of the analysis, 26 retained measures such as rainwater collection system, building energy efficiency, and transportation costs were found to be valid measures for post-occupancy evaluation of LEED-certified residential projects.

INTRODUCTION

Despite the importance of sustainability and the efforts toward its achievement in the development of residential communities, uncertainty arises when trying to measure the long-term successful performance of these types of projects comprehensively. Although the LEED guidelines have provided a great opportunity to step in the right direction, the focus is mainly on the technical aspects associated with building methods and materials with little or no credits given to user preferences and satisfaction concerns. This becomes more highlighted by understanding that accordance with human needs and expectations is recognized to be a crucial factor in determining the successful performance of the built environment. Therefore, it is important to investigate the feedback of users about their living environment and involve them in evaluating and developing standards and assessment tools (Berardi, 2013).

Satisfaction is a variable that encompasses residential priorities held by different people. As residential satisfaction is dependent on the place, time, assessment purpose, and the evaluation system of the assessors, it is considered a complex construct that involves a broad range of stakeholders (Mohit & Raja, 2014). Therefore, to successfully develop an evaluation model to measure the level of satisfaction with residential projects, the first step is to understand the theoretical and empirical aspects of residential satisfaction.

In most of the empirical studies on residential satisfaction, either one or a combination of the three theories: Housing Needs Theory (Rossi (1955), Housing Adjustment Theory (Morris & Winter (1975), and Psychological Construct Theory (Galster (1985) have been used. Acceptable measurements of residential satisfaction are dependent on studying the variables related to three different processes of "cognitive", "affective" and "behavioral" that exist in the dynamic interactions between the individuals and their residential environments and affect the overall satisfaction with the residential environment (Weidemann & Anderson, 1985).

Variables of residential satisfaction. Generally, a variety of factors have been investigated separately in residential satisfaction studies both regarding residential units and their surrounding neighborhoods. Physical attributes of the neighborhood have been explored as the main focus by many researchers (e.g. Hur & Nasar, 2014). In some studies, factors related to the sociodemographic aspects and resident characteristics are the main focus (e.g. Kweon et al., 2010). Variables such as housing and neighborhood condition and residents' characteristics have been evaluated in several studies as the main components affecting satisfaction (e.g. Parkes et al., 2002). Some studies have considered the economic aspects of the neighborhood as the predictor of residential satisfaction (e.g. Yaman et al., 2018). Finally, in many studies, only the overall satisfaction has been evaluated as the main factor of evaluation (e.g. de Jong et al., 2012). Considering the discussed variables and measures, residential satisfaction appears to be a multifaceted and complex subject, and more research is required to gain a better understanding of the correlations between the effective factors. Therefore, the work included in this research is an attempt to provide an evaluation model to understand the relations between sustainability, perceived performance, and residential satisfaction as the key determinant of the long-term success of residential projects. In order to develop this model, the first step is to create an a-priori model based on the literature.

DEVELOPING AN A-PRIORI MODEL

The model for evaluating the project effectiveness of sustainable communities combines indicators and methods from different research findings and sustainability indices to achieve the ultimate goal of this research. Based on the review of the theories, conceptual models, and processes regarding residential satisfaction and users' assessments of the built environment performance, a multi-dimensional evaluation model was developed to help this study find the relationships between sustainability, physical performance, cost performance, and satisfaction as the long-term success factors of sustainable projects. The model is a combination of several components each of which is measured through one or a few variables or indicators (Figure 1).



Figure 1. Conceptual model of long-term success factor interactions

METHOD: VALIDATION OF THE POST-OCCUPANCY EVALUATION MODEL

Data Collection. To test the application of the theoretical a-priori model, a questionnaire was developed to collect data from residents of LEED-certified communities. To ascertain the validity of the questions, the questionnaire was reviewed by two faculty members of the School of Planning, Design, and Construction at Michigan State University to improve the appropriateness of the questions to achieve the research objectives. Another expert from the MSU Office for Survey Research who had expertise in survey design reviewed the questionnaire from a technical standpoint. Furthermore, five non-experts read the survey to assure the face validity of the survey instrument focusing on readability, layout and style, feasibility, and clarity of wording. A pilot test was also conducted to evaluate the questionnaire from the participants' points of view and find out if the questions were appropriate and understandable. Availability sampling was used to survey residents of selected multifamily residential complexes across the US and a total of 55 responses were collected. There was a box in the pilot survey to allow participants to leave comments and suggestions regarding the survey. The results of the pilot test were also used for further reliability tests. The Chronbach's alpha of above 0.7 showed an internal consistency of the survey instrument.

After the revisions were made to the survey instrument, an online survey was conducted to collect responses from the residents of LEED-certified residential communities. The survey took eight months to complete (August 2020-March 2021). The sampling method in this research was multi-stage sampling; within each project selected for sampling, a random sampling was applied to survey the individuals that were eligible to participate (if they were residents of the community for at least six months and were older than 18 years).

Research Variables. Built attributes of the physical environment that are the concern of this research, can be classified into three main groups of buildings, infrastructure, and neighborhood features. Due to the scope of this study, we focused on these attributes as the main variables creating the structure of the built environment in the housing development projects. Furthermore, since the concern in this research was developing a model for evaluating the long-term successful performance of sustainable residential projects from the users' point of view, it was important to consider features that were specific to sustainable communities.

The independent variables in this study were measured via the "cognitive process". The participants were asked to rate the perceived performance of each attribute on a seven-point Likert scale with 1 being "very poor" and 7 being "very well". The key attributes that were considered as variables included only the sustainability-specific attributes, adopted from LEED-ND and LEED-

BD+C Multifamily Midrise standards to measure the physical performance of sustainable communities. Furthermore, a set of economic attributes were evaluated that were obtained from the literature to evaluate the cost performance of the communities. The dependent variable was "overall satisfaction" with the residential unit and neighborhood built environment. The overall satisfaction was evaluated from the two sets of processes. First the "affective process" was considered consisting of questions that asked the level of satisfaction with home and neighborhood from the residents' points of view. The second set of variables was achieved from the "behavioral process" including a set of questions asking about the residents' intentions to behave in response to the current attributes and general condition of their residential community (Weidemann & Anderson, 1985). In the "affective process", the level of satisfaction with home and community was asked to be rated from (1) very dissatisfied, to (7) very satisfied. In the behavioral process, each question evaluated the level of agreement of the participants with a pre-defined response from (1) totally agree.

DATA ANALYSIS AND RESULTS

In order to test the validity of the developed evaluation model, a confirmatory factor analysis (CFA) was conducted to find the fittest model that represents the variables and to assure that the developed model was providing a valid picture of what was expected to be evaluated. CFA also helps account for multicollinearity among the indicators and provides opportunities for defining the most appropriate latent variables resulted from the indicators. CFA is the appropriate method for confirming or disconfirming the fit of the empirical data to the theoretical structure where there is empirical and theoretical evidence for a construct that has multiple dimensions. As in this study, a model was developed based on housing satisfaction theories and existing satisfaction measurement models, it was necessary to test whether the data fit the developed model that aims to evaluate residential satisfaction in LEED-certified residential communities.

Respondents' Profile. A total of 192 responses was collected including 49% female, 49.5% males, and 1.5% others. The summary of respondents' profiles is presented in Table 1.

Variable	Number	Percentage	Variable	Number	Percentage
Gender			Education level		
Female	94	49	High school graduate or less	8	4.2
Male	95	49.5	Some College or two-year degree	36	18.8
Other	3	1.5	Four-year degree	59	30.7
			Graduate degree	89	46.4
Age			Income		
18-34	75	39.1	Less than \$59,999	30	15.8
35-54	104	54.2	\$60,000 - \$119,999	101	52.6
55 or above	11	5.7	\$120,000 or more	60	31.3
Undefined	2	1	Undefined	1	0.5

Table 1. Summary of sample characteristics

Reliability test. To test the reliability of the scale, first, a Cronbach's alpha test was conducted for the indicators of each latent variable. Besides, an overall Cronbach's alpha test was performed to examine the internal consistency of the entire survey data. The alpha values for all the variables and the entire survey data were above 0.7 indicating a high internal consistency of the measures.

CFA Assumption Test. In order to perform CFA, some assumptions must be met first. The first assumption for conducting CFA is a sufficient sample size ($n \approx 200$). The sample size for this

research question was 192 (n=192), which approaches the minimum sample size of 200 thus meeting this assumption. As the data was collected based on the random sampling method in each community, the assumption of random sampling assumption is also met. The third assumption of CFA is to have an appropriate a-priori model. As discussed previously, the model and the variables were supported by the existing literature and theoretical background thus providing an appropriate a-priori model to be examined through a CFA. Finally, the data should meet multivariate normality. The results for testing this assumption are discussed in the following.

Normality of Data. In CFA, the method that is commonly used is the maximum likelihood (ML), which assumes multivariate normality of the data and if the data is not approximately normal, the results will be biased (Fuller & Hemmerle, 1966). In this study, Mardia's test for multivariate normality was conducted using the WebPower Statistical power analysis online tool. The results of this test indicate that the data does not meet multivariate normality (Table 2).

Table 2. Mardia's multivariate skewness and kurtosis							
Test	В	Z	p-value				
Skewness	141.0779	4514.49211	< 0.0001				
Kurtosis	799.9258	13.05944	< 0.0001				

CONFIRMATORY FACTOR ANALYSIS FOR NON-NORMAL DATA

The purpose of CFA is to assess the model fit to the data and evaluate the strength of a defined model in providing a set of latent factors to evaluate the relationships between factors. It was indicated that the data is not normally distributed thus violating the assumption of ML estimation, which is the most often used method in CFA. Among the available solutions for the issue of nonnormality, the "robust" ML estimation, which is suggested by Satorra and Bentler (2001) was found to be the most appropriate approach to address the nonnormality issue (Finney & DiStefano, 2013). Robust ML is less affected by the negative impacts of non-normality and is available in many software packages including JASP, which is used for this analysis. Therefore, robust ML was considered as the estimation method under CFA for this research. The data analysis in this phase was carried out using JASP version 14.1, which uses Lavaan syntax for the data analysis.

Testing Fit Measures: Initial CFA Model. To test the model, an initial CFA was conducted for each latent variable (variable hereafter) to see how well the individual indicators are loading in their corresponding variable. In order to examine the fit of each model, the fit indices that are found to be the most popular measures were considered including Chi-square, CFI (comparative fit index), RMSEA (root mean square error of approximation), and SRMR (standardized root mean square residual) (Beauducel & Wittmann, 2005). The key results, including indicators' factor loadings and the fit measures of the initial CFA for each variable, are presented in Table 4. For the sake of brevity, all the results of the initial CFA are presented in one table although each variable has been analyzed separately. It is important to test each individual variable first to ensure that all the indicators are contributing to the variable and next evaluate the whole model to make sure that all factors work well in the model.

Among the five factors, factors 2 and 4 (perceived neighborhood design and perceived cost performance, respectively) showed a good fit of the variables. However, the Chi-square test for factors 1, 3, and 5 did not show a good fit (p-values < 0.05). However, it should be mention that Chi-square is the most sensitive fit index, and most of the time it shows poor fit especially when it comes to larger sample sizes. On the other hand, for small sample sizes, it lacks differentiating

between a good fit and a poor fit (Kenny & McCoach, 2003). Therefore, although the Chi-squares did not show good fits for some variables, they can be still considered as a good fit if other indices are acceptable. The other fit measures of variables 1and 3, (perceived infrastructure performance and perceived building performance respectively) showed good fits to the model. Factor 5 (residential satisfaction) however, did not show a good fit and needed further actions such as removing the indicators with low factor loadings or deciding to covariate residuals in order to improve the model. It should also be mentioned that any model modification should be theoretically supported besides being statistically meaningful.

Variable/Indicator	Estima	p-value	C+d	Fit Indices					
			Stu. Estimata	Chi-square		RMSE	SRM		
	ie		Estimate	p-value	CFI	А	R		
Factor 1: Perceived Infrastructure Performance									
GI1-Otdoor Water Efficiency	0.721	< .001	0.420		0.950	0.063	0.050		
GI2-Central Heating and Cooling	0.955	< .001	0.477						
GI3-Outdoor Lighting	1.03	< .001	0.740						
GI4-Rcycling Facilities	1.037	< .001	0.599						
GI5-Rainwater Collection System	0.891	< .001	0.532	0.008					
GI6-Public Transit Infrastructure	1.172	< .001	0.643						
GI7-Biking Infrastructure	0.917	<.001	0.560						
GI8-Proximity to School	0.8	<.001	0.461						
GI9-Road Quality	1.055	<.001	0.714						
Factor 2: Perceived Neighborhood Design									
ND1-Walking Infrastructure	0.937	<.001	0.651		0.991	0.037	0.035		
ND2-Neighborhood Density	0.721	<.001	0.584						
ND3-Mixed Use Neighborhood	1.045	<.001	0.712						
ND4-Housing Diversity	0.881	<.001	0.582	0.253					
ND5-Access to Public Space	0.93	<.001	0.664						
ND6-Neighborhood Greenness	0.65	<.001	0.434						
Factor 3: Perceived Building Performance									
BP1-Hot Water Distribution System	0.905	<.001	0.472		0.969	0.063	0.044		
BP2-Thermal Comfort	0.961	<.001	0.735						
BP3-Availability of Daylight	1.004	<.001	0.721						
BP4-Indoor Water Efficiency	0.865	<.001	0.645	0.010					
BP5-Quality Views from Window	1.04	<.001	0.754	0.019					
BP6-Indoor Materials Used	0.922	<.001	0.676						
BP7-Building Energy Efficiency	0.92	<.001	0.678						
BP8-Insulation	0.601	<.001	0.405						
Factor 4: Perceived Cost Performance									
EP1-Value/Rent	0.954	<.001	0.717		0.996	0.046	0.022		
EP2-Utility Bills	0.888	<.001	0.635						
EP3-Travel and Transportation Costs	1.102	<.001	0.735	0.247					
EP4-Other Fees (HOA/Condo fees, etc.,)	0.852	<.001	0.608						
Factor 5: Residential Satisfaction	Factor 5: Residential Satisfaction								
S1-Plan to Live permanently	1.271	<.001	0.840		0.973	0.091	0.039		
S2-Recommend to others	1.202	<.001	0.840						
S3-If look back, would move here again	1.034	<.001	0.755	0.00 <i>-</i>					
S4-Regulations and rules	0.92	<.001	0.431	0.005					
S5-Overall Neighborhood Satisfaction	0.999	<.001	0.701	1					
S6-Overall Home Satisfaction	0.934	<.001	0.740	1					
Overall model fit measures				< 0.001	0.908	0.051	0.059		

Table 3. CFA results for each variable

* Weak indicators with loading lower than 0.5 are removed and retained indicators are highlighted.

In order to improve the quality of the evaluation model, even with fit measures showing a good fit, it is important to check the factor loadings for each indicator of variables to make sure that all

the indicators have enough strength in the variable. Weak indicators with loading <0.5 reduce the unidimensionality of the measurement model and can damage the fit of the model when the factor that represents the poor indicator becomes part of the model with multiple latent variables (Awang, 2012). Therefore, among all the indicators that are presented in 4, GI1, GI2, GI8, ND6, BP1, BP8, and S4 were found to be weak indicators and were removed from the model after understanding that their removal was supported theoretically. As a result, 26 indicators were retained in the model to be represented by 4 independent variables and 1 dependent variable.

Final CFA Model. After removing the weak indicators, the fit measures were checked again and showed significant improvements. Therefore, after recoding the retained indicators in each variable, the final confirmatory factor analysis was conducted to check the fit of a model that includes all the variables and see if the model is plausible for the data (n=192). The results of the fit indices for the modified CFA model are summarized in Table 5.

As shown in Table 4, overall fit indices show that the overall model fits the data and can provide a valid and reliable structural equation model to evaluate the relationships between the latent independent and dependent variables.

Variable/Indicator	Estimate	p	Std. Est. (all)						
Factor 1: Perceived Infrastructure Performance									
GI1-Outdoor Lighting	1.176	< .001	0.645						
GI2-Rcycling Facilities	0.863	< .001	0.522						
GI3-Rainwater Collection System	0.851	< .001	0.519						
GI4-Public Transit Infrastructure	0.956	< .001	0.571						
GI5-Biking Infrastructure	0.897	< .001	0.548						
GI6-Road Quality	1.001	< .001	0.578						
Factor 2: Perceived Neighborhood Design									
ND1-Walking Infrastructure	1.035	< .001	0.719						
ND2-Neighborhood Density	0.712	< .001	0.577						
ND3-Mixed Use Neighborhood	1.052	< .001	0.716						
ND4-Housing Diversity	0.802	< .001	0.53						
ND5-Access to Public Space	0.879	< .001	0.628						
Factor3: Perceived Building Performance									
BP1-Thermal Comfort	0.949	< .001	0.726						
BP2-Availability of Daylight	0.999	< .001	0.717						
BP3-Indoor Water Efficiency	0.90	< .001	0.671						
BP4-Quality Views from Window	0.907	< .001	0.601						
BP5-Indoor Materials Used	0.96	< .001	0.704						
BP6-Building Energy Efficiency	0.901	< .001	0.665						
Factor 4: Perceived Cost performance									
EP1-Value/Rent	0.972	< .001	0.73						
EP2-Utility Bills	0.918	< .001	0.656						
EP3-Travel and Transportation Costs	1.084	< .001	0.723						
EP4-Other Fees (HOA/Condo fees, tax, etc.,)	0.811	< .001	0.579						
Factor 5: Residential satisfaction									
S1-Plan to Live permanently	1.264	< .001	0.836						
S2-Recommend to others	1.18	< .001	0.825						
S3-If look back, would move here again	1.02	< .001	0.744						
S4-Overall Neighborhood Satisfaction	1.002	< .001	0.702						
S5-Overall Home Satisfaction	0.972	<.001	0.77						

 Table Error! No text of specified style in document.4. Final CFA Results

Fit indices: X2/df= 1.3, p-value= <.001; CFI= 0.956; RMSEA= .040; SRMR= 0.051

DISCUSSION

Reviewing the literature and digging into the LEED-ND certification system, it was illustrated that the role of users' judgments and feedback was underestimated in defining the criteria for the development and evaluation of the long-term success of sustainable residential communities. Therefore, in this study, a model was developed to provide opportunities for evaluating the role of residents' perceptions and satisfaction to come up with a true understanding of the long-term successful performance of sustainable residential communities.

The model evaluated the long-term performance of sustainable residential communities mainly by investigating the perception of the users from the functionality of their residential environment attributes. Satisfaction, on the other hand, was evaluated both by asking questions about overall satisfaction with home and community and by investigating the residents' behavioral intentions toward living in their current communities. This research bridged the gap of knowledge about the sustainability-specific post-occupancy evaluation model for residential communities. This research took advantage of the most popular housing theories such as Housing Needs Theory (Rossi, 1955), Housing Adjustment Theory (Morris & Winter, 1975), and Psychological Construct Theory (Galster, 1985) as well as the conceptual model of residential satisfaction developed by Weidemann and Anderson (1985) to develop a model that could be useful in different contexts. All the measures used in developing evaluation constructs were adopted and modified from LEED certification standards and other building-related survey tools such as UC Berkeley Center for the Built Environment Survey tool. This approach was taken to provide reliable, valid, and generalizable outcomes that help identify the most important attributes in determining sustainability, perceived performance, and residential satisfaction.

The initial model included five constructs, each of which included several measures: Perceived Infrastructure Performance (9 measures), Perceived Neighborhood Design (6 measures), Perceived Building Performance (8 measures), Perceived Economic Performance (4 measures), and Satisfaction and Behavioral responses (6 measures). The model was tested using CFA (N=192). The initial CFA showed that perceived neighborhood design and perceived cost performance had a good fit to the data while perceived infrastructure performance, perceived building performance, and residential satisfaction did not show good fits. Among the 33 initial measures that entered the CFA model, the weak measures were removed if they had a low factor loading on their corresponding construct (loading < .50), and their removal was theoretically supported. As a result of the analysis, 26 retained measures were found to be valid measures for post-occupancy evaluation of LEED-certified residential projects. Among the nine infrastructure performance measures, outdoor water efficiency, central heating, and cooling system, and proximity to school were removed from the model due to having factor loadings lower than 0.5 while outdoor lighting, recycling facilities, rainwater collection system, public transit infrastructure, biking infrastructure, and road quality were retained in the model. Among the six initial measures of the neighborhood pattern and design, only neighborhood greenness was removed and walkability, neighborhood density, a mix of land uses, housing type diversity, and access to public spaces were retained. Among the eight building performance measures, the hot water distribution system and insulation were removed from the model while thermal comfort, availability of daylight, water efficiency, energy efficiency, quality views, and materials were retained in the model. All the cost performance measures showed to be strong indicators and were retained in the model. Finally, among the six initial measures of residential satisfaction, the only

factor that was removed from the model was "regulations and rules associated with living in the community". The other five measures were retained in the model.

After modifying the model by removing the weak indicators, the fit measures for all the variables showed to be within the acceptable limit thus demonstrating a good fit of the model. The findings of this research provide opportunities for understanding the relationships between the perceived performance of the built environment in green residential communities and the satisfaction of the residents by entering them into a structural equation modeling.

CONCLUSION

With green residential buildings and communities becoming more and more popular in the US., it is crucial to identify the key factors that contribute to residential satisfaction in green buildings. This research illustrated that residential satisfaction in sustainable residential communities is dependent on a specific set of neighborhood and building attributes. By assessing several specific aspects of residential satisfaction, the study highlighted some neighborhood factors and individual unit design and construction factors that are critical in satisfaction with green residential communities. Thus, the findings of this research can potentially contribute directly to the design and construction of sustainable residential buildings and communities, especially in the US. Given that there has been relatively little research on the green building-specific design and construction characteristics, the findings of this study provide opportunities for understanding, identifying, and encouraging developments that best meet residents' needs and expectations.

Although covering multiple aspects, this research has some limitations. One of the most important limitations of this study is the relatively small number of responses for testing the model validity. The other limitation of the research is a lack of focus on the social aspects of the residential communities. However, due to the complex nature of social aspects, those aspects demand separate research. Furthermore, due to the scope of this research, it seems reasonable to provide a model that focuses on physical aspects and the economic aspects that are associated with the built environment. Therefore, future research can add the social aspects to the scope of the research and improve the generalizability of the model by surveying a higher number of LEED-certified community residents.

References

- Awang, Z. (2012). Research Methodology and Data Analysis Second Edition Zainudin Awang -Google Books. Retrieved from https://www.google.com/books
- Beauducel, A., & Wittmann, W. W. (2005). Simulation study on fit indexes in CFA based on data with slightly distorted simple structure. *Structural Equation Modeling*, *12*(1), 41–75. https://doi.org/10.1207/s15328007sem1201_3
- Bentler, P. M., & Bonett, D. G. (1980). Significance tests and goodness of fit in the analysis of covariance structures. *Psychological Bulletin*, 88(3), 588–606. https://doi.org/10.1037/0033-2909.88.3.588
- Berardi, U. (2013). Sustainability assessment of urban communities through rating systems. *Environment, Development and Sustainability*, 15(6), 1573–1591.

https://doi.org/10.1007/s10668-013-9462-0

- de Jong, K., Albin, M., Skärbäck, E., Grahn, P., & Björk, J. (2012). Perceived green qualities were associated with neighborhood satisfaction, physical activity, and general health: Results from a cross-sectional study in suburban and rural Scania, southern Sweden. *Health & Place*, *18*(6), 1374–1380. https://doi.org/10.1016/J.HEALTHPLACE.2012.07.001
- Finney, S. J., & DiStefano, C. (2013). Non-normal and categorical data in structural equation modeling. *Structural Equation Modeling: A Second Course*, 269–314. Retrieved from https://psycnet.apa.org/record/2014-01991-011
- Fuller, E. L., & Hemmerle, W. J. (1966). Robustness of the maximum-likelihood estimation procedure in factor analysis. *Psychometrika*, 31(2), 255–266. https://doi.org/10.1007/BF02289512
- Galster, G. C. (1985). Evaluating indicators for housing policy: Residential satisfaction vs marginal improvement priorities. *Social Indicators Research*, *16*(4), 415–448. https://doi.org/10.1007/BF00333289
- Hur, M., & Nasar, J. L. (2014). Physical upkeep, perceived upkeep, fear of crime and neighborhood satisfaction. *Journal of Environmental Psychology*, 38, 186–194. https://doi.org/10.1016/J.JENVP.2014.02.001
- Kenny, D. A., & McCoach, D. B. (2003). Effect of the Number of Variables on Measures of Fit in Structural Equation Modeling. *Structural Equation Modeling*, 10(3), 333–351. https://doi.org/10.1207/S15328007SEM1003_1
- Kweon, B.-S., Ellis, C. D., Leiva, P. I., & Rogers, G. O. (2010). Landscape Components, Land Use, and Neighborhood Satisfaction. *Environment and Planning B: Planning and Design*, 37(3), 500–517. https://doi.org/10.1068/b35059
- Mohit, M. A., & Raja, A. M. M. A. K. (2014). Residential satisfaction-Concept, theories and empirical studies. *Planning Malaysia: Urban Planning and Local Governance*, *12*(July 2014), 47–66. https://doi.org/10.21837/pmjournal.v12.i3.131
- Morris, E. W., & Winter, M. (1975). A Theory of Family Housing Adjustment. *Journal of Marriage and the Family*, 37(1), 79. https://doi.org/10.2307/351032
- Parkes, A., Kearns, A., & Atkinson, R. (2002). What Makes People Dissatisfied with their Neighbourhoods? Urban Studies, 39(13), 2413–2438. https://doi.org/10.1080/0042098022000027031
- Rossi, P. H. (1955). Why Families Move A Study in the Social Psychology of Urban Residential Mobility. *The Free Press, Glencoe*. Retrieved from https://www.scirp.org/(S(lz5mqp453edsnp55rrgjct55))/reference/ReferencesPapers.aspx?Re ferenceID=1207629
- Satorra, A., & Bentler, P. M. (2001). A scaled difference chi-square test statistic for moment structure analysis. *Psychometrika*, 66(4), 507–514. https://doi.org/10.1007/BF02296192
- Weidemann, S., & Anderson, J. R. (1985). A Conceptual Framework for Residential Satisfaction. In *Home Environments* (pp. 153–182). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4899-2266-3_7

Use of Industrial Hemp and Bamboo Fiber in Construction

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ABSTRACT

In the construction industry, there has been increased interest in using alternative materials and nonwood fiber sources for building construction products. Two fiber sources which have attracted considerable attention are industrial hemp and bamboo. The recent relaxation of industrial hemp growth regulations in the United States has lead to increased development of hemp fiber products. While most commercial timber bamboo species are grown overseas, bamboo fiber is known as a strong, reliable product for building materials. Both hemp and bamboo are classified as rapidly renewable materials, making them favorable for green building systems. However, there is a current lack of knowledge and a large degree of speculative marketing related to the use of these products. For these markets to contribute to sustainability produce economic value, factual evidence needs to be presented from a rational perspective. The purpose of this paper is to discuss a range of current and soon to be released building construction materials using hemp and bamboo fiber. Products were examined through technical, marketing and environmental lenses to reflect on the value of these products to the construction industry. For the continued use of industrial hemp and bamboo products, reliable product information must be available from third party verified sources to confirm product attributes.

KEYWORDS: alternative building materials, industrial hemp, bamboo, green building

INTRODUCTION

World population is expected to exceed 9.3 billion by 2050, with 2.3 billion new urban dwellers (UN 2018). With this increase in population, there is a continuous need for new and increased housing in the United States and throughout the world. With the consequences of climate change and resulting global temperature increase, there is a need to limit carbon emissions. The need for housing and limits of carbon emission are currently in direct conflict, since it is estimated that carbon emissions could claim between 35% to 60% of the allotted carbon budgets required to reach global temperature benchmarks (Müller et al. 2013), leaving less emissions for food, energy and comfort. As more governments adopt carbon emission goals. Rather than seeing reduced carbon emissions as a limiting factor in design, we believe this will increase the adoption of cultivated plant-based fiber sources with a consequent reduction or optimization in the use of extracted ore and mineral-based products.

The construction industry is one of the largest sources of carbon emissions due to the reliance on concrete and steel elements. Carbon emissions can be subdivided into *embodied carbon*, which is used in the construction, repair and renovation of the structure, and *operational carbon*, which is related to the energy for operation use of the building. The embodied carbon in a group of studied buildings was found to account for between 2% to 80% of the total carbon emissions (Ibn-Mohammad et al. 2013), demonstrating the diversity of building types and construction used. The share of embodied carbon is only expected to rise as operational carbon mandates become more common. Geisekam et al. (2016) notes the temporal differences between embodied and operational carbon, where the majority of embodied carbon emissions are created during construction, while operational carbon emissions occur over the lifetime of the building.
Giesekam et al. (2016) discussed the changes to the UK construction industry in response to the EU Energy Performance of Buildings Directive. Increased governmental and regulatory efforts will begin to focus on embodied emissions and it is in the interests of the construction industry to help craft and administer these systems. Common strategies for embodied emission reduction include the minimization of carbon-intensive materials, removing extraneous materials (termed lightweighting), structural design optimization, and site-generated waste reduction (Giesekam et al. 2016).

The process of innovation in the construction industry with respect to the incorporation of new materials is complicated by many factors. Residential construction in the United States is a multi-disciplinary, diverse group of businesses with little central knowledge who are generally risk-averse. Time pressures on most projects prevent deeper analysis or incorporation of new products. The majority of new information is provided by suppliers who have a vested interest in encouraging contractors to purchase their products. Also, contractors feel constrained by the current heavy safety regulated environment and general litigious environment, which discourages adaption of new materials or processes.

Several authors have advocated for the use of wood and plant-based fiber sources (Churkina et al. 2020, IPCC 2014, McKinsey & Co 2009) as methods of carbon capture through product growth and sequestration through incorporation in buildings. Currently, the only economical and efficient method for the capture of carbon from the atmosphere is the growth of plant-based fibers, which can then be harvested and sequestered, allowing continued growth of fiber sources. Using available plant-based fiber sources for construction of homes and other buildings, especially employing new technology such as mass timber and alternative fibers, will allow us to create buildings which sequestering carbon (King 2017).

Orhon and Altin (2020) defined alternative building materials (ABM) as low-cost materials that "aim to reduce or eliminate the environmental impact of the construction" (p. 728). ABMs can include materials that are energy efficient, resource efficient, reduce embodied energy, minimize greenhouse emissions use rapidly renewable materials or have recycled content.

For residential structures, the use of alternative building materials centered around plant-based fiber not obtained from trees has the potential to become important in the future. While wood fiber is a renewable and sustainable material when harvesting and land conservation are performed correctly, the volume and need of fiber sources has the capacity to tax our forest resources, leading to a focus on quicker rotation crops.

PURPOSE OF PAPER

As previously mentioned, plant-based fiber sources are seen as the only economical method of carbon sequestration. The purpose of this article is to discuss the uses of plant-based fiber sources, most notably industrial hemp and bamboo, and cite some current and future building products which may become available in residential construction. These building products constitute low-carbon construction options, but may become attractive to homeowners because of the environmental or aesthetic qualities.

In the following sections of this paper, the biological materials of hemp and bamboo will be first described, noting the sources and particular aspects of the materials. Three construction products were then chosen for each material and described in detail. The quality of hemp and bamboo products used in construction, whatever reduction of carbon emission is allowed, must always represent consistent or better performance with current building products in use. Much of the marketing for these products is interlaced with a large "green" narrative, which is interesting, but, in the author's opinions, can often detract from the technical data which are required to ensure the product can be used in the building code.

In the United States, structural building products of a proprietary nature should have an evaluation service report (ESR) or similar third-party evaluation document from a group such as the International

Code Council Evaluation Service (ICC-ES). Without this proper documentation, which verifies independently testing of the manufacturer, these products are not able to be used in the construction of buildings.

INDUSTRIAL HEMP

Description of Fiber Source

Hemp (*Cannibis sativa*) is one of the earliest cultivated crops, first used by humans approximately 8500 years ago. Hemp has been used originally as a fiber source for cordage and canvas. Oils from hemp have also been used and are dominated by a current emphasis on cannabidiol (CBD). The story of hemp use is not complete without a mention of marijuana, an offshoot of hemp which contains high concentrations of tetrahydrocannabinol (THC), a psychoactive compound, that is currently regulated as a Schedule 1 drug (Malone and Gomez 2019). Distinctions between hemp and marijuana are sometimes difficult and both plants have been banned from use. In recent years beginning with the Agriculture Improvement Act of 2018 (2018 Farm Bill), production of hemp in the United States was allowed. Current production has increased to where some states now allow growth of hemp with consistent monitoring to maintain THC levels less than 0.3 percent dry weight (Congressional Research Service 2019).

Currently, most hemp production in the United States is being grown for oil production. However, there are optimal varieties available for fiber production, which is more common outside of the United States. Hemp fiber can be subdivided into two categories – bast, or outer fiber, and shiv (hurd) or inner fiber. The bast fibers are long, thin, continuous fibers with high tensile strength. Bast fibers are used in the production of clothing, insulation, and cordage. Hurd fibers are short, brittle and punky in nature. Hurd fibers are used in hempcrete production, as well as growth media, pulp and animal bedding (Fike 2016). It should be noted that at the current time, all hemp-related building products in the United States are non-structural.

Bast Fiber Products

Naturefibres (<u>www.naturefibres.com</u>) is a Canadian company that produces insulation materials from hemp. Bast fibers are woven together into a loose mat (Figure 1). Similar to fiberglass or rock wool insulation, these mats derive insulative properties from the air pockets trapped within the fibers. According to information on the manufacturer's website, this insulation has an R-value of 3.7 per inch, which is similar to fiberglass batt insulation. However, no ESR was found for the Naturefibres material, which may call this R-value into question.



Figure 1. Hemp Insulation from Naturefibres

Other advantages listed for Naturefibres include improve hygrothermal behavior, and a more efficient phase shift. These claims are interesting and may prove useful, but are not independently verifiable by quantitative test methods. Environmental criteria for the product are also given, including an embodied

energy value of 30 kW-hr/m³ and the company does state that a life cycle analysis and environmental product declaration (EPD) are available. Hempwood

Hempwood (<u>www.hempwood.com</u>) is a flooring company producing a mixed hardwood – hemp fiber flooring product. The wear surface of the flooring is composed of a composite using hemp fibers. The website notes that the materials are 'interior, non-structural'. However, one of the product categories is 'Lumber' and lists various lengths of a composite hemp product. The use of the term lumber may cause confusion of whether the product is listed as structural or not.

Claims of sustainability state 'the smallest ecological footprint of any lumber alternative." This is a specious claim since most lumber alternatives are formulated with a mixture of wood fiber and plastic. Also, no values or life cycle analysis of the products are included. There is little information about the manufacturing process, which may have to be revealed to explain a life cycle analysis. While wood and other plant-based composites do have the potential for reduced carbon emissions, careful documentation of the adhesive and additives are needed.



Figure 2. Hempwood Flooring Product

Hurd Fiber Products

The most common product from hemp hurd is hempcrete. Hempcrete is a mixture of hemp hurd, lime plaster and water (Golebiewski 2018). The material is tamped into place and used as a non-structural insulation material (Figure 3). The name of hempcrete is similar to concrete and gives the impression that the properties of hempcrete may be similar to concrete, which is false. Hempcrete is a non-structural building product. Insulation values of hempcrete is an R-2.08 per inch (Gibson, 2016), which is lower than conventional fiber-glass batts. Various manufacturers including Hempitecture, Inc., Americhanvre, and American Lime Technology, among others, are available in the United States. Compared to other insulation types, hempcrete has one of the lowest embodied carbon amounts of 0.142 kg CO₂eq./kg, compared to 1.35 kg CO₂eq./kg for fiberglass batt insulation (King, 2017). Therefore, even with a lower equivalent R-value of thermal resistance, hempcrete can provide equivalent insulation materials is that hempcrete can be extended beyond the stud wall cavity and be placed over top of the studs to prevent thermal bridging. Finishing materials for hempcrete use a lathe and plaster system capable of withstanding local environmental conditions.

Disadvantages of hempcrete are related to the installation of the material. Hempcrete must be troweled into the wall section and restricted by forms to depths of 18 to 24 inches at a time before the hempcrete is allowed to cure, and the forms can be removed. This represents a significant amount of labor and

time on the jobsite. Another disadvantage is the difference of working with bio-based fibers versus mineral aggregate. The hemp hurd itself will absorb a portion of the water used for the mix, so careful understanding of the mix is needed. Several companies sell pre-measured lime/hurd mixes which helps overcome this challenge, specifically on small scale projects.



Figure 3. Hempcrete Applied To A Wall Section

BAMBOO

Bamboo is a perennial, woody grass belonging to the family *Poaceae* and is the largest member of the grass family (Liese 1987). The main stalk consists of a series of hollow, jointed stems (culms) separated by interstitial plates. The bamboo material itself is composed of vascular bundles of cells. As a grass (monocot), bamboo does not contain ray cells which leads to an extremely low value of perpendicular to grain strength, which limits fastener capacity. The wall thickness of culms varies greatly by species, as well as between individual stalks. Typically, the interior and exterior of the culm both contain a waxy cuticle that can be prohibitive to adhesive.

Tensile strength of bamboo fibers has been reported to be as great as 140-280 MPa, which is within the range of mild steel (Patil and Mutkekar 2014). However, the advantage of strong tensile strength is often difficult to achieve in structural sizes of bamboo. Measurement of bamboo full culm poles between 75 to 125 mm diameter produced higher strength than 2x4 lumber, but similar stiffness values.

Advantages of using bamboo with respect to sustainability include:

- Fast growth of bamboo. Timber bamboo species can be produced within 4-8 years compared to 20-25 years for softwood lumber.
- Carbon sequestration. One hectare of bamboo can sequester 12 tons of carbon dioxide, and produce 35% more oxygen compared to an equivalent stand of trees (Goh et al. 2019).
- Low cost compared to steel
- Lower carbon emissions compared to steel.

Disadvantages to bamboo can include the lack of well-established testing standards, the lack of consistent methods and knowledge of species and age identification, differential size and lack of standardized shape of culms, potential for decay since bamboo is a biological material. While treatment options exist, there is still potential for decay in wet or aggressive environments. Also, bamboo tends to fracture along the grain, especially for any forces applied perpendicular to grain. This is particularly troublesome for forces applied at bolted connections to poles, requiring additional reinforcement.

Bamboo Full Culm Products

Bamboo Technologies, Inc. (https://bambooliving.com/) produces a structural full culm bamboo pole for use in their housing products. From exploring the website, the poles do not seem to be commercially available for sale. The poles are governed by ESR-1636, which is available from the ICC-ES website (www.icc-es.org). Bamboo poles have diameters between 2-11/16 inches and 3-15/16 inches. Mechanical properties of the bamboo poles are similar to solid-sawn lumber values. However, in order to compute the stresses of the individual poles, the dimensions are needed to compute the area, section modulus or moment of inertia. Procedures for these calculation methods are discussed by INBAR (International Bamboo and Rattan Organization, www.inbar.int) documents.

Engineered Bamboo Products

Current bamboo construction products in the United States use the bamboo fiber incorporated into veneers or composites, known as engineered bamboo products. This manufacturing system includes the mechanical or chemical removal of the inner and outer cuticle layers in conjunction with splitting of the culm or an 'unrolling' process where the culm is flattened and the interstitial plates are removed. It is important to note that the processing of bamboo fibers as well as industrial adhesive used for creation of the composites introduces greater embodied carbon emissions compared to full-culm materials.

Bamcore (<u>www.bamcore.com</u>) is a building structural system that incorporates unrolled and lightly milled bamboo pole layers. The structural system, shown in Figure 4, consists of two thickened plywood panels (approximately 1 inch thick) which are composed of a combination of Douglas fir and bamboo layers. Connected with light-gauge steel, the two plywood layers create the sheathing and structural members of this system, eliminating the need for studs inside of the wall, thereby increasing room for insulation and reducing thermal bridging. While the system is intended to be structural, there is little information available as to the details of the use of the system, and currently there is no ESR for the structural system available.



Figure 4: Bamcore Wall System

Lamboo (<u>www.lamboo.us</u>) produces architectural and structural building materials from bamboo. Architectural products include veneers, acoustic panels and stair treads. Exterior products including cross-layered panels, rainscreens and composite decking are available. Structural products include beams and columns (Figure 5). While the company provided a technical data sheet with structural design information, no ESR or similar document was noted. Material properties reported for the Lamboo products were significantly greater than conventional wood lumber.



Figure 5: Lamboo Beams and Columns

Hangzhou Zhunanmu Environmental Protection Technology Co., Ltd (<u>www.zhunanmu.com</u>) produces a laminated bamboo strand lumber (LBSL) product (Figure 6). This product is a structural material that has been approved for use in the 2018 and 2021 International Building Codes. ESR-4781, which is available from the ICC-ES website (<u>www.icc-es.org</u>), provides mechanical properties, fastener details and installation methods for using LBSL. Mechanical properties listed are similar to solid-sawn lumber and some engineered wood product values.



Figure 6: Bamboo Laminated Strand Lumber (BLSL)

CONCLUSIONS

Both hemp and bamboo products have demonstrated uses for products in construction among both structural and non-structural products. Acceptance of ABMs may be helpful in earning rapidly renewable material credits in green building systems or demonstrating sustainable concerns to customers, but there is a constant need for solid, technical data about these products as well. Currently, the hemp and bamboo products discussed here are limited to many non-structural roles. Several products display structural information, however without verified third-party sources.

A further concern is manufacturer volatility in the ABM market. An example is Sunstrand, a Kentucky company producing a fiberboard product from hemp. As of January, 2020, the business entered Chapter 7 bankruptcy, or liquidation bankruptcy. However, articles espousing the characteristics and use of Sunstrand products can still be found on the internet with no correcting information.

It is expected that as the markets for ABMs become larger, many of the concerns of lack of technical information and volatility will be lessened. It should be noted that many of the ABM products examined here (hemp insulation, Bamboo Technologies poles, Lamboo beams) did have similar mechanical and thermal properties to conventional materials and could easily be incorporated into the current construction systems with few changes. However, other products, such as hempcrete or the Bamcore system, may require rethinking of material use or changes in the structural system to

accommodate, but the consequences of modifying current construction methods could result in reductions in cost and carbon emissions if correctly applied.

While some of the products illustrated in this paper did have evaluation service reports (ESR) available, no product found has a corresponding validation of attributes report (VAR). The VAR system is similar to the ESRs and is governed by the ICC Evaluation Service and provides information directly related to the sustainability of various products for use in green building certification systems (LEED, International Green Construction Code, ICC-700, etc.). VAR reports include data on pre- and post-consumer recycled content, percent of bio-based content (which all of the ABMs profiled should be eligible for), and list of compliance with various green building certification systems. Obtaining VAR or similar reporting for ABMs would help to increase exposure of products and demonstrate how these materials can enhance green building projects.

REFERENCES

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., Schellnhuber, H. J. 2020. Buildings as a Global Carbon Sink. Nature Sustainability. 3:269-276. DOI: 10.1038/s41893-019-0462-4.

Congressional Research Service. 2019. Defining Hemp: A Fact Sheet. https://sgp.fas.org/crs/misc/R44742.pdf

Fike, J. 2016. Industrial Hemp: Renewed Opportunities for an Ancient Crop. Critical Reviews in Plant Sciences. 35(5-6):(406-424).

Gibson, S., 2016. Building a House of Hemp. Green Building Advisor. www.greenbuildingadvisor.com/article/building-a-house-of-hemp

Giesekam, J, Barrett, J. R., Taylor, P. 2016. Construction sector views on low carbon building materials. Building and Research Information. 44(4):(423-44).

Goh, Y., Yap, S. Y., Tong, T. Y. 2019. Bamboo: The Emerging Renewable Material for Sustainable Construction. *Encyclopedia of Renewable and Sustainable Materials*. DOI: 10.1016/B978-0-12-803581-8.10748-9.

Ibn-Mohammad, T., Greenough, R., Taylor, S., Ozawa-Meida, L, Acquaye, a. 2013. Operational vs Embodied Emissions in Buildings – A review of current trends. Energy and Buildings. 66:232-245.

IPCC, Intergovernmental Panel on Climate Change. 2014. Climate Change 2014: Synthesis Report. Contributions of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team R. K. Pachauri and L. A. Meyer (eds.)]. IPCC. Geneva, Switzerland. 151 p.

King, B. 2017. *The New Carbon Architecture: Building to Cool the Climate*. New Society Publishers. Gabriola Island, British Columbia, Canada. 159 p.

Liese, W. 1987. Research on Bamboo. Wood Science and Technology. 21:189-209.

McKinsey & Company. 2009. *Pathways to a Low Carbon Economy, Version 2 of the Global Green House Gas Abatement Cost Curve*. <u>https://www.mckinsey.com/business-functions/sustainability/our-insights/pathways-to-a-low-carbon-economy</u>.

Malone, T., Gomez, K. 2019. Hemp in the United States: A Case Study of Regulatory Path Dependence. Applied Economic Perspectives and Policy. 41(2):199-214.

Müller, D. B., Liu, G., Løvik, A. N., Modaresi, R., Pauliuk, S., Steinhoff, F. S., Brattebø, H. 2013. Carbon Emissions of Infrastructure Development. Environmental Science and Technology. 47:11739-11746.

Patil, S., Mutkekar, S. 2014. Bamboo As a Cost Effective Building Material for Rural Construction. Journal of Civil Engineering and Environmental Technology. 1:35-40.

United Nations. 2018. *Revision of World Urbanization Prospects*. United Nations Department of Economic and Social Affairs. New York, NY, USA.

Critical Review of the Characterization of Environmental and Mechanical Properties of Hemp Hurd and Hempcrete

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ABSTRACT

Industrial hemp (Cannabis sativa L.) is a promising bio-based building material that can be used as an alternative aggregate in the form of hemp-lime or hempcrete. Whereas hempcrete has been successfully used in construction in Europe, it has not been allowed to grow in the U.S because industrial hemp was classified as a Schedule I drug in the early 20th century. Recently, however, the cultivation of industrial hemp has been newly reinstated in the U.S., and there has been a growing interest in using hemp hurd in residential construction. Hemp hurd is promoted to provide better thermal insulation and hygroscopic performances, i.e., absorbing moisture during higher relative humidity seasons and giving out moisture during drier seasons. Existing literature concerning such characteristics of hemp-lime or hempcrete mostly involves hemp products made in Europe. To quantify the thermal and hygroscopic properties of hemp hurd, hemp-lime, and hempcrete based on hemp grown and produced in the United States, we should establish appropriate test protocols and standards. To that end, this paper aims to review existing studies, test protocols, and standards on the characterization of thermal and hygroscopic properties of hemp hurd. On the other hand, the use of hemp-lime or hempcrete is limited to non-load-bearing elements. However, we believe that it is possible to improve the load-bearing capacity of hemp-lime or hempcrete materials. Characterization of mechanical properties of hemp hurd will contribute to the effort to understand the load-bearing capacity of hemp-lime or hempcrete. This paper will review studies and existing standards of the mechanical properties of bio-based aggregate from the standpoint of the structural material.

INTRODUCTION

Reducing CO₂ emissions into the atmosphere is one of the most widely recognized tasks to mitigate global climate change. Given that buildings are responsible for about 39% of CO₂ emissions (9×10^9 ton of CO₂), there is an urgent need for developing construction materials and processes to reduce greenhouse gas emissions. In particular, because most of the building construction worldwide uses a significant amount of masonry, concrete, and steel, which have contributed to 1% increase in CO₂ emission since 2010, an alternative low-carbon or carbon-capturing construction materials and methods must be developed.

Few alternatives are available for traditional loadbearing structural systems. On the other hand, the market increasingly leans toward factory-built and assembled panelized and

modular systems. Such new materials and systems often require advanced technology and skilled labor. On the other hand, plant-based alternative concrete does not require significant investments or training.

Industrial hemp is a promising alternative for aggregates. While hempcrete (also referred to as hemp-lime) that uses milled industrial hemp shiv or hemp hurd with the natural lime binder and sometimes with a small amount of cement (to accelerate setting) offers excellent hygroscopic and insulation properties, the mechanical performance is not as optimal. Therefore, the current use of such plant-based concrete is considered to be non-load bearing and treated as insulation. Improving the mechanical performance of hempcrete is expected to promote the utility of hempcrete in construction. With the recent interest in environment-friendly construction materials, there have been studies on characterizing the mechanical, thermal, and hygroscopic properties of hempcrete. This paper reviews relevant literature in the field to help us understand the challenges of developing hempcrete with better and reliable performances.

INDUSTRIAL HEMP

Hemp is an industrial variant of cannabis that is grown mainly for its fiber, hurd, and seeds. Because of the long-time ban on growing and doing research related to industrial hemp, hemp has not been considered a viable renewable resource for U.S. building products. However, recently, Senate Bill S.2667 by the 115th Congress debarred the ban on hemp cultivation and use (<u>https://www.congress.gov/bill/115th-congress/senate-bill/2667</u>).

Because of the prolonged ban on hemp, there are many challenges to adopt hemp back to the field and for other industrial uses. As of 2018, only about 10,000 acres in the U.S. grew this crop (Popescu 2018). In addition to the limited cultivation of industrial hemp, there exists a great need to figure out the usage of industrial hemp to expand markets.

From an agricultural crop perspective, the yield of hemp is reported to be quite high (2.5 to 8.7 tons of dry straw per acre), which makes it hard to match by any other plants to provide this volume of biomass (Green Home Gnome 2017). Also, the growth rate is fast (about four months), which offers a potentil to be a highly profitable crop for farmers (Popescu 2018).

As far as carbon sequestering is concerned, according to Tradical Hempcrete (2019), hempcrete sequesters 110 kg of CO_2 per 1 m³ of hempcrete, even when taking into account the carbon emission due to producing the lime binder. Based on another report (Green Home Gnome 2017), on average, a 2000 ft² home would sequester about 5 tons of CO_2 if built using hempcrete. This is a 5-folds increase of the carbon sequestration of batt insulation, which achieves 1 ton of CO_2 .

Hemp fibers that make up the exterior surface of the stalk have tensile capacity comparable to steel. The woody core hurd can be chopped as shiv and used as an aggregate material with high thermal insulation and thermal mass properties. As hemp grows (as tall as 4.5 m and 25 mm dia.), it absorbs a significant amount of CO_2 (e.g., 716 lb. (325 kg) of CO2 in one tonne of dried hemp) (Green Home Gnome 2017). Other estimates mention that the hemp used in 1 m³ of hempcrete has sequestered 165-180 kg CO_2 .

HEMPCRETE

From an environmental and sustainability perspective, hemp hurd (Figure 1) can be considered a by-product of hemp fiber producers. In particular, since the use of hemp hurd in hempcrete provides resistance to thermal conduction, hempcrete offers an important advantage over conventional construction materials. Other advantages include being renewable, low-impact on the environment, and obtained from the waste stream as a by-product.

The hemp hurd also has a high level of capacity to absorb moisture. This is considered a desirable attribute for construction material; however, this can adversely affect the mechanical performances over time due to potential biodegradation due to higher moisture content.



Figure 1 A bulk sampe of Kanabat Building Grade Hemp Hurd that can be used as alternative aggregate of hempcrete

However, the mechanical performances of hempcrete are rather poor. For example, the typical compressive strength for 2:1 (binder:hemp by weight) ranges from 0.2 to 1.20 MPa (Hirst et al., n.d.; Walker, Pavia, and Mitchell 2014). For flexural strength, some authors found it to be in a low range, between 0.06 and 1.2 MPa (Elfordy et al., 2008; Walker et al., 2014). Therefore, there have been continued efforts to improve the mechanical performance of hempcrete.

In summary, the performance of hempcrete as a construction material should be characterized with the combined properties, including mechanical, thermal, and hygroscopic properties. Therefore, most of the studies attempt to quantify mechanical, thermal, hygroscopic, or some combinations of those properties of hempcrete.

Characterization and Improvements of Mechanical, Thermal, and Hygroscopic Properties of Hempcrete

As mentioned in the previous section, the performance of hempcrete has combined aspects of mechanical, thermal, and hygroscopic characteristics. Therefore, most studies characterize all or some combinations of these properties. Further, most studies concern processes and alternative materials that influence the properties of hempcrete.

Juntaro et al. (2007) attempted to improve hemp and sisal fiber bundle derived from an agave using nano-crystalline cellulose produced with cellulose producing bacteria (*Gluconacetobacter xylinus*). The authors report that a significant improvement was achieved. However, this has not been used widely as of yet.

Stevulova et al. (2013) studied hemp hurd mixed with hydrated lime without and with cement, i.e., zeolite, MgO-cement. Authors report that the MgO-cement binder improves the mechanical strength of the hempcrete. Importantly, the authors report that the particle size of hemp hurd influences mechanical performance. This point and linkage can be explored from the perspective of the mixture design.

Walker et al. (2014) report the quantified effect of the binder type on the mechanical strength and durability, including freeze-thaw, salt exposure, and biodeterioration of hemp-lime concrete made of hydrated lime, hydraulic lime, portland cement, and

industrial hemp shiv (La Chanvriere De L'aube) in central France. Walker et al. (2014) determined the change in mechanical performance over a one-year period for resistance to freeze-thaw and salt exposure and over a two-year period for resistance to biodeterioration.

Walker et al. (2014) report that typical compressive strength for 2:1 (binder:hemp by weight) ranges from 0.2 to 1.20 MPa. This study finds the compressive strength to be $0.02\sim0.04$ MPa at 5 days and $0.29\sim0.39$ MPa in one year. Hydraulic binder immersed in water after curing doubled the strength after one year. This finding suggests that the higher mixing water content is important in strength development. This study reports the flexural strength to be $0.06\sim0.13$ MPa after three months, depending on the mixture.

Walker et al. (2014) attribute the low strength level of hempcrete to the ductile behavior of hemp particles and disordered arrangement or the high porosity of the shiv. Walker et al. (2014) also report that freeze-thaw negatively affects the compressive strength of hempcrete and decreases it by up to 35%. However, Walker et al. (2014) show that mixtures with higher strength and lower water absorption properties are less influenced by the freeze-thaw effect. Suprisingly, Walker et al. (2014) report that, in some mixtures, there is 60% strength gain, which is attributed to the additional hydration. Walker et al. (2014) also find that salt exposure incurs a limited loss or increase in compressive strength due to additional hydration. No biodeterioration of inoculated micro-organisms was attributed to the insufficient nutrients or inaccessible nutrients combined with limited accessible moisture due to the hydration of the binder.

Although characterizing freeze-thaw or biodeterioration protocol in an alternative concrete mixture with bio-based aggregate is critically important, it is notable that there is no established test protocol. This area needs urgent attention for further study and development of a test protocol to promote the use of plant-based alternative materials in construction. Also, it is notable that there is an increase in strength after exposure to a freeze-thaw environment. This finding suggests that there can be a way to improve the strength of hemp-lime concrete in the temporal regions.

Chabannes et al. (2014) studied hemp-lime using commercial hemp hurd, rice husk (Biosud, Arles), hydraulic lime, and hydrated calcic lime. Chabannes et al. (2014) quantified compressive strength, thermal conductivity, and physical properties, including porosity, water absorption capacity, matrix analysis using thermogravimetric analysis (TGA). As a baseline characterization, Chabannes et al. (2014) report that rice husk mixture has a similar strength (0.33 ± 0.03 MPa) after 60 days compared to hemp concrete (0.48 ± 0.02 MPa).

A more important aspect of the Chabannes et al. (2015) study is the investigation of mechanical and thermal properties of hemp-concrete with a multi-scale finite element modeling of thermal and elastic properties of hempcrete. Chabannes et al. (2015) demonstrate that the developed approach is a useful framework that can be used in the design of mixture to achieve a target mechanical and thermal properties of hempcrete. This study compared the simulation results with macroscopic properties of hempcrete mixture and found that quantitative properties of hemp particles and lime should be further explored as the variability in these is expected to be critical.

Mazhoud et al. (2017) used hemp and clay mixture with dried and milled clay collected from a gravels production site. Materials used in this study include hemp and clay composites and hemp-stabilized clay (5% of lime binder and 5% of Portland cement). Chabannes et al. (2015) focused on the water absorption of hemp hurd, which is characterized by immersing hemp hurd in water which is relevant to the mixture but not on the environmental exposure. This study reports that the water absorption improves tensile strength from 0.021 to 0.026 MPa to 0.026 to 0.059 MPa. Similarly, this study finds that the water absorption improves the compressive strength ranges from 0.39 to 0.48 MPa to 0.47 to 0.68 MPa. The main finding of Chabannes et al. (2015) is that the stabilized clay mixture improved mechanical performances. However, considering the extra energy and process, the economic aspects should be considered. Notably, Chabannes et al. (2015) suggest additional stabilizer (Portland cement) can be replaced with rice husk or rice-husk ash. This is an important point because the use of Portland cement is one of the larger sources of CO_2 emission in construction.

Page et al. (2017) measured the capillary water absorption, mechanical strength, thermal conductivity, and shrinkage of hemp-flax composite made with 90% hemp shives and 10% flax fibers. The authors attributed the low mechanical performance to the high water absorption capacity. They also report that the addition of flax fibers improves the density and mechanical strength, which is attributed to the improved compactness of the material.

Nadezda et al. (2018) measured the compressive strength, thermal conductivity coefficient, and water absorption of the hemp composites. However, the main focus of the study of Nadezda et al. (2018) is the improvement of the mixture of hemp hurd and alternative binder of MgO-cement with chemical (NaOH, CaOH2, EDTA, Hot water boiled) and mechanical treatment (exposing to ultrasound) of hemp-hurd to improve the mechanical performance of hempcrete. This study characterized density, thermal conductivity coefficient, water-absorption behavior, and compressive strength.

Nadezda et al. (2018) report determining compressive strength of 0.90-5.75 MPa. Regarding the effect of treatment of hemp hurd, this study reports that chemical treatments hampered the mechanical strength, whereas ultrasonic treatment improved mechanical strengths. Nadezda et al. (2018) attribute the improvement of the mechanical strength of ultra-sound treated hempcrete to the hardening aspect. Again, this process should be further investigated from an economic standpoint to consider additional costs. Alternatively, these effects can be incorporated in the harvest or post-harvest processes. Overall, chemically treated hempcrete shows an improvement in the water sorption behavior, which is not necessarily a good thing. Investigation of the implication of increased water sorption capacity requires the characterization of desorption as well.

Effects of Alternative Binders and Additives

Typically, hemp hurd is mixed with lime instead of Portland cement. Especially, natural hydraulic lime is widely used in hempcrete to reduce carbon footprint. Lime cures more slowly than Portland cement, but unlike Portland cement, it absorbs CO_2 as it sets and dries. While CO_2 is generated during calcining limestone to make quick lime, once water is added to make hydrated lime, it re-absorbs 20-75% of the original CO_2 from the atmosphere as the concrete cures, a process known as the "lime cycle." Therefore, studies have focused on the effects of different lime binders on the properties and performances of hempcrete.

Nozahic et al. (2012) explored a mixture of plant-derived aggregates, i.e., hemp and sunflower stems and a pumice-lime binder. Nozahic et al. (2012) report that hemp and sunflower materials show similar morphology and mechanical performances. This study also reports that the elevated level of compaction during casting increases the compressive strength up to as high as 7.11 MPa. This finding points to the need for a study on the mixture design in terms of workability and construction method, which will aid with introducing additional compaction to the structure under construction.

Arizzi et al. (2015) studied the hygric behavior of hempcrete composite because the elevated ability to absorb water may negatively affect the long-term durability of a structure. Arizzi et al. (2015) report that hemp-natural hydraulic lime mixtures lower water absorption, although they exhibit higher transpirability and drying rates. Nonetheless, this study reports that certain environmental conditions, e.g., dry-wet cycles and scarce ventilation, may lead to bio-decay that can be a disadvantage in building

material.

Chabannes et al. (2016) introduce processes that can improve the mechanical performances of hemp hurd and rice husk mixtures with a lime-based binder. These processes include a lime-water treatment before adding plant aggregates into the mix and exposing materials to the moist curing and elevated temperature. The former improved the compressive strength of the hemp concrete while the latter improved the strength of hydraulic lime mortar but negatively influenced the mechanical performances of plant aggregates resulting in unchanged or lower mechanical performances of the plant-based concretes overall.

Diquélou et al. (2016) characterize the less than optimal binding between the surface of hemp particles and hydraulic binder, e.g., lime. The authors find that setting delay is caused by the moisture trapped in the hemp particles. Most importantly, Diquélou et al. (2016) report that a high specific surface area of lime improves the mechanical performance by improving the level of hydration of lime. This study demonstrates an important aspect of hempcrete mixtures that should be further investigated in increasing the mechanical performance of hemp-based concrete.

Williams et al. (2016a) study provide a crucial quantitative improvement in the internal structure of the bio-aggregate, which reveals the structural aspect of the hemp-concrete, as well as the pore structure, paving the way to studies on optimizing the performance of bio-based, concretes, which are renewable and help with lowering the carbon emission. Williams et al. (2016a) use the digital visual imaging of sectioned samples and computer tomography scanning of aggregate. Automatic segregation was developed and used to identify the hemp particles' dimensions and arrangements. Williams et al. (2016a) touch on a very important aspect of the mechanics of bio-based materials, which is the anisotropy and variation. By using automated image analysis, these two challenging properties can be quantified and further connected to the subsequent studies on the properties of hempcrete or other bio-based concrete. Relation of the observed anisotropy to other properties is also reported in Williams et al. (2016b).

Along the same line, Williams et al. (2016b) report that the elevating binder ratio increases thermal conductivity and flexural strength. Notably, Williams et al. (2016b) report that the effect of median length of particles not to be significant on the physical properties of hempcrete samples. More importantly, this study reports that the uniformity of hemp particle size has an advantageous effect on mechanical properties. This finding signifies that the potential importance of post-harvest processes of hemp or hemp hurd with the intention of use in hempcrete.

Williams et al. (2018) show the influence of anisotropy on physical properties and compressive behavior. The authors also show that the additional compaction improves the mechanical performance but with lower thermal resistance. This study also suggests that the alignment of hemp hurd or any other biomass aggregates has a fundamental effect on the mechanical and thermal behavior of hemp-based concrete.

Lawan et al. (2018) aim to improve the durability of hemp in cement composites by chemically treating (alkaline copper quaternary type D) hemp twine followed by inducing coats with paraffin wax, epoxy acrylate, and waste engine oil, respectively. These treatments inhibit the water absorption capacity of hemp twine and therefore improving hemp's resistance to the degradation by micro-organisms. All three treatments show some improvement in the mechanical performances and reduced the water absorption of the hemp twine significantly. It is notable that the tensile strength and modulus of hemp twine are approximately 400 MPa and 16 GPa, approximately. It is apparent that hemp has great potential as an alternative aggregate, especially for structural elements under tension. This study did not show the compressive properties of hemp twine or any of the mechanical performances of hemp-based concrete.

Niyigena et al. (2018) highlighted the large specific surface area of shiv as the source of weak binder-aggregate bonding. In the classification of hemp shiv samples, properties examined include bulk density, initial water content, final water content after 48 h of immersion, mean particle surface (area), mass of particle, length, width, elongation, and feret diameter.

Although the mean particle surface area includes information on the bulk structure, particle density or porosity can be further investigated to improve the findings of Niyigena et al. (2018). Moreover, the intensity of milling is assumed to have significant effects on the surface characteristics and the particle size distribution, which determines the mean specific surface area. These should be further investigated to quantify the effects of physical properties of hemp particles' on the performances of hemp-based concrete.

It should be noted that the compression strength reported in Niyigena et al. (2018) ranges between 0.2 and 1.1 MPa. This result demonstrates the limit and range of expected compressive strength of hempcrete, which should be further improved for hemp-concrete to be used as a load-bearing element of structures.

CONCLUSION

Industrial hemp is a promising plant that can be processed as a bio-based aggregate. In addition to the outstanding carbon-sequestering capability, industrial hemp stalk offers high tensile stiffness and strength. However, when the woody core part of the hemp stalk is milled and used as a plant-based aggregate, the mechanical performance of hempcrete is poor. On the other hand, because of its outstanding thermal and hygroscopic properties as a construction material, hempcrete has been more widely used and studied in countries where the growth hemp is legal.

There have been many studies on the characterization and improvement of mechanical, thermal, and hygroscopic properties of hempcrete. As the U.S. has also recently legalized the cultivation of hemp, it is expected that the use of industrial hemp to grow rapidly. The successful adaptation of hempcrete to the residential building construction practices will create a new market demand for hemp and hempcrete as a construction material. Furthermore, by replacing some of the existing materials in select applications for reinforced concrete structures with materials of agricultural origin, the adoption of hempcrete will contribute to promoting the sustainability of society with positive impacts on the economic opportunities of farmers and the environment.

From existing studies, it is evident that improved mechanical performance is one of the most critical technological challenges in promoting the adaptation of hempcrete. This review highlights existing efforts in characterizing and improving the performances of hempcrete. Especially, many studies focus on improving the low mechanical strength of hempcrete (Table 1). We believe that this review identifies multiple possibilities for improving the performance of hempcrete.

On the other hand, we found that the limited studies have been conducted on the longterm durability of hempcrete, especially regarding the interactions between hemp aggregates and binder. Further, being biological material, hemp aggregate can degrade over time. There exist annecdotal claims on the protective environment of lime-binder mixture due to high acidity and low mositure content during mixing and curing. However, there is limited quantitative studies on long-term degradation of hemp aggregate. Therefore, in addition to improving mechanical and environmental performances of hempcrete, studies on the long-term durability and degradation of hempcrete are needed for hempcrete to be adopted as a green construction material.

Authors and Year	Reported Compression Strength	Remarks
Elfordy et al. 2008	0.06 ~ 1.20 MPa	
Hirst et al. 2010	0.2 ~ 1.20 MPa	
Nozahic et al. 2012	7.11 MPa	Elevated compaction during pouring
Chabannes et al. 2014	$0.48 \pm 0.03 \text{ MPa}$	60 days curing
Walker et al. 2014	0.29 ~ 0.39 MPa	1 year curing
Chabannes et al. 2015	0.47 ~ 0.68 MPa	Submarged curing
Nadezda Stevulova et al. 2018	0.9 ~ 5.75 MPa	Chemically treated hemp hurd before mixing
Niyigena et al. 2018	0.2 ~ 1.1 MPa	

Table 1	Summary	of reported	compressive	strenght o	f hemncrete
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References

Arizzi, Anna, Monika Brümmer, Inés Martín-Sanchez, Giuseppe Cultrone, and Heather Viles. 2015. "The Influence of the Type of Lime on the Hygric Behaviour and Bio-Receptivity of Hemp Lime Composites Used for Rendering Applications in Sustainable New Construction and Repair Works." *PLoS One; San Francisco* 10 (5): e0125520.

http://dx.doi.org.ezaccess.libraries.psu.edu/10.1371/journal.pone.0125520.

- Chabannes, Morgan, Jean-Charles Bénézet, Laurent Clerc, and Eric Garcia-Diaz. 2014. "Use of Raw Rice Husk as Natural Aggregate in a Lightweight Insulating Concrete: An Innovative Application." *Construction and Building Materials* 70 (November): 428–38. https://doi.org/10.1016/j.conbuildmat.2014.07.025.
- Chabannes, Morgan, Eric Garcia-Diaz, Laurent Clerc, and Jean-Charles Bénézet. 2015. "Studying the Hardening and Mechanical Performances of Rice Husk and Hemp-Based Building Materials Cured under Natural and Accelerated Carbonation." *Construction and Building Materials* 94 (September): 105–15. https://doi.org/10.1016/j.conbuildmat.2015.06.032.
 - 2016. "Effect of Curing Conditions and Ca(O.H.)2-Treated Aggregates on Mechanical Properties of Rice Husk and Hemp Concretes Using a Lime-Based Binder." *Construction and Building Materials* 102 (January): 821–33. https://doi.org/10.1016/j.conbuildmat.2015.10.206.
- Diquélou, Youen, Etienne Gourlay, Laurent Arnaud, and Bernard Kurek. 2016. "Influence of Binder Characteristics on the Setting and Hardening of Hemp Lightweight Concrete." *Construction and Building Materials* 112 (June): 506–17. https://doi.org/10.1016/j.conbuildmat.2016.02.138.
- Elfordy, S., F. Lucas, F. Tancret, Y. Scudeller, and L. Goudet. 2008. "Mechanical and Thermal Properties of Lime and Hemp Concrete ('Hempcrete') Manufactured by a Projection Process." *Construction and Building Materials* 22 (10): 2116–23. https://doi.org/10.1016/j.conbuildmat.2007.07.016.
- Green Home Gnome. 2017. "6 Advantages of Building With Hempcrete." *Green Home Gnome* (blog). June 29, 2017. https://www.greenhomegnome.com/advantages-building-hempcrete/.
- Hirst, Edward AJ, Peter Walker, Kevin A Paine, and Tim Yates. 2010. "Characterisation

of Low Density Hemp-Lime Composite Building Materials under Compression Loading." In , 11. Italy.

- —. n.d. "Characterisation of Low Density Hemp-Lime Composite Building Materials under Compression Loading," 11.
- Juntaro, Julasak, Marion Pommet, Athanasios Mantalaris, Milo Shaffer, and Alexander Bismarck. 2007. "Nanocellulose Enhanced Interfaces in Truly Green Unidirectional Fibre Reinforced Composites." *Composite Interfaces* 14 (7–9): 753–62. https://doi.org/10.1163/156855407782106573.
- Lawan, Ibrahim, Li Qiang, Weiming Zhou, Jia Yi, Jianbin Song, Mingxin Zhang, Zhaohui Huang, Jie Pang, and Zhanhui Yuan. 2018. "Modifications of Hemp Twine for Use as a Fiber in Cement Composite: Effects of Hybrid Treatments." *Cellulose* 25 (3): 2009–20. https://doi.org/10.1007/s10570-018-1668-8.
- Mazhoud, Brahim, Florence Collet, Sylvie Pretot, and Christophe Lanos. 2017. "Mechanical Properties of Hemp-Clay and Hemp Stabilized Clay Composites." *Construction and Building Materials* 155 (November): 1126–37. https://doi.org/10.1016/j.conbuildmat.2017.08.121.
- Nadezda Števulova, Julia Cigasova, Ivana Schwarzova, Alena Sicakova, and Jozef Junak. 2018. "Sustainable Bio-Aggregate-Based Composites Containing Hemp Hurds and Alternative Binder." *Buildings* 8 (2): 25. https://doi.org/10.3390/buildings8020025.
- Niyigena, César, Sofiane Amziane, and Alaa Chateauneuf. 2018. "Multicriteria Analysis Demonstrating the Impact of Shiv on the Properties of Hemp Concrete." *Construction and Building Materials* 160 (January): 211–22. https://doi.org/10.1016/j.conbuildmat.2017.11.026.
- Nozahic, V., S. Amziane, G. Torrent, K. Saïdi, and H. De Baynast. 2012. "Design of Green Concrete Made of Plant-Derived Aggregates and a Pumice–Lime Binder." *Cement and Concrete Composites* 34 (2): 231–41. https://doi.org/10.1016/j.cemconcomp.2011.09.002.
- Page, J., M. Sonebi, and S. Amziane. 2017. "Design and Multi-Physical Properties of a New Hybrid Hemp-Flax Composite Material." *Construction and Building Materials* 139 (May): 502–12. https://doi.org/10.1016/j.conbuildmat.2016.12.037.
- Popescu, Adam. 2018. "There's No Place Like Home, Especially If It's Made of Hemp." *The New York Times*, January 29, 2018, sec. Science. https://www.nytimes.com/2018/01/29/science/hemp-homes-cannabis.html.
- Stevulova, N., L. Kidalova, J. Cigasova, J. Junak, A. Sicakova, and E. Terpakova. 2013. "Lightweight Composites Containing Hemp Hurds,." In *Procedia Engineering*, 65:69–74.
- Tradical Hempcrete. 2019. "Tradical Hempcrete." 2019. http://www.americanlimetec.com/tradical-hemcrete.
- Walker, R., S. Pavia, and R. Mitchell. 2014. "Mechanical Properties and Durability of Hemp-lime Concretes,." *Construction and Building Materials* 61: 340–48.
- Williams, Joseph, Mike Lawrence, and Pete Walker. 2016a. "A Method for the Assessment of the Internal Structure of Bio-Aggregate Concretes." Construction and Building Materials 116 (July): 45–51. https://doi.org/10.1016/j.conbuildmat.2016.04.088.
- 2016b. "The Influence of the Casting Process on the Internal Structure and Physical Properties of Hemp-Lime." *Materials and Structures* 50 (2): 108. https://doi.org/10.1617/s11527-016-0976-4.
 - ——. 2018. "The Influence of Constituents on the Properties of the Bio-Aggregate Composite Hemp-Lime." *Construction and Building Materials* 159 (January): 9– 17. https://doi.org/10.1016/j.conbuildmat.2017.10.109.

A Multi-manufacturer Platform Approach to Modular Volumetric Construction – An Experiment in Cross-pollinating Design and Fabrication¹

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Abstract

A design platform or a platform approach to DfMA (design for manufacturing and assembly) is a product design and production concept. Common in automobile manufacturing and first applied by General Motors¹ (Nutt, 2017), a platform outlines a structural or modular framework among several differentiated products made from the same basic dimensions, components, sub-assemblies or parts. Broadened during the twentieth century, all manufacturers deployed and shared platforms. The Ford Escape and the Mazda Tribute were both based on the Ford CD2 platform in the early 2000s, pooling resources in matters of research, development and production optimization. In architecture and construction, a similar idea was arguably first articulated by Albert Farwell Bemis (The Evolving House, 1933) and conveyed even earlier by Walter Gropius' kit-of-parts concept in 1909 (Gilbert, 1984); Both proposed multiple design variants from a small number of standardized and coordinated elements. In 2004, architects Kieran and Timberlake published an important manifesto *Refabricating* Architecture that reaffirmed the potential of applying industrial methodologies used for making automobiles, airplanes and ships in building construction. Powered by new digital modeling and fabrication potentials, the DfMA platform concept is being studied and endorsed by well known protagonists, Bryden Wood, Project FROG, Z modular and many others as an integrated digital project delivery strategy for harmonizing design, fabrication, procurement and construction. The present research explores an opportunity to examine platforms as centralized logistical data sets for multiple fabricators to pool their collective infrastructure toward scaling their individual production capacities. A type of open-source approach is described to cross-pollinate software and hardware into a collective integrated modular design ecosystem. Explored with a group of manufacturers in Canada, the platform approach can also be seen as a way forward for a fragmented building industry to collectively harmonize products, processes and supply chains toward greater efficiencies and a better built environment.

Context

Leveraging three previous research projects mandated by the SHQ (Québec's Housing Authority)², this current research, funded through an industrial research grant, involves local manufacturers, a trade association (QWEB – Quebec Wood Export Bureau) and a

¹ The A platform was employed from 1923 - 1959

² Three reports :

¹⁻ Neuf cas d'intégration de systèmes de construction préfabriqués available at -<u>https://www.dropbox.com/s/99y28hv7he7mq02/Rapport%20final.pdf?dl=0</u>;

^{2- 2-} Préfabrication : Un argumentaire pour un Wikiprefab Québec available at https://drive.google.com/file/d/0B5Te_qsSnKzpWG9KTjdMS0EzZWc/view?resourcekey=0-GCDgrhajPjgCV-GekaCv4A ;

^{3- 3-} Noyaux de services, panneaux muraux et kits de construction intégrés, trois manières de voir l'évolution de l'industrie du bâtiment préfabriqué available at https://drive.google.com/file/d/1NNplPyPaSUQeRoZDxREcy2nM7yEcFKWx/view

manufacturing consultancy firm all brought together through the objective of outlining and proposing a common DfMA platform to scale, harmonize and increase competitiveness for light-frame volumetric modular producers in Québec, Canada.

The off-site construction industry in Québec is not considerably different from the industry in North America as a whole; it is composed of a majority of small light wood frame producers. About 90% are delivering modular volumetric or panelized stick-built systems assembled in a factory in much the same way they are assembled on onsite. Single-family dwellings have dictated the market for the longest time. However, as both local demand has turned to multi-unit residential and international competition has entered the market, producers, their associations and governments are taking note and organizing policy to increase industrialized construction, assist local producers to focus their efforts and educate the industry toward automation to increase efficiencies and competitiveness.

Platforms in architecture and construction

In the off-site construction sector, or more precisely in its present theorization, the term platform refers to hardware (a common structure or elemental organization) or software (coordinated information and data sets). In construction in general, platforms also represent building systems, supporting frames or loadbearing scaffolds for carrying an arrangement of elements or spaces. Combining these definitions from theory and practice the term platform suggests a coordinated configuration that can be composed of physical or virtual chunks that define a standardized way of managing design, parts, information, operations and logistics.

In manufacturing, a product platform communicates potential economies of scale. Sharing modular pieces among many nuanced products can reduce expenses and distribute research and development costs among several product offerings or even between cooperating manufacturers. Employed early in the twentieth century by General Motors (Nutt, 2017), the platform approach was then federated among most automotive manufacturers (Brylawski, 2017) to pool resources, penetrate unfamiliar markets or interconnect industrial potentials. This type of product conceptualization circumscribes design, fabrication and management as a coherent and repeatable course of action from model to model. Beyond the familiar platform structures in the automobile sector, a notable example of platform thinking has been applied in industry since the early 1950s: containerization. The standardized shipping container is the dimensional support structure for international transportation and logistics (Bernhofen, Daniel & El-Sahli, Zouheir & Kneller, Richard, 2016). Arguably the most standardized innovation to be accepted globally as a procedure for shipping, the container synchronizes how things are packed, stacked, delivered and organized in every industrial and economic sector.

Since the beginning of industrialization, protagonists have argued for a similar regulation, normalization and standardization to direct manufacturing efficiencies, both Fordisms and Taylorisms, toward building construction. Making things quicker, better and cheaper was successfully applied in almost every other industry save construction, which is still

mired in a very artisanal paradigm notwithstanding the mass production of every component that goes into building an edifice (doors, windows, screws, sawn lumber etc).

The tale of arguing for an efficient relationship between factory production and architecture is the subject of vast and rich narratives (Dietz, A. G. H., and Cutler, L. S., 1971; Herbert, 1984; Davies, 2005; Smith, R. E. and Quale, J. D., 2017). First inspired by Henry Ford and then years later the Toyota Manufacturing lean model paved the way for manufacturing methodologies to integrate architectural vocabulary. Even the idea and usefulness of platforms has been posited for a long time in architecture. Bemis (1933) articulated a specific vision of the building platform compared to the automobile industry through dimensional coordination of systems using a 4-inch three dimensional and interoperable matrix. Walter Gropius' expandable house (Herbert, 1984), Stelco's steel houses (Bergdoll and Christensen, 2008), Raymond Camus' concrete panel building (Camus co., 1960) and even Lustron's kit-of-parts (Bergdoll and Christensen, 2008) can be considered as historic and pioneering examples of product platforms in architecture as all proposed a variety of designs or models from modular and interoperable parts. Today, industrial principles still inspire academia and practice to continuously suggest manufacturing models to reform building construction.

In 2004, Kieran and Timberlake's manifesto *Refabricating Architecture* reaffirmed the potential for production methodologies to generate more efficient construction. Recently, pursuing similar objectives, UK firm Bryden Wood published their ideas under the title: *Platforms : bridging the gap between architecture and manufacturing* (Bryden Wood, 2017).

It can also be argued that the platform approach is already employed in architecture. Platform or balloon framing with 6 meter spans has been the principal generic support system for small-scale residential, 7.5 meter spanning steel skeletons are largely used for commercial buildings and 7 meter spanning flatslab reinforced concrete construction is a staple of high-density collective housing. These are all systemized ways of building, understood as the framework for multiple custom designed constructions defined by a set of parameters and linear or surface components. However, apart from this basic structural modularity, the building process remains archaic and highly wasteful. It is with augmenting efficiencies and reducing wastefulness that the platform approach is being explored as a method for harmonizing all building systems and construction management logistics.

Platform approach to DfMA Design for Manufacturing and Assembly

Completing the product-platform approach, DfMA is an engineering methodology (Molloy O., Tilley S. and Warman E.A., 1998) that focuses on simplifying the design of a good to optimize manufacturing and simplify assembly. Replacing the over-the-wall design and manufacturing paradigm (Bohemia, Erik & Harman, Kerry, 2008) by a collaborative design and manufacturing concept demands that architectural design principles be federated with manufacturing principles bridging two fields that have rarely interacted in an cohesive manner.

By optimizing links between design criteria and fabrication parameters, DfMA leverages both to reduce costs, increase productivity and ensure quality control. The building platform approach cross-pollinates DfMA principles with the design and construction of edifices by synchronizing on and offsite production determined by a common design framework. Beyond a common coordinated framework, adding value gained from factory production reduces the contextual pressures related to conventional construction.

Concretely, this research outlines a method for applying DfMA product development processes in practice to architecture and construction and questions if these manufacturing methodologies outline a new era for industrialized construction. Industrialized construction and prefabrication have until now been directed to commercializing standardized, made-to-stock visions or engineered-to-order procurement. DfMA production methodology remains close to prefab theory but involves a far more integrated design, production and construction process (see figure 1) involving manufacturers early in planning and in this way is completely distinct from the traditional way of producing buildings, prefabricated or not.



Figure 1 : An integrated DfMA process applied to architecture (source : Bryden Wood, 2017)

The challenge of applying DfMA principles in architecture involves spanning the conceptual distance between industrial production and architectural values. This entails a more involved, complex and twofold dissection of the «D» in the DfMA approach: The architectural «D» and the production engineering «D». Both are required for construction but implicate different fields, which are rarely harmonized during design. This «dual-D» interplay is perhaps the most notable difference, and challenge, between architecture as a systemic layering of elements and platform – DfMA as an industrial process. Industrial design production of objects and products requires fewer interactions between their parts and external values, parameters or contextual elements whereas a building's attachment to site, its non-generic design criteria, remain difficult to reconcile with industrialized production principles.

Our approach to this particular issue was first to outline similarities between building types defined from analysing government procured affordable housing in Québec and setup functional, technical and spatial criteria that would organize a streamlined design process from common characteristics; Facilitating the architectural design «D». In the same way UK firm Byden Wood analysed the spectrum of government procured buildings to construct a field of similarities in their 3 proposed frameworks (Bryden Wood, 2017). From typological and topological parameters including budget constraints, square footage criteria, site information and functional requirements it becomes possible to match-up or specify manufacturing patterns for volumes and specific functional elements like kitchens and baths with design parameters. From this analysis we devised a product platform ecosystem, an open volumetric approach, a generic structural skeleton that in terms of spatial requirements addresses the low-medium density scopes and spans ordinarily served by on-site built lightwood platform frames or concrete flat slab construction.

Four platforms for building construction

Along with adjusting manufacturing methods according to new standards, manufacturers wanted to address what they see as foreign competition and platform economies percolating the local industry. Mega companies like Amazon's Plant³, factory OS⁴ and Katerra⁵ were perceived as menaces by small and medium sized producers. A common design platform would be a lever in being able to respond to large scale RFPs. The platform approach also aimed to address the longstanding issue of competing with on-site cost structure and flexibility. Repeating a standardized volume and a regulated process would allow for increased supply while reducing unit costs; a basic principle of manufacturing.

Formed through multiple design charrettes, stakeholders worked out a basic framework, an open modular volumetric design strategy. Four business models and innovative building construction platforms inspired the approach. The four examples represent specific responses to underlying challenges that have hindered Offsite construction uptake for a long time. Each example is briefly described, identifying the conceptual canon that would inform our DfMA platform strategy.

Base 4 modular

https://www.base-4.com https://www.z-modular.com/vectorbloc/

Deploying an open volumetric approach based on Z-modular's licensed version of the Vectorbloc connector (see figure 2), Base 4 is an integrated group of architects and engineers that have developed a concept for repetitive multi-unit residential projects. The

³ https://www.plantprefab.com

⁴ <u>https://factoryos.com</u>

 $^{5 \}text{ <u>https://katerra.com</u>}$ (take note the company no longer exists and filed for bankruptcy in 2021)

modular strategy proposes the systemic separation of stacked units and their on-site built enclosure making it possible to develop bespoke buildings from standardized boxes. The standard volume unit - a type of normalized container structure is the basic building block synchronizing things like material procurement, dimensional coordination and site assembly as tolerances are rigorously controlled in the factory. This type of modular standardization is a basic requirement for multiple manufacturers to build coordinated units delivered from different factories to one building site to be set in position and assembled as if fabricated by one integrated company.



Figure 2: Vectorbloc Module (source : Modular Building Units and Methods of Constructing and Transporting the Same. US Patent 9 458 619)

Bryden Wood

https://www.brydenwood.co.uk

The strategies described in *Platforms : Bridging the Gap Between Architecture and Manufacturing* (Bryden Wood, 2017) develop many ideas regarding platform theory in architecture from mass procurement to outlining government mandated buildings and using a DfMA approach to facilitate a streamlined relationship from design to construction.

The platform approach specified by Bryden Wood is focused on examining common traits of government procured buildings. Traits include spans, heights and room sizes. From these shared characteristics, building sub-assemblies can be adapted to structure and fit-out a diversity of buildings. Three particular platforms are described: small span residential, large span factory for hangar structures and medium span commercial structures. This methodology devises and coordinates simplified data sets and instructions for designing and producing similar building types.

Bryden Wood's kit-of-parts inspiration has particular resonance for our current research. In lieu of absolute volumetric modularity, which seems to be the current state of the art approach, the firm argues for a type of Ikea methodology, making a varied number of objects or products from a controlled number of intelligible and intelligent parts. Further this type of parts library is discussed as a strategy where data and documentation is seamlessly integrated between designers, manufactures and on-site logistics through Building Information Modeling. In the multi-producer space, this type of kit approach could be used to harmonize supply chains upstream of manufacturing to develop a type of standard «modular kit» that could be distributed between manufacturers who could then assemble the same exact volume in different facilities potentially servicing greater demand.

Sekisui Heim

https://www.sekisuichemical.com/about/outline/segment/housing/unit/

A key player in the off-site construction space for decades, Japanese manufacturer Sekisui Heim has been building prefab houses since 1971. Their Sekisui Heim M1 prototype, employed a rudimentary volumetric unit, a chassis or a basic rectangular skeletal steel structure (2.4 x 4.8 x 2.4 m) stacked, aligned and juxtaposed to develop singular massings. Linked to the tradition of modularity in Japanese building culture, Sekisui's chassis is the closest example of how a platform relates to architecture based on an analogous methodology used in the automobile industry. Today, Sekisui's chassis is available in sixty different spatial configurations making a great variety of housing designs possible. The company also developed factory made ceramic skins and weatherstripping to stitch the boxes together on site that closely mimics the type of joints and joinery that is used in automobile industry.

Project FROG

https://www.projectfrog.com

California company Project FROG founded in 2006 proposes an idealized stakeholder that bridges the ever-extending gap and entanglement between designers, fabricators and builders. A middleman between design and construction, FROG produces and supplies project specific kits coordinated through their modular design system. Designers virtually assemble projects from the company's parts database, a platform ecosystem⁶, using standardized elements and detailing to facilitate design and mitigate risk. This risk mitigation is then conveyed on-site as builders simply assemble kits that have in a sense been pre-validated through DfMA for the architecture and construction process.

Open volumetric modular and six focuses of a multi-user platform

Base4 and Sekisui share a volumetric foundation that complemented by Bryden Wood's kit-of-parts methodology and Project FROG's virtual design catalogue frame an *open volumetric modular* approach outlined by a generic modular unit. This approach is not a new one. Laurence Stephan Cutler and Sherrie Stephens Cutler (1974) proposed three versions of a modular system: A light timber frame, a light gauge steel and a precast hollow core slab and wall system. The basic unit was a modular coordinated box that when juxtaposed created either a linear bearing wall system, a post and beam or a panelized wall and slab system. In a similar way, The Vectorbloc connector invented by Julian Bowron (2016) uses a licensing agreement can be shared between multiple

⁶ see Kit Connect process diagram at <u>https://www.projectfrog.com/kitconnect</u>

producers to achieve a type of homogeneous box unit limited in scalability only to the number of producers involved.

From this general strategy of an open volumetric construction ecosystem we projected six key components to harmonize manufacturers onto a common production strategy.

1. Platform modularity

A prerequisite for both variability and standardization, dimensional coordination frames and outlines interoperability among manufacturers. A shared set of parameters to fabricate, connect and stack boxes is the starting point for a multi-user platform approach to modular construction. Along with the habitual volumetric transport constraints, we developed 4 x 4 foot-grid based-on 8-inch increments controlling dimensional tolerances and quality control. The grids multiplied or divided into numerical allotments inform material choices, arrange elements and define their positioning. A vertical grid is divided from volume height dictating floor to floor dimensions, which makes it possible to standardize things like stairs and other accessories. Strict dimensional coordination also systemizes procurement, delivery, and assembly and is arguably the first and fundamental step toward a multi-user platform approach in architecture (see figure 3).



2. Platform sub-assemblies

From the grid, the primary idea of dimensional interoperability, a subassembly matrix of preset mechanical openings and networks facilitate architectural flexibility. The predetermined areas for horizontal and vertical ducts and chases arrange positions for wet cores and services cores anywhere in a basic 3.6 m by 6 m. volume. Bathroom pods, kitchen pods and other subassemblies based on the same modular grid could be slipped into or removed from the system as required without affecting the underlining superstructure (see figure 3). This layering of elements is also part of an overall provision for systemic adaptability and evolution.

3. Platform customization

Adaptability and flexibility are functions of customization or more correctly mass customization. All three concepts relate to sequencing a diversity of possibilities from predetermined rules presenting consumers with a range of choices or options. Here again the open volumetric modular elemental unit can be adapted in length or width within the established grid. The basic dimensional and sub-assembly framework are programmed into an Open BIM format. A library of data sets (see figure 4), elements, and nested families are the cloud objects that facilitate design, fabrication and specification. In this way multiple hierarchies of customization are possible. For architectural design, the predetermined components translate a modular variability that is programmed to respond to stacking, juxtaposing and clustering of boxes according to preset criteria for walls, floors or any other architectural determinant. For manufacturers, the same database contains parameters and a streamlined potential for generating shop drawings with CAM software compatibility. At still another level, BIM objects facilitate architectural specification as they are set-up for programmed individualization for fitting, combinations or for performance. For instance, catalogued designs for bathroom pods, kitchen pods and combo-pods could propose adjustable dimensions, finishes but also for wall types and could also integrate different compositions. For example, material choices could be adjusted according to if a pod is against a firewall or a regular interior wall.



Figure 4: Object process organisation (source : author)

4. Platform supply chain management

The multi-manufacturer network charged with operating the platform demands a masterful control of supply chains from procurement to distribution. The construction consolidation center model, a pilot project deployed in London in 2005-2007 (Transport for London, 2008), was examined to facilitate servicing multiple projects from centralized locations. A consolidation center services multiple projects through centralized logistics and just-in-time delivery (Department of Trade and Industry, 2004). Combining the general contractor model habitually related to construction with the integrator model familiar with automobile manufacturing, the multi-manufacturer model requires a centralized control center synchronizing supply of products and components supporting commercial prognoses to identify demand and harmonize onsite and offsite relationships. Building Information Modeling becomes a central part of supply chain regulation as parts and schedules are controlled in a centralized virtual model assuring

continuous task management and distribution.

5. Platform distribution

As the research is ongoing many elements are still in development. Our process compared two versions of how the platform would be distributed. On the one hand we argued for an open source approach to intellectual property delineated by a Creative Commons framework where any manufacturer could structure their personal streamlined process according to shared development tools established by the platform designs and criteria. This option requires a centralized regulator who would deal with umbrella issues and updating or maintaining the platform, both from hardware and software perspectives. On the other hand a centralized platform owner could offer a unified control, licensing the platform to any manufacturer who wishes to be part of the multi-user network. These issues regarding intellectual property are still in discussion along with the implications for each participating partner.

6. Virtual design and construction

Normalized documents, integrated product delivery and a tool for virtual design and construction are the three Information-based tools for ensuring a streamlined process from design to construction. One of the major hurdles manufacturers deal with integrating manufacturing with onsite construction is the lack of clear documents, details, task distribution and responsibility allocation that leads to difficult coordination with cost and timeline overruns. A BIM based object catalogue and coordination tool will directly link design models, with CAM software, to quantity takeoffs and operate on site management of supply chain and assembly logistics. The Québec Wood Export Bureau has been developing this type of software integration for Offsite timber construction⁷. Virtual Design and Constuction regulates the platform approach to DfMA by integrating all project decisions into digital content shaping a coherent thread from design to fabrication, assembly, construction and operation.

Conclusion

In regards to our model specifically, the first simulation of a complete DfMA platform will be published in the summer of 2022) with the release of a modular on-line design tool. This application will offer a configurator for architects to design volumetric modular projects according to preset data sets based on design, manufacturing and procurement criteria. This step toward a DfMA platform approach is also currently being compared to a similar baseline project using a conventional construction process to further study questions of costs, supply chains and to circumscribe further research and development on the topic.

One of the most important questions in regards to applying industrialization in construction remains the high level of customization required by owners and demanded

⁷ see the Offsite wood plugin

https://apps.autodesk.com/RVT/fr/Detail/Index?id=2282574255824847612&appLang=en&os=Win64

by architects. Singularity and uniqueness are the core elements of architectural design and have often challenged a streamlined manufacturing approach. In conventional construction, even though each project repeats the use of standardized components there is a perceived sense of originality impeding greater levels of prefabrication. So, what is changing? Increasing digitization and information technologies are disrupting old paradigms and are bringing the architect closer to the manufacturer. Architectural design in a DfMA platform setting can lead to uniqueness but composed of preset DfMA pieces.

It remains to be seen if this new era of digitally driven modularity will bare an increased and sustainable uptake in Offsite construction. Issues of reduced manpower supply and declining trades are probably for the first time so acute that even conventional builders, usually against this type of strategy, will be looking for solutions to build more efficiently. Further, attaining goals such as reducing carbon emissions while responding to increased urbanization imply a necessary search for methodologies that are more productive and sustainable.

References

Bemis, A.F. (1933) *The Evolving House, Volume III: Rational Design*. Cambridge. Massachusetts Institute of Technology Press.

Bergdoll, B. & Christensen P. (2008). *Home Delivery. Fabricating the Modern Dwelling*. Moma, New York.

Bernhofen, D. & El-Sahli, Z. & Kneller, R. (2016). *Estimating the Effects of the Container Revolution on World Trade*. Journal of International Economics. 10.1016/j.jinteco.2015.09.001.

Bohemia, Erik & Harman, Kerry. (2008). *Globalization and Product Design Education: The Global Studio*. Design Management Journal. 3. 53 - 68.

Bowron, J.(2016). *Modular Building Units and Methods of Constructing and Transporting the Same*. US Patent 9 458 619

Bryden Wood. (2018) *Platforms: Bridging the gap between construction and manufacturing*. Construction innovation hub. accessed <u>https://www.cdbb.cam.ac.uk/files/platforms_bridging_the_gap_small.pdf</u> August 10, 2021

Brylawski, M. (2017). Uncommon Knowledge : Automotive Platform Sharing's Potential Impact on Advanced Technologies. Hypercar, Inc. Accessed <u>https://rmi.org/wp-content/uploads/2017/05/RMI_Document_Repository_Public-Reprts_T99-10_UncommonKnwldg.pdf</u> August 10, 2021

Camus cie. (1960) *Les procédés industriels de construction Camus*. Athens, conférence Centre de recherche pour le développement de l'industrialisation de la construction

Cutler L.S. and Cutler S.S. (1974). *Handbook of Housing Systems for designers and developers*. New York. Van Nostrand Reinhold Company.

Davies, C. (2005) The Prefabricated House. London. Reaktion Books.

Department of Trade and Industry, and alt. (2004). Construction Logistics Consolidation Centres: An examination of new supply chain techniques – managing and handling construction materials, Executive

Summary Report. Constructing Excellence. Accessed

http://www.constructingexcellence.org.uk/zones/logisticszone/downloads/dti_executi ve_summary.pdf August 10

Dietz, A. G. H., and Cutler, L. S. (1971). *Industrialized building systems for housing*. Cambridge. MIT Press.

Herbert, G. (1984) *Dream of the Factory-Made House: Walter Gropius and Konrad Wachsmann*. Cambridge. MIT Press.

Kieran, S. and Timberlake, J. (2004). *Refabricating architecture: How manufacturing methodologies are poised to transform building construction*. New York. McGraw-Hill.

Molloy O., Tilley S. and Warman E.A. (1998). Design for Manufacturing and Assembly, concepts, architecture and implementation. Springer-Science + Business Media.

Nutt, J. (2017). *Different GM Body Platforms and What They Mean*. 1A Auto Blog. Accessed https://blog.laauto.com/letter-general-motors-body-styles-mean/ August 10, 2021

Smith, R. E. and Quale, J. D. (2017). *Offsite Architecture: Constructing the Future*. New York. Taylor & Francis.

Transport For London (2008) *London Construction Consolidation Centre*. Accessed from https://www.ndslogistik.se/files/reports/1425975813 9.pdf on August 10, 2021

Design Grammar of Scaffold-Free 3D Printed Shells

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ABSTRACT

The construction of large-scale structures through additive manufacturing methods have been abundantly addressed by researchers from engineering disciplines with focus on rheological and mechanical issues and their interrelationship with achieving shape accuracy while 3D printing concrete structures. However, the designers have had fewer opportunities to share their investigations in this realm regarding aesthetics and design functionality. The design of 3D printed shells must intrinsically address the mechanics of structures and technological constraints during design computing and construction process. Scaffold-free 3D printing (SF3DP) of shells using ancient masons' accumulated knowledge and methods opens broad solutions for fabrication-aware design thinking. Formerly the form-finding investigation for SFP of shells with quadrilateral boundaries is studied in (Motamedi et al. 2020). This paper expands the form-finding investigation range for SF3DP of shells to almost any boundary configuration. The design grammar called Patching technique is introduced to make possible fabrication-aware design thinking in SFP. Patching technique is applicable to any form of 3D Printing in terms of material choice as long as there is a possibility for printing interruptions considering 3D Printing setup capability. Using Patching technique users can explore more ambitious forms in 3D Printing thanks to step-wise printing system. This technique uses the computer graphics numerical tools to analyze the configuration of shapes and decomposes them topologically. We demonstrate through several examples the outcomes and solutions given by the Patching technique. This technique enables designers to explore printable forms by enhancing the geometries for structural performance

for their proposed boundaries with the chosen printing-mortar-paste. The advantages of using Patching form-finding techniques are as follows:

- The patching technique applies to almost any boundary condition.
- It provides the information on the tool-path direction and slicing method.
- It offers various options of forms' decomposition, while facilitating an iterative process of studying, evaluating, and as such enabling the designer to make informed decisions to arrive at acceptable design and structural solution.
- It provides a flexible design space to designers for geometrical exploration and tool-paths options.
- The use of design grammar allows the designers to be more involved in design-thinking and decision making, in comparison with form-finding methods where objects are able to define themselves relying only on structure and loads with minimal input from the designer.
- The Patching techniques proves that it is possible to print ambitious forms with complex geometries and long spans using no temporary supports and even with material with low reliability if done step-wisely.

Keywords Scaffold-Free 3D printing, Step-Wise 3D Printing, Compression Shells, Large-scale 3D Printing, Form-Finding, Topology Design

INTRODUCTION

Is this possible to 3D Print an entire shell using nothing but printing mortar? Nowadays, construction is one of the most wasteful industries and one of the main contributors to climate change. The concrete structures consume considerable material as form-work and produce the same amount as construction waste, filling up the landfills. In addition, the convention methods of construction are labor-intensive. Traditionally in arid areas, the masons were used to build habitats and shells using nothing but adobe. Due to the lack of wood resources, they had to invent methods and techniques to make the roofs of the buildings without using pallets or any temporary supports. Additive manufacturing has been well-established as a construction method in recent years, at least in developed countries. Several well-known advantages of additive manufacturing are as follow:

- Using material wisely by topological optimization, consecutively reduce the volume of used material in a structure.
- The possibility of automation in construction significantly reduces the in-site workers and drafters.
- Precision, rapidity, and ability to fabricate complex designs.

The current construction sector leverages additive manufacturing and benefits the 3D Printing features by fabricating only vertical elements such as walls and columns. However, when it comes to roofs or openings, the form-works and supports are still in use, making the construction wasteful in material consumption and less automotive.

Research background and parallel works

Most of the material used in a building lies in roofs and slabs rather than walls and columns (De Wolf et al. 2016). The attempts for devising solutions for efficient fabrication of buildings using additive manufacturing can be categorized as below:

- Researches based on efficient distribution of the material in building elements through topological optimization.
- Researches that study the solution of omitting scaffolds in the 3D printing process or using stay in place form works in 3D Printed structures.

There are researches that studies the possibility of reducing material in building elements specially roofs and slabs through topological optimization such as (Vantyghem et al. 2020) and (Jipa et al. 2016). Some researchers study the possibility of reducing material in building elements, especially roofs and slabs, through topological optimization such as (Vantyghem et al. 2020) and (Jipa et al. 2016). Some researches such as (Motamedi et al. 2021) (Curth et al. 2021) (Rodiftsis 2020) (Duarte et al. 2021) had studied the possibility of 3D Printing cantilevers without using temporary supports by inspiration from ancient vaulting techniques. However, the design is restricted to a single element, such as dome and barrel vaults with circular and rectangular bases. There is a gap for a reliable design tool that can combine design and structural necessities in a dynamic platform that can offer numerous solutions for design and fabrication.

Research Objectives

The main objectives of this research are as follow:

- Introducing the Patching Grammar as a design tool for SC3DP of the shells.
- Proposing the multi-vaults as solution for covering long spans with SF3DP method step-wisely.
- Proposing the new design tools where designers can it intuitively rather than going through the blind process of form-finding tools.

In this paper first, the Patching grammar and its' rules and terms are defined. Second, two methods of design using the Patching grammar is introduces through three examples.

PATCHING DESIGN GRAMMAR

Rule-based design applies to topological modification based on a set of rules within a grammar. The Patching design grammar provides the designers with the sets of rules to cover the spans of boundaries with multi-vaults. The rules are inspired by the ancient vaulting techniques with no form-work. Figure 1 shows the elements of a multi-vault. Below, terms Rule,Layer,Patch,Multi-Vault and Patching are defined which we will adopt to explain the patching grammar. The objectives of this research are as follow:

- Introducing Patching Grammar as design tool for 3D Printing of Multi-vaults without temporary supports.
- Defining the multi-vaults as mean to cover long spans step-wisely.
- Designers can use patching grammar as a tool for intuitive design rather than using it as a form-finding tool with blind process.



Fig. 1. The components of a multi-vault

- **Rule:** Rules in Patching grammar are the sets of the patches that are defined by their supports types. The users can define the rules by combining different support types. However, the primary rules are defined based on the ancient vaulting elements such as squinches and pendentives.
- **Layer:** The layer is a substrate formed by the extruded material from the nozzle head during printing.
- Patch: A patch is a 3D-Printed domain where a layer is continuously printed.
- Multi-Vault: Multi-vaults are vaults that are composed of several patches.
- **Patching:** There are two main definitions for patching:
 - 1. The process of covering a boundary with the aggregation of several patches.
 - 2. The process of splitting a geometry into several pieces and convert them into patches.

This paper first introduces the Patching grammar and its' rules and terms. Second it introduces two discreet methods for designing the multi-vaults using Patching grammar through examples. Finally it briefly describes the challenges and experiences in 3D Printing of a multi-vault with three patches using Kaolin clay.

Patching Grammar Rules

Now that we have defined the necessary terms to describe the Patching Grammar, we can present the rules. The rules encapsulate the information of the patches. This information is related to the patches' supports and printing direction. The designers can embed these rules within the parametric form-finding tools to design multi-vaults. Figure 2 shows the different types of supports for the patches. There are two main types of supports for the patches.

- 1. **Ground Support :** The continues red lines in Fig 3 stands for ground support. The ground support is the intersection of a patch with the patch's base.
- 2. **Patch Support :** The purple dashed line in Fig 3 stands for the patch support. The patch support is the intersection of the patch with other patches.

The rules are given labels based on their type, supports condition and print direction. Each label has four letters of R, S, C and P. R stands for the Rule, S stands for the support, C stands for the configuration of support and P stands for the Pole's position. Poles are the specific types of singularities in meshes that are adjacent to triangle face



Fig. 2. Support types for the patches

(Pseudo quads) (Oval et al. 2019). The poles define the printing direction of patches by the topological design of Patches meshes with quad topology in 2D. We classify the rules into two classes.

- 1. Primary Rules: Primary rules are the patches that are initially inspired by self supporting components in ancient vaulting precedents. This class comprises of following rules: Wall, Squinch, Pendentive, Nubian Vault and Dome.
- 2. Hybrid Rules : These rules share the characteristics of two primary rules at the same time. This class includes the following rules: Squinch-Pendentive and Hybrid Domes.

Figure 3 shows the list of primary and hybrid rules in Patching Grammar. The gradient color of the layers shows the sequence of printing for each rule that starts from the pale color and ends with dark color. The dark gray layers are printed in the previous iteration and presented to explain support types better. The Points represent the Poles. The users can make their own rules by changing the configuration of supports and the Pole position. Here we only present the basic rules.

Rules Naming

The principle of naming rules is as follow: $R_x S_y C_z^k P_j^q$, where R stands for Rule type, S stands for Support type, C stands for Configuration of boundary and P stands for Pole type. The superscripts and subscripts are defined as follow: **x(Rule type number)**, 0 = Wall, 1= Squinch, 2= Pendentive, 3= Nubian Vault, 4= Dome, 5= Squinch-Pendentive, 6= Hybrid-Dome. **y(Support Type Number)**, 0 = Ground Support, 1 = Patch Support.**z(Support configuration type number)**, 0=Line, 1=Polyline or Curve, 2=Closed Polyline. for curve boundaries this number is equal to ∞ . For the boundaries with several supports this number should be attributed separately to each support. Normally the supports are sorted clock-wise.**k(Boundary's kink number without considering end points. j(Pole type number)**, 0= Full Pole (The poles that are adjacent to only quad faces), 1= Partial Pole (The poles that are adjacent to both triangle or quad faces). **q(Pole position with respect to boundary**, 0= Inside the



Fig. 3. The Rules of Patching Grammar

support, 1= Outside the support, 2= On the support.

Design Methods

There are two main design approaches using Patching Grammar. Each of two approaches use the following principle:

- 1. Take a boundary or geometry as input.
- 2. Analyze the input and divide its' spans using the rules of Patching grammar.
- 3. Make a Multi-Vault from the achieved rules in step 2.
- 4. Enhance the geometry of the patches relative to the properties of the printing mortar.
- 5. Run finite element analysis for estimating printability of the multi-vault.

1. Generative Design Approach

Through this approach the designers will intuitively choose the rules from patching grammar and pose them on the proposing boundary to make the configuration of a multi-vault which will cover the spans of a given boundary. Figure 4 shows the process of generative design using Patching grammar. The



Fig. 4. Generative Design Approach using Patching Grammar

gradient color of the layers in step 6 depicts the sequence of the printing at each part. The pale colors are the printing start position, and the dark brown is the print ending position. The sequence of printing parts is represented on the bottom. The type of rules and their labels are presented based on the patching grammar.

2. Analytical Design Approach

This approach is either boundary based or geometry based.

- **Boundary-based analytical design approach:** In the boundary base analytical design approach, the users have to analyze the large spans of a given boundary using the Delaunay triangulation method and divide the identified spans using the rules of Patching grammar. In addition, one has to modify the boundary configuration before analyzing that boundary with Delaunay triangulation. For having the best result from Delaunay triangulation, the topological skeleton of that boundary should have one branch at each end, Hence the boundary may need modification before the analysis.
- Geometry-Based analytical design approach: In this design approach, the users split a given geometry using Heat method for distance computation


Fig. 5. Boundary-Based Analytical Approach using Patching Grammar

(Crane et al.) with respect to the existing rules in the patching grammar 6. The heat sources can be obtained from the end points of the given geometry's boundary's topological skeleton. The apertures in geometry can only exist in Dome type (R_6) rules because the domes are the final elements to be printed, and no parts are printed above them. Therefore, one must keep those apertures inside the dome topology while splitting and enhancing the initial geometry.

Conclusion

This paper has introduced the Parching Grammar as a design tool for designers and engineers to help them make the geometries tailored for Scaffold-Free additive manufacturing of large-scale shells. The 3D Printing using the Patching method can significantly boost the chance of full automation in residential and non-residential structures using additive manufacturing techniques. The advantages of using Patching grammar as a design tool are as follow:

- The designers can directly influence the form-finding method using the combination of grammar and form-finding tools.
- The patching Grammar allows printing of complex forms that are not printable in any other printing methods but step-wise printing.
- Using Patching Method, the users have direct control over changes in the composition of the patches. Furthermore, they can change the patches' geometries



Fig. 6. Geometry-Based Analytical Approach using Patching Grammar

using different methods, making the patching method a flexible design tool.

• The Patching Grammar significantly reduces the prototyping cost by omitting the need for form-work. Furthermore, the Patching Method's adaptability with Earth-based materials encourages sustainable fabrication.

The coherence and relevance of this paper are entirely affected by the advances in Robotic additive manufacturing setups. The overview of large-scale fabrication is subjected to advancements in the robotic industry and fabrication setups. The cable-driven robotic setups such as one explained in (Bruckmann and Boumann 2021) and (Zhang et al. 2021) are good candidates for fabrication in factories and in-situ construction. In addition, in-situ fabrication is possible with robots that are made for mobility, such as what is described in (Dielemans and Dörfler 2021). The next step of developing the Patching technique is to identify more complex rules and enrich the library of the rules in Patching grammar. In parallel, the study on physical experimentation and identifying the challenges in actual fabrication are needed.

REFERENCES

Bruckmann, T. and Boumann, R. (2021). "Simulation and optimization of automated masonry construction using cable robots." *Advanced Engineering Informatics*, 50, 101388.

- Crane, K., Weischedel, C., and Wardetzky, M. "The Heat Method for Distance Computation." 10.
- Curth, A., Brodesser, T., Sass, L., and Mueller, C. (2021). *Multi-objective optimization* of 3D printed shell toolpaths (August).
- De Wolf, C., Ramage, M., and Ochsendorf, J. (2016). "Low Carbon Vaulted Masonry Structures." *Journal of the International Association for Shell and Spatial Structures*, 57(4), 275–284.
- Dielemans, G. and Dörfler, K. (2021). *Mobile Additive Manufacturing A robotic system for cooperative on-site construction* (October).
- Duarte, G., Brown, N., Memari, A., and Duarte, J. P. (2021). "Learning from historical structures under compression for concrete 3D printing construction." *Journal of Building Engineering*, 43, 103009.
- Jipa, A., Bernhard, M., Meibodi, M., and Dillenburger, B. (2016). "3D-Printed Stay-in-Place Formwork for Topologically Optimized Concrete Slabs." 10 p. Artwork Size: 10 p. Medium: application/pdf Publisher: ETH Zurich.
- Motamedi, M., Mesnil, R., Oval, R., and Baverel, O. (2021). "Scaffold-Free Robotic 3D Printing of a Double-layer Clay Shell." *Proceedings of the IASS Annual Symposium* 2020/21 and the 7th International Conference on Spatial Structures Inspiring the Next Generation, Guilford, UK.
- Motamedi, M., Oval, R., Carneau, P., and Baverel, O. (2020). "Supportless 3D Printing of Shells: Adaptation of Ancient Vaulting Techniques to Digital Fabrication." *Impact: Design With All Senses*, C. Gengnagel, O. Baverel, J. Burry, M. Ramsgaard Thomsen, and S. Weinzierl, eds., Cham, Springer International Publishing, 714–726.
- Oval, R., Rippmann, M., Mesnil, R., Mele, T., Baverel, O., and Block, P. (2019). "Feature-based Topology Finding of Patterns for Shell Structures." *Automation in Construction*.
- Rodiftsis, A. (2020). "From the ground up:: Robotic Additive Manufacturing (RAM) of a structurally optimized earthen shell through computational design.
- Vantyghem, G., De Corte, W., Shakour, E., and Amir, O. (2020). "3D printing of a post-tensioned concrete girder designed by topology optimization." *Automation in Construction*, 112, 103084.
- Zhang, D., Zhou, D., Zhang, G., Shao, G., and Li, L. (2021). "3D printing lunar architecture with a novel cable-driven printer." *Acta Astronautica*, 189, 671–678.

UTILIZING ARTIFICIAL INTELLIGENCE FOR DESIGNING CEMENT-BASED MATERIALS FOR 3D CONCRETE PRINTING APPLICATIONS

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ABSTRACT

3D concrete printing (3DCP) is an innovative method used in construction for the erection of cement-based building structures. It uses a mortar mix that is extruded through a nozzle which is then controlled in three dimensions by a computerized system, typically a gantry or a robotic arm. The process is largely automated providing several advantages over conventional construction methods. 3DCP typically uses High Performance Concrete (HPC) due to the complex material requirements. Artificial Intelligence (AI) is a collection of various technologies that can extract insights and patterns from datasets. Based on the datasets provided, they are able to make reasonable predictions. Machine learning (ML) is a subset of AI which has the ability to learn without being explicitly programmed. The most common approach of ML is supervised learning which are algorithms that learn from labelled datasets. Concrete technology has generally not leveraged the power of AI, especially for 3DCP purposes. This is also largely due to the lack of availability of datasets that are structured for AI applications. The objective of this paper is to assess the viability of using machine learning for designing concrete mixes that can be used for 3DCP. Experiments were conducted where various mix designs were tested with the following materials - Cement, Sand, Fly Ash, Silica Fume and Superplasticizer. The mixes were used as the datasets for training the ML models which have varying statistical features such as the standard deviation, mean and coefficient of variance. The performance of the model and accuracy of the algorithms were also assessed using R-squared value and Root Mean Square Error (RMSE). In this paper, the materials statistical requirements, parameters and choice of algorithm will be assessed with the experiments conducted and a recommendation will be provided for optimum performance and accuracy in the design of mixes for 3DCP.

Keywords: 3D Concrete Printing, Artificial Intelligence, Machine Learning

INTRODUCTION

3D Concrete Printing (3DCP) is a novel and innovative construction method that can be used for the erection of high precision construction components. If this technology is correctly utilised it could have several advantages over traditional construction methods. The added advantage is that the technology creates opportunities to erect structures effectively through an automated process that has an impact on labour cost. Due to its material requirements, 3D Concrete Printing uses High Performance Concrete (HPC) to allow the material to have good Workability, Extrudability, Buildability and Open time (Le, T T, 2011).

Artificial Intelligence (AI) is a collection of technologies that extracts patterns from large sets of data with the ability to making predictions based on the data acquired. The most commonly

used machine learning method is called Supervised Learning. The method seeks patterns and relationship between variables and groups of variables.

There are many variables to consider for 3DCP. However, advancements in AI algorithms have made it possible to leverage this technology and various parameters that would usually be challenging to compute using conventional methods or traditional Logical programming.

The data in this study comprises of various cement-based mix designs that will be used for 3DCP. The primary materials that will be used will be Cement, Sand, Fly Ash, Silica Fume and Super plasticizer. The various mix proportions will be used to train machine learning models, the models will subsequently have the capability to design mix proportions after training. These predictions will be the ideal mix design that can be used for 3DCP applications. The performance and accuracy of the model in designing mix proportions will be assessed by using various statistical techniques.

AIM OF THE STUDY

The purpose of the study is therefore to explore the following:

- To develop various cement-based mixed designs for 3DCP applications which will become the dataset used in this research;
- Train various AI models with this datasets;
- Assess the performance of the models in designing viable mixes that can be used for 3DCP; and
- Make recommendations on the approach that can be used to leverage AI for 3DCP material design based on performance and accuracy.

LITERATURE REVIEW

3D Concrete Printing (3DCP) is an additive manufacturing process that uses a computer based digital design to create physical components using cement-based material (Ji et al., 2019). The components can be formed by extruding the material layer-by-layer until the intended digital design is completed using a robotic arm or gantry system. This technology opens up many architectural opportunities due to minimal design constraints.

The origins of 3DCP was through a proposal to introduce automated construction by using an additive manufacturing process instead of conventional methods with sand and cement in 1997 (Pegna, 1997). A year later, Professor Khoshnevis and his research team invented a process called contour crafting which used a computerized gantry system that used trowels to ensure that the material is smooth and that the process produced quality surface finishes and high structures. There has been numerous research done on this topic and breakthrough advancements have been achieved on 3DCP as the technology continues to evolve (Khoshnevis, B, Russell R, Kwon, 2001).

The material design plays an important role in ensuring that the 3DCP is successful. Traditional concrete materials such as cement, superplasticizer, fly ash, fibre, accelerators, retarders are commonly used in 3DCP (Le, Austin, Lim, Buswell, Law, et al., 2012). The critical material properties to take into account are the workability, extrudability, flowability and open time to ensure successful printing.

Studies have shown that cement as the only binder has negative impact on strength if the process has large printing gaps (Darvas & Wolff, 2016). Furthermore, when its combined with binders such as fly ash and silica fumes it has a strength reduction of about 23% (Khan, 2020). Binder of up to 30% has shown to be insufficient for the materials to be extruded. However an addition of 1 to 2 % Superplasticizer is shown to extrude the material with sufficient paste. In research conducted by Le et al in 2012 showed that strengths of up to 100 MPa can be achieved with a 3DCP mix design (Le, Austin, Lim, Buswell, Gibb, et al., 2012).

The rheology of concrete is important in understanding the materials behavior and assessing its static and dynamic yield strengths. It is defined as the science of flow and deformation of materials. The materials thixotropy is also important to consider in the design process, it is the property of material viscosity when it is subjected to applied stress (Ojeda-Farías et al., 2019). This physical phenomenon can be explained as the structuration and de-structuration of particles in the material when stress is applied. This approach helps in understanding the flowability of the design material, it is commonly measured as the area under the hysteresis loop of the shear strain and shear stress under cyclic tests as shown in Figure 1 (Kruger et al., 2019).



Figure 1: Describing thixotropy by means of stress growth rheological characterization test that depicts the static and dynamic yield stress (Cho et al., 2019)

Studies have shown that that a slump-flow of 130 - 210 mm is acceptable for 3DCP applications (Tay et al., 2019). Furthermore, low pumpability has been observed for mixes with low slump-flow values. Conversely, mixes with very high slump-flow values do not possess sufficient static yield stress to carry the layers above it. The primary contributors to slump-flow values are water content and the proportions of aggregate in the mixes.

Artificial intelligence (AI) is a collection of various technologies that are good in analysing a large dataset and have the ability to extract underlying patterns to make reasonable predictions on new data. Common AI subfields include computer vision, natural language processing, machine learning.

Machine Learning (ML) algorithms use four main methods. Supervised learning, Semi-supervised learning, unsupervised learning and Reinforced learning. Studies have shown that these models have immense capacity for mining valuable insights from data for numerous applications in various sectors (Lee & Shin, 2020).

To develop high performing machine learning models, it is important to follow a ML development workflow or life cycle (Maleki et al., 2020). The phases are data preparation, data splitting, choice of algorithm and model evaluation.

Data preparation involves selecting the data that will be used to achieve the intended predictive objective. During data preparation most models require that all missing values are removed or replaced from the data set to function, therefore domain knowledge and in-depth understanding of the data is critical (Biswas et al., 2021). Data splitting, which is primarily splitting the data into training and testing. This prevents bias in the prediction due to a phenomenon called overfitting. This occurs when a model is too specific to the data points instead of generalizing itself against the data, overfitting generally performs poor on new data as well as predictive performance (Datarobot, 2001).

The choice of a ML model to use is based on the type of available dataset. This informs the choice of the algorithm. Traditionally, the data is presented in tabular form where each row is a representation of the unique datapoint and each column indicating the predictor variable. There are many options to choose from. Common and easy to use ML models are regression models that predict numerical data and logistic regression models that make categorical or classification predictions. The more complex and advanced models are Artificial Nueral Networks (ANN) and Convolutional Neural which have powerful prediction abilities (Chen & Li, 2020).

The final phase before deployment of model is often model evaluation. This process evaluates how well the model performs on the test data. Typically, logistic regression problems use classification matrix that provides good visualization reports. For regression problems, Root Mean Square Error (RMSE) which is a measure of a model's error when predicting quantitative data. Coefficient of determination (R^2) measure the strength of the relationship of the trained models and the data a commonly used (Paper, 2016).

There are many types of regression models available, one of the most popular and simplest using supervised learning is K-Nearest Neighbours (Yeo & Aksakalli, 2021). The algorithm uses feature similarity in predicting numerical and categorical outcomes on new data and calculates how it closely resembles the data in the training dataset. The model uses methods such as Euclidean distance to calculate the distance between each training point against the new point presented in the new dataset. Furthermore, a k value is selected to neighbors that fall within similar regions and allocates a weight to the k value. This k value is then used to make predictions of datapoints that fall in the same class (Jose, 2018).

Based on literature, High Performance Concrete (HPC) is a viable approach for 3DCP applications. The use of AI can be helpful in modelling data from various mixes that can be used for training a model that will be able to design HPC mix proportions. Le et al proposed a mix design that was composed of CEM I 52,5 N cement, Fly Ash, Silica Fume, Sand and

Superplasticizer(Le, 2012). In the research, it was shown that binder of more than 30% is required for extrudability and that 1 to 2% Superplasticizer improves extrudability.

In 1991 Ghaboussi used ANN's to predict the compressive strength of HPC with reasonable accuracy and low error margins (Ghaboussi, 1991). Nguyen et al used conducted research that used Support Vector Machines, eXtreme Gradient Boost Machine for preeicting compressive strength of various mixes with a RMSE of 5 and 3.78 respectively. A lot of research has been conducted of theirs years using different models and data. However, the power of using these models has proved to me by helpful with high accuracy. Furthermore, 2% Fly Ash and Silica Fume can print up to 260 mm (Zhang et al., 2018). Ideally, for 3DCP a slump between 130 - 210 mm is required.

EXPERIMENTAL PROGRAMME AND METHOD

The experimental work was broken down in the following process: The initial focus was developing a dataset, the dataset in this context are various mix designs. The materials used were fine sand, CEM I 52.5N OPC cement, fly ash and superplasticizer based on recommendations in literature (Le, T T, 2011). The water cement ratio remained fixed for all mixes at 0.3 as well as a cement to sand ratio of 0.58. The primary varying materials were fly ash and silica fume with the guidance of research previously conducted. This dataset was then prepared and split in a format that can be used for a ML model. A total of 19 mixes were created. Based on literature, the allowable range for flowability is 130 - 210 mm for 3DCP(Tay et al., 2019). The predicted mix design was tested using a flow table test to assess the accuracy of the prediction. Furthermore, the analysis was done in four batches; 5 mixes, 4 mixes, 5 mixes and finally 5 batches. Each batch had different mix proportions and varying statistical representation for analysis. The mix design proportions were varied in every batch to attempt to achieve a workability within a printable range. The K- Nearest Neighbor algorithm was used for predicting and designing the HPC mix proportions using RMSE and R^2 to measure performance and accuracy.

RESULTS AND DISCUSSIONS

Experiment 1: (Batch 1)

The first five mixes had no fly ash with increasing content of silica fume. The slump-flow test was conducted, mix 1 - 3 was too wet and could not be contained within apparatus' surface area, mix 4 and 5 were measurable and had a workability of 265mm and 182mm respectively. The results have also show that increasing silica fume and reducing all the remaining materials reduced the slump-flow value. The results are shown in Table 1 and Figure 2 and 3 below. Based on the number of the mixes or datapoint, a decision was taken to not to train a model as the performance would be poor.

Table 1:Mixes 1-5 (Batch 1)

Mix	W/C	Water	Cement	Silica	Fly	Fine	Superplasticizer	Workability
No.	ratio	(g)	(g)	Fume	Ash	Aggregate	(g)	Slump-
				(g)	(g)	(g)		Flow (mm)

1	0.3	120	400	0	0	680	16	270
2	0.3	105	350	20	0	595	14.4	270
3	0.3	90	300	42	0	510	12.84	270
4	0.3	75	250	60	0	425	11.2	265
5	0.3	60	200	80	0	340	9.6	182



Figure 2: Slump-flow of mixes 1-3



Figure 3: Slump-flow of mix 4

Experiment 2: (Batch 2)

Mixes 6 - 9 did not contain silica fume content. Based on literature the acceptable range for workability is between 130mm and 210mm (Tay et al., 2019). Mix 6 and mix 7 were measured at 230mm and 222mm respectively. Mix 8 measured 190mm which was within the acceptable range for workability. Mix 9 was too stiff and visibly not ideal for workability for 3DCP. The results are shown in Table 2 and Figure 4 below.

Tabl	le 2:	Mixes	6-9	(Batch	2)

Mix	Water	Cement	W/C	Silica	Fly	Fine	Superplasticizer	Workability
No.	(g)	(g)	ratio	Fume	Ash	Aggregate	(g)	Slump-
				(g)	(g)	(g)		Flow (mm)
6	105	350	0.3	0	40	595	14.8	230
7	90	300	0.3	0	80	510	13.6	222
8	75	250	0.3	0	120	425	12.4	190
9	60	200	0.3	0	180	340	11.6	10



Figure 4: Slump-flow of mix 6-9

The model was trained on the 9 cumulative mixes using the KNN algorithm. For the workability of the mixes, the mean value was 212mm with a standard deviation of 83.3. For performance, the batch scored a RMSE and R^2 of 2147 mm and 0.882 respectively. The trained model was required to design a mix with a slump-value of 130mm and 210mm. The model's predicted a mix proportions that only achieved a slump-flow of 10mm for both which displayed poor performance as shown is Table 3 and Figure 5.

Table 3: Predicted mix proportions

Required	Water	Cement	Silica	Fly	Fine	Superplasticizer	Achieved
Slump	(g)	(g)	Fume	Ash	Aggregate	(g)	Slump
			(g)	(g)	(g)		(mm)
130	78	260	16	84	442	15.12	10
210	81	270	28	48	459	12.32	10



Figure 5: Outcome from predicted mix for experiment 2

Experiment 3: (Batch 3)

Mix 10 to 14 had both silica fume and fly ash content. Mix 10 and 11 proved to be too wet. Mix 12 and 13 measured 210 and 170 mm respectively which is within the acceptable boundaries for 3DCP. Mix 14 measured 230mm which was slightly outside the range shown in Table 4. Table 4: Mixes proportions of mix 10 -11 (Batch 3).

Mix	W/C	Water	Cement	Silica	Fly	Fine	Superplasticizer	Workability
No.	ratio	(g)	(g)	Fume	Ash	Aggregate	(g)	Slump-
				(g)	(g)	(g)		Flow (mm)
10	0.3	67.5	225	0	60	382	44	270
11	0.3	74.25	247.5	44	60	421	36	270
12	0.3	81	270	48	60	459	24	210
13	0.3	37.125	123.75	22	54	383	16	170
14	0.3	67.50	225	40	48	383	20	230

The cumulative mixes had a mean of 219 mm and a statistical deviation of 83.3 mm for workability, which were both higher than that of experiment 2 (batch 2). Subsequently the model was trained inclusive of this dataset. The model was required to design a mix proportion that would achieve a required slump-flow of 130 mm and 210 mm, the model predicted a mix proportion with a flow of 128 mm and 270 mm respectively. The RMSE and R^2 was 240 mm and 0.945 respectively which substantially showed better performance in comparison to the results from experiment 2. The results are show in Table 5 below and in Figure 6.

Table 5: Predicted mix proportions

Required Slump	Water	Cement	Silica Fume	Fly Ash	Fine Aggregate (g)	Superplasticizer	Achieved Slump
130	68.625	228.75	30	62.8	423,4	15.12	128
210	83.70	279	17.6	69.6	474.40	16.96	270



Figure 6: Slump-value outcomes from predicted mix for experiment 3

Experiment 4: (Batch 4):

The last experiments mix proportions were designed to have most mixes to fall within the recommended range for workability. Mix 15 to 18 were within the acceptable range which is 130 mm - 210 mm expect for mix 9.

Mix	W/C	Water	Cement	Silica	Fly	Fine	Superplasticizer	Workability
No.	ratio	(g)	(g)	Fume	Ash	Aggregate	(g)	Slump-
				(g)	(g)	(g)		Flow (mm)
15	0.3	59.06	196.875	35	57	420.75	22	160
16	0.3	64.96	216.56	38.5	62.7	462.83	16.91	185
17	0.3	70.875	236.25	42	68.40	504.90	18.44	180
18	0.3	76.78	255.94	45.5	74.1	546.98	19.99	190
19	0.3	82.69	275.625	49	79.80	589.05	21.52	270

Table 6: Slump flow of mix 15 -19: (Batch 4)

The cumulative mean for the mixes was 213mm with a standard deviation of 63. Furthermore, the RMSE and R^2 scored 640.87mm and 0.832 respectively which reduced in comparison to experiment 3. The required slump by the trained model was also 130mm and 210mm, the model predicted mix proportion only achieved 180 mm and the second mix was too wet. Overall, the performance was poor as shown in Table 7.

Table 7: Predicted mix proportions

Required	Water	Cement(g)	Silica	Fly	Fine	Superplasticizer	Achieved
Slump	(g)		Fume(g)	Ash(g)	Aggregate	(g)	Slump
					(g)		(mm)
130	58	194.00	44	48.00	422	17.00	180
210	84	279	18	70	474.	17.00	270

The observations were that the more data that is provided to the model does not necessary translate to better accuracy and results as shown in experiment 3. In other words, data quantity is not necessary directly proportional to accuracy and performance of the model.



Figure 7: `Slump values - Predicted vs Actual

It was evident that the type of data collected from a statistical point of view is critical. Factors such as standard deviation, mean value etc. should be closely observed in the data collected as seen in experiment 3. The results show that mix designs dataset with an estimated RMSE and R2 value of 240 mm and 0,9 respectively generally yield good accuracy and performance. Also, an estimated mean of 219 mm and an estimated Standard deviation of 69 mm of display good performance with regards to slump flow values for the purposes of 3DCP using ML.

Batch	Root Mean Square Error	R 2		
	(RMSE)			
(9 Mixes) Batch 2	2147	0.882		
(15 Mixes) Batch 3	240.95	0.945		
(19 Mixes) Batch 4	640.87	0.832		





Figure 9: R Squared values

It was also observed that the model does not take into consideration the chemical nature of the materials and mix, after training it makes predictions on the mathematical correlation of the dataset. Furthermore, the trained model does not take costing into consideration in recommending a mix design which is also an important aspect in industry, the model primary objective is the mix proportion for an accurate prediction.

CONCLUSION

The results presented in this article are proof that AI particularly machine learning models can be used for concrete mix design if the right dataset is used as well as the appropriate statistical structure. The use of the K-nearest Neighbours model has shown promising results for prediction purposes. However, other models such as as Ridge regression, Lasso regression, Decision tree regression, Random forest, Artificial Neural Networks etc must also be investigated. The research has shown and proven that Artificial Intelligence is viable for designing mixes for 3D Concrete printing and that it can be a useful tool and approach with the correct strategy.

REFERENCES

- Biswas, A., Saran, I., & Wilson, F. P. (2021). Introduction to Supervised Machine Learning. *Kidney360*, 2(5), 878–880. https://doi.org/10.34067/kid.0000182021
- Chen, Y., & Li, H. (2020). DAM: Transformer-based relation detection for Question Answering over Knowledge Base. *Knowledge-Based Systems*, 201–202, 106077. https://doi.org/10.1016/j.knosys.2020.106077
- Cho, S., Kruger, J., Zeranka, S., & Zijl, G. Van. (2019). 3D Printable Concrete Technology and Mechanics. 158(September), 11–18.
- Darvas, Z., & Wolff, G. B. (2016). *An anatomy of inclusive growth in Europe*. http://bruegel.org/2016/10/an-anatomy-of-inclusive-growth-in-europe/
- Datarobot. (2001). Overfitting. https://www.datarobot.com/wiki/overfitting/
- Ghaboussi. (1991). Knowledge-Based Modeling of Material Behavior with Neural Networks. Journal of Engineering Mechanics, 117.
- Ji, G., Ding, T., Xiao, J., Du, S., Li, J., & Duan, Z. (2019). A 3D printed ready-mixed concrete

power distribution substation: Materials and construction technology. *Materials*, *12*(9). https://doi.org/10.3390/ma12091540

- Jose, I. (2018). KNN (K-Nearest Neighbors). Towardsdatascience.
- Khan, M. A. (2020). Mix suitable for concrete 3D printing: A review. *Materials Today: Proceedings*, *32*, 831–837. https://doi.org/10.1016/j.matpr.2020.03.825
- Khoshnevis, B, Russell R, Kwon, H. & B. (2001). Contour Crafting A Layered Fabrication Technique. *Special Issue of IEEE Robotics and Automation Magazine*.
- Kruger, J., Zeranka, S., & van Zijl, G. (2019). An ab initio approach for thixotropy characterisation of (nanoparticle-infused) 3D printable concrete. *Construction and Building Materials*, 224, 372–386. https://doi.org/10.1016/j.conbuildmat.2019.07.078
- Le, T T, A. S. A. & L. (2011). Hardened properties of high-performance 3D Concrete printing. *Cement and Concrete Research*.
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., & Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures/Materiaux et Constructions*, 45(8), 1221–1232. https://doi.org/10.1617/s11527-012-9828-z
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Law, R., Gibb, A. G. F., & Thorpe, T. (2012). Hardened properties of high-performance printing concrete. *Cement and Concrete Research*, 42(3), 558–566. https://doi.org/10.1016/j.cemconres.2011.12.003
- Lee, I., & Shin, Y. J. (2020). Machine learning for enterprises: Applications, algorithm selection, and challenges. *Business Horizons*, 63(2), 157–170. https://doi.org/10.1016/j.bushor.2019.10.005
- Maleki, F., Ovens, K., Najafian, K., Forghani, B., Reinhold, C., & Forghani, R. (2020). Overview of Machine Learning Part 1: Fundamentals and Classic Approaches. *Neuroimaging Clinics of North America*, 30(4), e17–e32. https://doi.org/10.1016/j.nic.2020.08.007
- Ojeda-Farías, O., Hebraud, P., Lootens, D., Liard, M., & Mendoza-Rangel, J. M. (2019). Thixotropy of reactive suspensions: The case of cementitious materials. *Construction and Building Materials*, 212, 121–129. https://doi.org/10.1016/j.conbuildmat.2019.03.319
- Paper, C. (2016). An Experimental Study : Strength Prediction Model and Statistical. International Conference on Advances in Civil Engineering, December, 21–23.
- Pegna, J. (1997). Exploratory investigation of solid freeform construction. *Automation in Construction*, 5(5), 427–437. https://doi.org/10.1016/S0926-5805(96)00166-5
- Tay, Y. W. D., Li, M. Y., & Tan, M. J. (2019). Effect of printing parameters in 3D concrete printing: Printing region and support structures. *Journal of Materials Processing Technology*, 271(April), 261–270. https://doi.org/10.1016/j.jmatprotec.2019.04.007
- Yeo, G. F. A., & Aksakalli, V. (2021). A stochastic approximation approach to simultaneous feature weighting and selection for nearest neighbour learners. *Expert Systems with Applications*, 185, 115671. https://doi.org/10.1016/j.eswa.2021.115671
- Zhang, Y., Zhang, Y., Liu, G., Yang, Y., Wu, M., & Pang, B. (2018). Fresh properties of a novel 3D printing concrete ink. *Construction and Building Materials*, 174, 263–271. https://doi.org/10.1016/j.conbuildmat.2018.04.115

Drone-based scanning technology for characterizing the geometry and thermal conditions of building enclosure system for fast energy audit and design of retrofitting strategies

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ABSTRACT

The United States Department of Energy (DOE) has set a goal of 30% reduction in energy use intensity (EUI) in the building sector by 2030. The majority of opportunities to meet this clean energy goal will be in retrofitting the existing building stock. Approximately 50-90% of energy reduction of existing buildings has been achieved through deep retrofits. An initial step for planning building energy retrofit is to perform a building energy audit and determine inputs for creating an energy model baseline (existing condition of the building). Most of these inputs can be captured using building envelope scanning techniques, including but not limited to Infrared Thermography, Laser Scanning, or Ultrasound. This study created a workflow for collecting thermal and visual data during building inspection and using the data for energy simulation. The workflow is demonstrated in a building envelope inspection case study in the city of Syracuse, New York. We transformed the data into inputs for the building model. Furthermore, there is potential to integrate the framework with building energy modeling toward enriching the energy assessment process in retrofit projects. This study contributes to creating a more robust connection between energy auditing and retrofitting in the building sector and providing quick, inexpensive, and reliable approaches to inspect, assess, and report buildings for building retrofit projects.

KEYWORDS

Building energy audit, Building reconstruction, Energy model, Building retrofit

INTRODUCTION

Buildings are responsible for almost 40% of total primary energy consumptions and associated greenhouse gas (GHG) emissions (UNEP, 2017). The United States Department of Energy (DOE) has set a goal of 30% energy use intensity (EUI) reduction for the building sector using cost effective technologies by 2030 (US DOE, 2015). The majority of opportunities to meet this clean energy goal will be in retrofitting the existing building stock. As the commitments to increase energy efficiency and reduce GHG continue to grow, the construction market for building energy retrofit is expanding.

The initial step of retrofitting process is conducting building inspections and energy audits. ANSI/ASHRAE/ACCA Standard 211 (2018) establishes consistent procedures required to perform energy audits at three Levels. The gross area, the level of insulation of building components (e.g., roof, wall, fenestration, floors, and underground walls), and the overall enclosure airtightness are among the vital and required information to be collected in the energy audit process (Masri and Rakha, 2020). In addition, it is necessary to determine inputs for creating an energy model baseline (existing condition of the building). Even though the performance identification of building components is crucial for energy audit, the traditional process is usually time-consuming, laborintensive, destructive, not scalable, coupling with safety challenges (Shapiro, 2009). Therefore, built environment professionals would need to access quick, inexpensive, and reliable approaches to inspect, assess, and report buildings' existing condition and, in particular, building enclosures in this process. They usually use building envelope scanning techniques to capture most of these inputs fast and accurately. Some of these techniques include Infrared Thermography (IRT), Laser Scanning (Light Detection and Ranging, or LiDAR), Ultrasound, Through Wall Imaging Radars (TWIR), Close Range Photogrammetry (CRP), and Ground Penetrating Radar (GPR) (Masri and Rakha, 2020). The Literature Review section in this paper addresses the applicability of the techniques providing a classification of input categories for creating building energy models.

Creating hybrid workflows to collect various building energy model inputs is essential for automated building energy auditing. An automated vision-based energy assessment can represent (1) reconstruction of building model; (2) automating extraction of envelope opening layouts; (3) identifying thermal anomalies (e.g., thermal bridges) of building envelopes; and (4) estimating real thermal resistance (or transmittance) of envelope as an essential parameter for building energy model. In a previous study, we used drone thermography to create an automated workflow for envelope thermal bridge identification (Mirzabeigi and Razkenari, 2022). The proposed workflow represents various benefits of reducing labor, time, and hazards for a building envelope inspection while solving problems of inaccessible building envelope components. This study explores the application of an Unmanned aerial system (UAS) equipped with thermal and visual sensors to collect data from building sites for automated 3D reconstruction of building models. Consequently, it contributes to creating a more robust connection between energy auditing and retrofitting in the building sector by offering a quick, inexpensive, and reliable approach for energy auditing

LITERATURE REVIEW

This section provides a preliminary evaluation of the pre-mentioned envelope scanning techniques and their use case for collecting input for building energy models. The input categories that have been considered in this study include 3D reconstruction and geometry information, building envelope thermal characteristics and defects identification, occupancy information, HVAC performance, and air leakage location and tightness characteristics.

IRT is a technique that measures the reflected and emitted radiation from a surface and shows the image as a spectrum (Clark et al., 2003). This technique can be divided into qualitative and quantitative methods. Qualitative IRT is based on potential thermal anomalies identification, while quantitative IRT is characterized by numerical analysis to quantify thermal anomalies (e.g., thermal transmittance determination) (Kylili et al., 2014). Overall, this approach has been used for detecting thermal anomalies (Mirzabeigi and Razkenari, 2022), tracking moisture-related problems, air leakage location and HVAC performance (Snell and Spring, 2007), identifying cracks (Bauer et al., 2016), monitoring room occupancy (Berger and Armitage, 2010), and reconstructing 3D models (Rakha et al., 2018). However, it might not be efficient for subsurface component identification (Masri and Rakha, 2020). In addition, although this approach is useful for air leakage identification, no literature was found related to using IRT for identifying the whole air tightness characteristic of building enclosure.

Laser Scanning (or LiDAR) represents utilizing a laser beam to measure the distance between the device and the object of interest. This technique uses repeated measurements along an entire field of view to create point clouds of physical objects (Riveiro and Solla, 2016). Laser scanners are generally categorized as terrestrial and mobile scanners. Mobile scanners are handheld devices that offers more flexibility and ease for data collection, but generally lower accuracy (corresponding to less uniformity and density in the point cloud). However, using a terrestrial scanner takes more time but the accuracy and overall data quality is much higher (Burrows, 2020). Grussenmeyer et al. (2008) compared 3D faces on the photogrammetric wireframe as well as automatic extracted planes to laser scanner's point cloud for a medieval castle. They showed small differences in the deviations between the models (model precision) and found they can be applied equivalently for regular shaped objects. However, the time and effort required for laser scanning is much higher compared to other techniques. Some other advantages of this technique include feature extraction (Previtali et al., 2013), differentiation between windows and walls (Kim et al., 2006), and assessing cracks in structures (Wood and Mohammadi, 2015). Some laser scanners are also equipped with thermal sensors, so the collected data can be used to identify thermal defects, but not necessarily for identifying envelope thermal properties.

CRP is another technique that uses a wide range of cameras, from metric to semi-metric cameras, to construct a 3D model by analyzing 2D images. Jiang et al. (2008) showed use of CRP for cracks and defects identification.

Ultrasound technique represents utilizing short wavelengths that enables a detailed assessment of building components (Masri and Rakha, 2020). It is applicable for fault, physical defects, material depth detection, and duct localization (Schickert, 2005). Various material properties such as resistance capacity and deterioration have also been

explored using this technique in wood structures (Liñán et al., 2015). Shah and Ribakov (2010) showed its applicability in detecting micro-cracking in materials.

TWIR utilizes electromagnetic waves to capture objects in buildings. It also extracts the physical properties of objects and records through the wall microwave scattering to form scenes (Masri and Rakha, 2020). In addition to detecting wall properties, Ren et al. (2015) investigated TWIR application for identifying gaps in multilayered walls. Sévigny and Fournier (2014) showed its application for material composition identification in multilayered assemblies. In addition, they explored its use for thickness detection and material characterizations for front walls in tandem with LiDAR technology for feature extraction. Masri and Rakha (2020) reviewed nondestructive testing techniques. They introduced detecting cracks in concrete structures and identifying potential defects in multilayered assemblies as benefits of the approach. GPR utilizes electromagnetic waves to inspect subsurface of objects regarding thickness and properties of material layers (Zhang, 2014). Giunta and Calloni (2000) implemented this approach to collect information about different wall elements and assemblies in the preservation of St. Peter's Basilica in the Vatican. According to (Masri and Rakha, 2020), other advantages include identifying discontinuities between materials and recording them due to the different dielectric properties of each material, detecting chlorides and moisture and moisture penetration depth, and measuring the electromagnetic sensitivity of materials. Figure 1 shows the matrix of relationships between the different building envelope scanning techniques and various building energy model inputs.



Figure 1. The matrix of relationships between the different building envelope scanning techniques and various building energy model inputs.

Even though IRT may provide more benefits compared to other techniques, it cannot fully provide all the required information. IRT might be useful for extracting information regarding leakage location through the building envelope. Still, none of these techniques could be used for characterizing the airtightness level of the whole building or enclosure. Other tools (e.g., blower door test) might be used in a hybrid workflow to fully characterize thermal and airtightness properties. While IRT approaches might not be efficient for subsurface component identification, building energy simulation requires detailed thermal and visual surface and subsurface properties (e.g., thickness, thermal conductivity, and solar absorptance information of each layer). Therefore, a combination of two or more (e.g., IRT and GPR) techniques could collect all the inputs needed for the thermal simulation engines (e.g., EnergyPlus). It should be noted that the IRT method may be applied to measure the real total effective thermal resistance of the building envelope, but not detailed layerby-layer properties. Therefore, future studies could quantify the accuracy of energy models when using simplified total thermal resistance compared to the detailed one.

METHODOLOGY

Figure 2 shows the overall workflow of the study. After selecting the scanning technique, general steps include (1) the flight path design and collecting data for 3D point cloud creation; and (2) creating the building model and developing energy simulation. Details of each step are provided in the following sub-sections.



Figure 2. Overall workflow of the study.

1. *Flight path design and data collection:* The Building Envelope Systems Test (BEST) lab (two-story building) on the Syracuse University campus, located at Syracuse, New York, was selected as the case study. This building is a baseline residential building used for research and development related to building envelope and energy performance. An ongoing study sponsored by the DOE Advanced Building Construction (ABC) program uses the BEST lab to demonstrate an exterior add-on panel system to improve the thermal insulation and airtightness of the building envelope, it

is necessary to characterize the geometry of the existing facade including its corners, openings, and locations for structural support. The present study explores the use of the drone-based scanning method to obtain the required geometrical information.

After receiving the required authorizations from the Federal Aviation Administration (FAA) and University Office of Risk Management, we organized a site visit to collect data. Figure 3 demonstrates elliptical flight path designed for creating a 3D point cloud of the building, in addition to actual camera path over the tie points. A rectangular flight path was designed and conducted as well, which is more useful for an automated vision-based envelope inspection (Mirzabeigi and Razkenari, 2022), but it is out of the scope for this paper. Pix4Dcapture (the circular flight capability) was used to control the drone during the elliptical flight. Three different altitude scenarios of 18.3, 24.4, and 30.5 m were considered and called Scenario 1, 2, and 3, respectively. The top view design of the flight plan for collecting data was taken with a 10° angle between images.



Figure 3. Elliptical flight path design (left) and actual camera path (right) for the BEST lab experiment.

We used a DJI Mavic 2 Enterprise Dual equipped with visual and thermal sensors for data collection. Both thermal and visible images were taken during the experiment. The former can be used for thermal envelope assessment and the latter for 3D reconstruction. The experiment was conducted in mid-August, during evening time with a semi-cloudy sky and stable temperatures without precipitation. Air temperature of 23.3°C and relative humidity of 41% were recorded during the experiment.

2. Building reconstruction and energy model development: In this step, the Pix4Dmapper was used to generate 3D point clouds from our collection of input images. We used the classification tool to segment the points into ground, road surface, vegetation, building, and human-made object. Then, we imported the points in the building category into the Autodesk ReCap software to create a 3D model. The raw data from digital photogrammetry lacks the necessary information to create a building energy model (e.g., wall, window, and roof). Therefore, this intermediate step was required to transform point cloud to 3D model. Accordingly, the constructed model was transformed into the Rhinoceros 3D environment. This model was used to provide inputs for building energy modeling. Thermal simulation engines (e.g., EnergyPlus)

requires a 3D model to be a closed volume concerning boundary conditions (Alawadhi, 2017). Therefore, a 3D model that does not represent a closed volume might not be used for this purpose. The feasibility of this workflow was verified by running a successful energy simulation, using EnergyPlus, which is handled via Honeybee in the Grasshopper interface. The default construction set of Honeybee was assigned to the building model, and other simulation parameters were extracted from (Zhang et al., 2016) according to the residential use. Furthermore, the hourly annual weather data was selected for Syracuse from the EnergyPlus Weather (EPW) repository.

RESULTS AND DISCUSSION

After collecting data, a dataset containing images with GPS positioning was imported into the Pix4Dmapper. The software extracts pixels from images and creates a point cloud model. This step is done by triangulating individual pixels from multiple geolocated images. Initial processing is needed to create tie points, which is the preliminary step for creating point clouds and mesh reconstruction. Figure 4 demonstrates the result of point clouds and classification for three different altitude scenarios.



Figure 4. Point clouds and classification results for three different scenarios.

As expected, according to point clouds, Scenario 1 with lower altitude showed a more precise model. The observed trend is that by increasing the altitude from 18.3 m to 30.5 m, the quality of point cloud at corners of the building is reduced. This can be characterized by the angle of taking picture from the camera to points of interest. From the perspective view, false-positive points have been labeled as vegetation along the

vertical corner edges and behind the roof overhang. Additional algorithms may be needed to further post-process and improve the accuracy of the labeling task. Then, the class of building has been separated and exported to Autodesk ReCap that can be translated into a building energy model. Figure 5 renders the constructed energy model visualized in Rhinoceros in addition to the energy intensity results of the heating and cooling for the simulated case. The results show that the Honeybee model is debugged. Therefore, a successful experiment was conducted to use drone scanning technology and create a building energy model.



Figure 5. Energy model visualized in Rhinoceros and simulation results.

The energy simulation results, along with automated building envelope inspection, are essential in conducting and reporting energy audits. This information is required for designing retrofitting strategies considering two aspects. First, creating an energy model baseline to apply and compare various retrofit strategies. Second, detailed geometry model help conducting a successful design phase for each retrofitting project. However, different steps of the provided workflow can be improved as follows:

- We used FLIR dual-sensor camera, but to improve the quality of images, it is possible to use cameras with higher resolution. It is also possible to install other sensors, or even laser scanners on drones.
- 3D point clouds reconstruction and point segmentation is performed in the Pix4D software and works accurately. However, if the goal is to create an end-to-end platform for automated building inspection, point clouds can be generated using various available APIs and implement more precise point segmentation algorithms.
- Point cloud to BIM is generated using ReCap. It is possible to get accurate geometry in the end-to-end platform by implementing scan-to-BIM algorithms. Furthermore, incorporating different layers of information from various sensors is feasible.
- The last steps, which is energy simulation in grasshopper, can be also integrated in the end-to-end platform using grasshopper APIs. Additional missing data for creating an energy model must be realized based on building characteristics or additional onsite measurements. The missing data includes detailed thermal and visual properties, and the airtightness level of the whole building enclosure.

CONCLUSION AND FURTHER DEVELOPMENT

In this paper, we first conducted a literature review on the applicability of building envelope scanning techniques for collecting inputs for building energy modeling. Then, a workflow was proposed to collect data during building inspection and use them as

the geometry input for energy simulation. A case study in Syracuse demonstrated the applicability of the method and verification of creating a building energy model. This study contributes to building energy retrofit projects by providing a quick, inexpensive, and reliable approach to inspect, assess, and report existing building conditions. However, the exchange of data between various tools and platforms is a limitation in this study. Generation of point clouds, segmentation, and their transformation to BIM should be improved and automated. For instance, some improvements provided in (WuDunn et al., 2020) for point cloud segmentation. Further research can seek to address this issue using custom code and APIs to evaluate its broader applications. A comparison between the results of scanning method and actual condition of building is required to show how it can be further improved if it is necessary in an additional study. In this study, we implemented a simple case study. More research is needed to characterize the difference between scanning techniques (sensors) that are applicable for 3D reconstruction to better understand and differentiate between simplified building layout (without internal walls), detailed layout with internal walls (without differentiating building program for various thermal zones), and detailed layout with internal walls and detailed zone program to develop building energy models in energy auditing phases. Furthermore, future studies may address conducting a sensitivity analysis to evaluate the impact of various input parameters on the output of the energy model considering residential building energy use.

REFERENCES

- Alawadhi, M. S. A. A. M. (2017). Building Energy Model Generation Using a Digital Photogrammetry-Based 3D Model. Texas A&M University.
- ANSI/ASHRAE/ACCA. (2018). Standard 211-2018, Standard for Commercial Building Energy Audits.
- Bauer, E., Pavón, E., Oliveira, E., & Pereira, C. H. F. (2016). Facades inspection with infrared thermography: cracks evaluation. Journal of Building Pathology and Rehabilitation.
- Berger, M., & Armitage, A. (2010). Room Occupancy Measurement Using Low-Resolution Infrared Cameras. Signals and Systems Conference (ISSC 2010).
- Burrows, P. (2020). Five Things to Know When Choosing a Mobile or Terrestrial Laser Scanner. Retrieved from Leica Geosystems website: https://shop.leicageosystems.com/blog/five-things-know-when-choosing-mobile-or-terrestrial-laserscanner.
- Clark, M. R., McCann, D. M., & Forde, M. C. (2003). Application of infrared thermography to the non-destructive testing of concrete and masonry bridges. NDT and E International, 36, 265–275.
- Giunta, G., & Calloni, G. (2000). Ground Penetrating Radar applications on the Façade of St. Peter's Basilica in Vatican Giuseppe. 15th World Conference on Non-Destructive Testing. Rome, Italy.
- Grussenmeyer, P., Landes, T., Voegtle, T., & Ringle, K. (2008). Comparison Methods of Terrestrial Laser Scanning, Photogrammetry and Tacheometry Data for Recording of Cultural Heritage Buildings. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVI.
- Jiang, R., Jáuregui, D. V., & White, K. R. (2008). Close-range photogrammetry applications in bridge measurement: Literature review. Measurement, 41, 823-834.

- Kim, J., Shin, S., & Kim, K. (2006). Automatic Building Feature Extraction Using Lidar Data and Digital Map. MAPPS/ASPRS 2006 Fall Conference. San Antonio, Texas.
- Kylili, A., Fokaides, P. A., Christou, P., & Kalogirou, S. A. (2014). Infrared thermography (IRT) applications for building diagnostics: A review. Applied Energy, 134, 531–549.
- Liñán, C. R., Morales Conde, M. J., de Hita, P. R., & Gálvez, F. P. (2015). Application of Non-Destructive Techniques in the Inspection of Wooden Structures of Protected Buildings: The Case of Nuestra Señora de los Dolores Church (Isla Cristina, Huelva). International Journal of Architectural Heritage, 9(3), 324-340.
- Masri, Y. El, & Rakha, T. (2020). A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections. Construction and Building Materials, 265, 120542.
- Mirzabeigi, S., & Razkenari, M. (2022). Automated Vision-Based Building Inspection using Drone Thermography. CI and CRC Joint Conference 2022. Arlington, Virginia, USA.
- Previtali, M., Barazzetti, L., Brumana, R., Cuca, B., Oreni, D., Roncoroni, F., & Scaioni, M. (2013). Automatic façade segmentation for thermal retrofit. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 197–204.
- Rakha, T., & Gorodetsky, A. (2018). Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones. Automation in Construction, 93(May), 252–264.
- Rakha, T., Liberty, A., Gorodetsky, A., Kakillioglu, B., & Velipasalar, S. (2018). Heat Mapping Drones: An Autonomous Computer-Vision-Based Procedure for Building Envelope Inspection Using Unmanned Aerial Systems (UAS). Technology|Architecture + Design, 2:1(September), 30–44.
- Ren, K., Burkholder, R. J., & Chen, J. (2015). Investigation of Gaps Between Blocks in Microwave Images of Multilayered Walls. 2015 APS/URSI, 691–692.
- Riveiro, B., & Solla, M. (2016). Non-Destructive Techniques for the Evaluation of Structures and Infrastructure.
- Schickert, M. (2005). Progress in ultrasonic imaging of concrete. Materials and Structures, 38(283), 807–815.
- Sévigny, P., & Fournier, J. (2014). Automated Front Wall Feature Extraction and Material Assessment Using Fused LIDAR and Through-Wall Radar Imagery.
- Shah, A. A., & Ribakov, Y. (2010). Effectiveness of nonlinear ultrasonic and acoustic emission evaluation of concrete with distributed damages. Materials and Design, 31, 3777– 3784. https://doi.org/10.1016/j.matdes.2010.03.020
- Shapiro, I. (2009). Energy audits in large commercial office buildings. ASHRAE Journal, 51.
- Snell, J., & Spring, R. (2007). Testing Building Envelope Systems Using Infrared Thermography. Retrieved from www.snellinfrared.com
- United Nation Environment Programme (UNEP). (2017). Global status report: Towards a zeroemission, efficient, and resilient buildings and construction sector.
- United States Department of Energy. (2015). Increasing Efficiency of Building Systems and Technologies. In Quadrennial Technology Review.
- Wood, R. L., & Mohammadi, M. E. (2015). LiDAR Scanning with Supplementary UAV Captured Images for Structural Inspections. International LiDAR Mapping Forum 2015. Denver, CO.
- WuDunn, M., Dunn, J., & Zakhor, A. (2020). Point Cloud Segmentation using RGB Drone Imagery. 2020 IEEE International Conference on Image Processing (ICIP).
- Zhang, R., Stenson, T., Rais, A., Liu, Z., & Zhang, J. (2016). Definition of a reference residential building prototype for evaluating IAQ and energy efficiency strategies, Part 1: Energy.
- Zhang, W. (2014). Two-Dimensional Microwave Tomographic Algorithm for Radar Imaging through Multilayered Media. Progress In Electromagnetics Research, 144, 261–270.

Energy Modeling to Determine Optimum Order of Component Installation in Stepwise Retrofit Towards EnerPHit Standard

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ABSTRACT

As the world strives to drastically reduce energy consumption, the potential of the residential sector cannot be understated. While new construction has been shifting steadily to higher performance in energy efficiency, seen with voluntary standards and changing building codes, the transition for existing structures-the majority of the residential sector- is infrequent or inadequate. To help address this, Passive House Institute created the more accessible EnerPHit standard, which has the same principles as Passive House, but with slightly less stringent requirements, making it easier for the complications that are typical when retrofitting existing designs. Its overarching retrofit plan enables upgrades to be done an incremental manner overtime, without the risk of compromising the overall energy goal of EnerPHit certification. These are known as stepwise retrofits. Presently, there is no recommendation from the Passive House Institute on the optimal order for which these steps ought to be done, thereby providing little insight as to how such projects should begin and continue. The authors seek to determine the optimal order for implementation of the parts of a stepwise retrofit project through using energy modeling and an energy analysis to study the impact of the order of the implementation of each component. This order can be used not only to aid decisions for homeowners in terms of retrofit order and financing requirements, but also to show which steps have the least benefit for the cost, pinpointing areas primed for innovative ideas.

INTRODUCTION

It is well known that the residential building sector makes up a significant portion of global energy use and much of that energy goes into space conditioning. As a result, voluntary standards, such as Passive House, that focus on reducing heating and cooling loads to nearly zero in an effort to conserve energy have emerged. Such

programs have been popular and proven to the point where their lead tenets are starting to find their way into new construction codes (Weber, 2011). Codes for new construction, however, does little for a building already built. Considering the life span of buildings, 60% of buildings projected to exist in 2040 already exist today, meaning that if the strict global energy goals are to be met, existing buildings will also need to tackle their energy consumption (Architecture 2030, 2021). EnerPHit is the Passive House standard specifically for retrofit projects. Many of the details included in Passive House design such as site orientation, foundation design, shape, and sometimes even floor plan, are permanently set. EnerPHit acknowledges the challenges presented by existing buildings through lessening the strict standards to allow for certification based on components (Passive House Institute, 2015). EnerPHit also encourages phased retrofits where an overarching retrofit plan is carried out through one smaller project at a time until the whole home is retrofitted (Theumer, 2016).

Various studies have been done on the optimization for building retrofits with almost all the evaluation methods used in such optimization strategies based on economic parameters such as LCCs or LCCAs (D'Alpaos and Bragolusi, 2018). This can pose a problem because assumptions have to be made for future prices, and variations in these assumptions can drastically change the results of the optimizations (Pombo et. al. 2016). Therefore, it is good to look at energy reduction alone. This information can theoretically be paired with any applicable cost data to create payback period models for nearly infinite potential scenarios. However, there appears to be limited research on the optimization of component order based strictly on energy reduction. Prioritizing methods have been studied by modeling energy reduction based for each component to determine which component has the greatest effect. It found that building typology had a significant influence on the effectiveness of each strategy with building envelope components with larger surface areas having a more evident influence(Blazak, and Richman, 2013). A related study looking at the same housing typologies tried to optimize retrofit solutions and found that each typology could, in fact, reach the passive house standard, they just required different levels of retrofits according to the house typology, meaning a simple one-size-fits-all solution was not feasible (Jermyn and Richman, 2016). A Norwegian study, while not looking specifically at the effect of components, showed the feasibility of step-by-step retrofits (Hrynyszyn and Felius, 2019). These studies, while helpful to the advancement of project-based retrofits, did not investigate if the order of implementation also had an effect. Understanding this order can aid in the creation of phased retrofit plans. It can help homeowners and designers plan "step-by-step" retrofits and help the industry to determine which systems ought to be prioritized to aid in the uptake of certain retrofit strategies. If a certain component reduces the most energy use but tends to be overlooked due to whatever barriers, then the industry can focus on accessibility for those options. While these phased projects can be broken up into many small components, a simple study focusing on three components will

suffice to begin exploration into the effects of order on energy consumption reduction of single-family homes.

METHODOLOGY

The model used to study the effects of component order on energy reduction references a Toronto war-time house archetype, a simple wood-framed house with a rectangular floorplan than can feasibly be retrofitting to passive standards (Blazak and Richman, 2013). The single-story home has a 42' by 21' footprint with 8' wall heights. Our study of the effects of the order of retrofits was based on investigating the the reduction of energy consumption that can be attributed to three components - the three components studied here are the walls, the roof, and the windows. Studying the effects of order is done through combinations of retrofit packages, so the number of studies required is based on the number of components selected. Combinations require factorials of studies, so three components result in six cases, four components would require 24 cases, five components would require 120 cases, and so on. Three were selected to keep this study as an introduction to the question of the effect of order on energy reduction.

A model of the completely retrofitted home was developed using BEopt software. The R-values of the post-retrofit, or AFTER, model for the wall and roof were R-46 and R-85, respectively. The AFTER windows are triple paned, have a U-value of 0.10 and an SHGC of 0.6. These numbers are based on the recommendations of Passive House Institute of the U.S. (PHIUS, 2021a; PHIUS, 2021b) for buildings in ASHRAE climate zone 7. Each component was custom-made. The wall was made of a double studded 16in. o.c. and R-12 polyisocyanurate sheathing. The roof was all cellulose to reach the target goal of R-85.

Existing constructions were used to create the pre-retrofit, or BASE model. The walls were set to single wood stud walls 16in. o.c. with R7 fiberglass batt and no exterior insulation. The roof was similarly insulated, using R7 fiberglass batts, vented, in the unfinished attic. The windows were set to single pane non-metal frames. Only these three components were changed on the BASE model. Everything else was left as the post-retrofitted values of the original model. The effect of the order of these components on the overall energy consumption of the home was tested through modifying the BASE model was modified to include one of the three component retrofits. The energy use was recorded, then another component was added, another reading of the energy use, and then the final component was added to reach the fully retrofitted model. The difference in energy consumption is measured by subtracting the new energy use from the previous energy use. This is done for all the combinations of component orders.

RESULTS

Since the component retrofits all deal with the building's envelope, the change in energy use components is seen exclusively in space conditioning. The cases are written out in the order each component was installed, and these are referenced as "steps" in the proceeding figures and tables. For example, the retrofit of the windows is considered step 1 in cases A and B, step 2 for cases C and E, and step 3 for cases D and F. Figure 1 shows the total electricity use of the model at each stage of the retrofit process. The case study pre-retrofit uses 9648 kWh/yr of electricity in total and the post-retrofit house uses 6480 kWk/yr.



Figure 1: Total electricity use of model at various stages of the retrofit process.

The original value and the step 3 value remained constant because the pre-retrofit and post-retrofit scenarios are all ultimately the same regardless of component retrofit order, also called "steps". Since the total difference doesn't change, the reduction due to specific components for each case can be compared using percentages of the total difference between pre-retrofit and post-retrofit energy usage values. This can be seen in Figure 2. These were calculated by taking the difference of energy use results of before and after the component retrofit and dividing it by the total difference of 3168 kWh/yr.



Figure 2: Cases, the order in which the components were added, and the percentage of total energy reduction attributed to each component for that case.

The number of kilowatt-hours per year reduced due to each step can be seen in Table 1. Figure 3 shows the values of Table 1 in a visual format. This allows for an easier comparison across steps as opposed to components as shown in Figure 2.

	Case A:	Case B:	Case C:	Case D:	Case E:	Case F:
	Window-	Window-	Wall-	Wall-	Roof-	Roof-
	Wall-	Roof-	Window-	Roof-	Window-	Wall-
	Roof	Wall	Roof	Window	Wall	Window
Step 1	1160	1160	1113	1113	1046	1046
Step 2	991	1076	1038	1079	1190	1146
Step 3	1017	932	1017	976	932	976

Table 1: Energy reduction in kWhr/yr due to each step.



Figure 3: Energy reduction due to each step displayed graphically.

While each of the three components had about an equal share of reduction regardless of order, there are some key insights that can be gleaned. First, when a component is implemented first in the order, its effect on energy reduction is the same regardless of the order of subsequent retrofits. This makes sense, because it is the same procedure for both cases and thus the reduction will be the same. Perhaps what is less obvious is the fact that when a certain component is implemented last, it also has the same effect on energy reduction, regardless of the order of the preceding components. Interestingly, though, the reduction values the component sees when it is first is not the same as when it is last. This would mean that the first two (or the last two) components together would have to equal the same total reduction of energy. This means that the component in the middle is subject to even more change. As can be shown in figure 1, component values match among themselves when they are listed first and last, but no values repeat for components when they are in the second place of the retrofit order. Take, for instance, cases A and B from Figure 1. Window is the first component for both cases, and both cases show window accounts for 36.63%. In cases D and F, where window is the final component, window is responsible for 30.81%. In cases C and E, window reduces energy consumption by 32.77% and 37.56%, respectively. This means windows result in the most energy reduction when preceded by the roof retrofit and followed by the wall retrofit. Each of these reduction values are unique among the various components as well. Walls also perform best (36.17%) when second in order and preceded by the roof. The roof performs best (34.06%) when following the wall. Window's best (37.56%) is also the largest of all retrofit options and orders, while walls last produce the smallest result (29.42%). It is also interesting to note that each component's smallest reduction can be seen when it

is placed as the third and final component and that each component's largest reduction occurs when it is placed in the middle. However, it is not always the case that the third component has the smallest reduction, see case A. Nor is it always true that the second component is responsible for the largest reduction of the case, see case C.

With this information, it is clear to see that order has some effect on the energy reduction of component retrofits. If there was no effect, then the numbers would not change among the cases. However, a simple answer is not available, either. Since each component has its maximum reduction when placed second in the retrofit order, it is not possible to select an order in which each component has the largest reduction. Instead, an optimum case can be selected through a different values system.

The optimum solution is selected based on reducing the most energy as early as possible. This was done by selecting the cases with the largest reduction for the first round and the smallest reduction for the last round. By selecting the smallest reduction for the last round, this means the first two rounds in combination resulted in the highest reduction and that only a small amount remained to reach the AFTER model results. Window first has the largest reduction of the options, coming in at 36.62%, with Wall and Roof having 35.13% and 33.02% reductions, respectively. Between Roof and Wall, Wall was far less than Roof when placed last, with values of 29.42% and 32.10% respectively. As such, using this method, the optimum solution for this model is Window first, Roof second, and Wall last, with energy reduction percentages of 36.62%, 33.96%, and 29.42%, respectively.

DISCUSSION

While an optimum order for this case was recommended, it is easy to see how these results can easily be shifted. As shown by Blaszak and Richman (2013), different houses require different strategies to reach the same point. The study done here focused only on the effects of retrofitting strategies on one simple and small house. Changing things like wall-to-window ratio, surface area to volume ratio, etc. can considerably impact the effects each component has on energy reduction, effect of order aside. In addition, since there is no clear trend, it is not certain yet whether any trends or effects are present. Increasing the number of components and exploring different housing types can help answer these questions. Unless clear trends can be found with the expansion of the study, optimization of energy reduction for such studies can still utilize the method used here, where the cases with n number of components use the largest reduction for component one through n-1, which result in selecting the option with the smallest value for the final component. While this optimization may work for energy reduction as the only selection criteria, it is easy to see how these optimizations could quickly change if other evaluation strategies, such as life cycle cost assessments or embodied carbon, were employed. This is

particularly apparent on a small study such as this, where the differences between components are minimal. Analyses that require many assumptions and are affected heavily by changing global markets. So, while the magnitude of the energy reduction values may change with the expansion of component options and housing typologies, these decisions are concrete ones and can be modeled relatively easily. Having such a base can then be paired with more fickle values, such as economic data, to help quickly create additional evaluation methods for retrofit projects.

CONCLUSION

The purpose of the study was to determine if implementation order of component retrofits has an effect on their respective energy reduction. It is not unreasonable to assume that retrofit measures would reduce the energy of a building by the same amount regardless of order, particularly in this study where all of the retrofit projects are part of the envelope and only affect the energy used for space conditioning. This would have potentially made optimization based on energy reduction as simple as a question of component surface area. However, it does not appear that such uniformity and consistency of energy reduction is the case. What is clear that order can and does affect the energy reduction caused by that component. What is not clear, however, is why that is the case. This makes it difficult to claim a general "optimum order" for stepwise retrofit projects.

The optimum solution for energy reduction for the house using the retrofit projects depicted here are based off of the found energy reduction results of this particular study. To optimize energy reduction, the component with the largest reduction for step 1 was selected. Next, step 2 for the cases that had the largest initial energy reduction were analyzed, and the component that had the largest reduction was picked. This way, the energy consumed by the building would be reduced as fast as possible. The optimum order for the case study model is to do the windows first, then retrofit the roof, and finish with the walls. This optimization process will work for any project similarly modeled, it will just require the full modeling at this stage to obtain all the reduction values, since there are no overarching and ubiquitous patterns. Small insights were found, like components have their largest respective reduction when placed second and smallest when placed last, or how a single component will have the same value regardless of the order of the other components when placed first. The same is true when placed last, but the value is not the same as when it is in the first position. However, it is not clear if these findings are constant or will vary with changes in modeling procedure.

In addition, the differences in values between the various components were certainly present, but not very large, indicating that results can easily be overpowered when paired with additional data, such as cost implications. It is fair and reasonable, however, to want to know how this additional information can impact how one

defines "optimum order". Studies that focus on energy reduction, however, form a very useful framework for such advanced analysis and thus ought to be encouraged.

Additional work must be done to include a larger number of retrofit component options as well as different building typologies. Additional questions can also be explored, such as what happens if two components are implemented at the same time. Also, the question of "practicality" is not one to be taken lightly and should also be included in future work. By expanding upon this study, insights and patterns might be found to answer the initial question of optimum order for stepwise retrofits.

REFERENCES:

- Architecture 2030. (2021, February). Existing Buildings Actions. Architecture 2030. https://architecture2030.org/existing-building-actions/
- Blaszak, K. M., Richman, R. (2013). Prioritizing Method for Retrofitting Toronto's Single-Family Housing Stock to Reduce Heating and Cooling Loads. Journal of Architectural Engineering, 19(4), 229-244. Doi: 10.1061/(ASCE)AE.1943-5568.0000102
- D'Alpaos, C. & Bragolusi, P. (2018). Buildings energy retrofit valuation approaches: State of the art and future perspectives. Valori e Valutazioni, (20) Retrieved from http://ezaccess.libraries.psu.edu/login?url=https://www-proquestcom.ezaccess.libraries.psu.edu/scholarly-journals/buildings-energy-retrofitvaluation-approaches/docview/2531523085/se-2?accountid=13158
- Hrynyszyn B.D., Felius L.C. (2019) Upgrading of a Typical Norwegian Existing Wooden House According to the EnerPHit Standard. In: Johansson D., Bagge H., Wahlström Å. (eds) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham. https://doi.org/10.1007/978-3-030-00662-4_16
- Jermyn, D., Richman, R. (2016) A process for developing deep energy retrofit strategies for single-family housing typologies: Three Toronto case studies. Energy and Buildings, 116, 522-534. doi: 10.1016/j.enbuild.2016.01.022
- Passive House Institute. (2015) EnerPHit certified retrofits with Passive House components. Passive House Institute. https://passiv.de/en/03_certification/02_certification_buildings/04_enerphit/0 4_enerphit.htm. [Accessed 22 7 2020].
- PHIUS. (2021). Passive house FAQS. FAQ: Passive House Institute U.S. Retrieved August 1, 2021, from https://www.phius.org/what-is-passive-building/passive-house-faqs.

- PHIUS. (2021). Performance criteria by climate zone. Performance Criteria by Climate Zone : Passive House Institute - United States. Retrieved August 1, 2021, from https://www.phius.org/phius-certification-for-buildingsproducts/phius-verified-window-performance-data-program/performancecriteria-by-climate-zone.
- Pombo, O., Rivela, B., Neila, J. (2016) The challenge of sustainable building renovation: assessment of current criteria and future outlook. Journal of Cleaner Production, 123, 88-100. doi: 10.1016/j.jclepro.2015.06.137
- Theumer, Susanne.S. (2016) Step-by-step retrofit to achieve EnerPHit Standard, the example of a single-family home. International Passive House Association/Passivehouse Institute [Brochure]. Retrieved from https://passipedia.org/_media/picopen/microsoft_word_-___06_fachinfo_schrittweise_modernisierung_sth.pdf. Website: passipedia.org/planning/refurbishment with passive house components.
- Weber, V. (2011). Passive House in local, state, and national codes successes and others. Presentation, https://www.phius.org/NAPHC2011/Weber-PHCode.pdf.

Creating a Virtual Environment for Safety Data Collection of Small Construction Businesses

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ABSTRACT

The residential construction industry in the United States is a complex system of interdependent businesses and workforces. Many of these businesses qualify as small businesses (under 19 employees), which are known to have challenges accessing technical resources, enforcing safety regulations and protocols due to a reduced amount of organizational structure with few personnel for oversight. Other disadvantages include that rates of injuries in small businesses are often underreported and small business needs are not often considered when safety legislation or regulation changes are proposed. A challenge in working with many small businesses is to find unique and valuable ways to engage with employees. Several authors have noted success using game-based system including virtual reality (VR) and social networking campaigns to facilitate safety assessment and training. The purpose of this paper is to discuss the development a novel VR environment for assessing safety knowledge and planned survey activities focused on residential construction workers. Survey deployment the VR environment will use local home building associations (HBAs) to engage workers in a non-regulatory environment compared to previous methods.

KEYWORDS

Construction Safety, Virtual Reality, Home Building Associations, Residential Construction
INTRODUCTION

Small Businesses in Residential Construction

The residential construction industry in the United States is a complex system of interdependent businesses and workforces (Memari et al. 2014). According to estimations based on a survey by the National Association of Home Builders, 96% of homebuilders, 94% of land developers, and 97% of specialty trade contractors qualify as small businesses (NAHB 2008). Small businesses have several distinct challenges including less access to technical resources, lower organizational structure, and less oversight personnel. According to the National Occupational Research Agenda (NORA) for construction, "managers in small businesses often work in isolation without sufficient access to peer opinion and industry best practices." (CSC 2018)

Most of the health and safety regulations applied to construction are based on experiences of large firms which have detailed organization and specifically designate safety personnel (Legg et al. 2015). However, small businesses in residential construction do not have such specialized personnel, even for safety. Several authors have noted that small businesses in construction are exposed to more safety hazards and workers in these firms may suffer more injuries and illnesses (Micheli and Cagno 2010, Sørenson et al. 2007).

Safety Assessment and Training Needs

An essential part of the Occupational Safety and Health Administration is the legal obligation to provide accurate and timely information about occupational safety and health to workers. Methods of information dissemination related to safety information can be defined as risk and health communication, including characterizing hazards, risks and risk-reducing actions, and training and education, including instruction in hazard recognition and use of protection (Schulte et al. 2003). Masi and Cagno (2015) explored barriers to occupational health and safety (OSH) interventions and found that regulation, resources and information were three of the main issues.

Current events have also impacted the ability of residential construction due to the COVID-19 pandemic. Alsharef et al. (2021) surveyed early impacts of the COVID-19 pandemic (data provided up to July 2020) and identified disparities of construction operations being considered essential, material shortages, delays in inspections and permits, reductions in efficiency, slowing or suspension of projects, and price escalations. New safety measures related to COVID-19 were also adopted, including social distancing, the use of masks, increased training, temperature checks, and increased use of cleaning products.

The recent challenges of the COVID-19 pandemic has also shown a need for updated information dissemination, but also a change from traditional classroom methods. Even before the pandemic, Eiris et al. (2018) noted that "current lecture-based and passive methods of teaching hazard identification are losing their relevancy" (p.1).

Safety assessment tools are an important part of construction safety research in terms of assessing the initial knowledge level (pre-treatment) and knowledge level after

intervention (post- treatment) for documenting safety interventions (Choudhry, 2009; Jazayeri & Dadi, 2017; NIOSH, 2020). Assessment of current knowledge level can help document training activities (Huang & Yang, 2019). Assessment tools can consist of structured questions, semi-structured interviews, or focus groups to spark discussion. From a statistical viewpoint, more structure embedded in a survey tends to represent a more rigorous statistical model which can be tested for accuracy and validity (Cheung, 2014).

However, many participants tend to dislike highly structured surveys because of the analytical nature, and rigid structure. Unintentional bias in the choice of questions or wording may also influence participants' response or lack thereof. Also, detailed surveys may ask for specific safety-related incidents which can erode participant anonymity. A review of current construction safety topics related to the use of surveys shows emphasis on the use of surveys, but little study of how to improve response rates or content generated. This points to the need for better and more engaging survey tools within the domain.

Eiris et al. (2018) suggests the use of virtual reality (VR) technology for the creation of an active engaging environment. The use of panoramas of reality (PARS) was investigated for construction safety training. Prior to this, other authors have used VR for training (Lin et al. 2011; Wang and Dunston 2007). Furthermore, remote VR methods for training and assessment can also address safety concerns related to COVID-19 procedures, which limit surveyor proximity to workers and eliminate sanitation of writing utensils and surfaces. Since younger workers are more familiar with gaming related platforms and environments, there may be an increased level of comfort for these future workers.

Purpose of Paper

In reviewing current construction safety research sources, the use of VR technology has been explored for training and simulation purposes, but has received minimal attention for use in survey and knowledge collection. We feel that such a tool may be a valuable way for workers to "interact with the survey itself" and help generate a richer form of context and data. Virtual environments may also allow greater anonymity of the participants which could reduce bias and associated stigmas and, we hypothesize, bring out more truthful responses to scenarios posed in the VR environment. The purpose of this paper is to develop a virtual environment tool for assessing safety knowledge in residential construction.

Following the work of Marin and Roelofs (2018) to use community-based participatory research strategies to engage small businesses, we have begun establishing a relationship with local home builders associations (HBAs) in the region of Soutwestern Virginia to serve as a point of contact with residential construction firms. HBAs provide an important link to the residential construction community, serving as a conduit for education, networking and mentorship. HBAs also are linked to state programs and the National Association of Home Builders (NAHB). Due to the lobbying of NAHB, residential construction was declared an essential occupation in March of 2020 (NAHBNow 2020) and allowed to continue working during the pandemic. As well as safety assessment questions, the workers were also questioned

about their knowledge and understanding of the HBA resources to hopefully inspire companies to further their involvement in HBA and gain more knowledge about construction safety.

METHODS, STRATEGIES, AND TOOL DESIGN

The main data collection tool will explore the use of a virtual reality environment, using customized Mozilla Hubs, for improving the efficacy and richness of context within the survey environment. The research tools will bridge the gap between the surveyor and target population via three types of online survey tools, one of which will be a unique virtual reality surveying instrument (via Mozilla Hub). The virtual reality tool will allow the target population to interact with an environment that is symbolic of an actual job site and allow them to respond to questions/scenarios that will 'test' the user's working knowledge or decision-making skills associated with the topics presented.

Designing the Mozilla Hubs Virtual Reality Survey Tool (Hubs VR Survey)

The Hubs VR Survey was created using the free source, Mozilla Hubs. Mozilla Hubs is first and foremost a customizable social chat room. Our team's decision to use Mozilla Hubs was because it is a free resource for uploading and sharing 3D rooms and can be accessed by anyone with a smart device and moderate internet connection. Once a 3D room is published to the Hubs server, it is given a unique URL. Because of this, the number of users in a particular VR environment can be limited to control anonymity. Mozilla Hubs is primarily used for social gatherings and teaching through videos, live broadcasts of presentations, embedding pdfs for material browsing, and embedding URL links to outside questionnaire surveys and other external resources.

The Hubs VR Survey will have two aspects to it: teaching and data gathering. The teaching aspect will relay information about the HBA and construction safety. On the other hand, the data gathering will be completed by recording the user's session within the VR environment. The ingenuity of the Hubs VR Survey tool lies with the creativity of the developers in designing the interactive scenarios. Mozilla Hubs has limited user interaction with objects and the types of content that can be shared (videos, pdf, linked websites). Developers were tasked with creating multiple ways to use these features such that data could be gathered from the interactions and meaningful conclusions drawn

In addition, Spoke is a free, powerful, and easy to use online editor developed for Mozilla to create scenes and publish as 3D rooms. A scene is created in Spoke by either uploading already developed 3D scenes or using Spoke's architecture kit to build customized scenes. Spoke also allows developers to upload 3D objects as glb files into scenes with objects being static or animated. Multiple objects can be uploaded to create scenarios for users to observe or tasks for users to complete. For this project, the team utilized free 3D objects from Skecthfab and CGTrader. The 3D objects were imported as gltf files into Blender, a free and open-source 3D graphics software tool, and then converted and exported as glb files into Spoke.

Survey Process

Before entering the Hubs VR Survey, participants will complete an online questionnaire survey to gather demographic information. Questions include company trade, job title, years of experience, HBA membership length, and questions to gauge the participants' level of familiarity with computer technology. The online survey concludes with a url linked directly to the customized Hubs VR Survey.



Figure 1. Outline of Safety Assessment Procedure

While within the Hubs VR Survey, participants will navigate through four rooms, each with various scenarios. Room 1 is designed to be a Jobsite Trailer. The user will watch a tutorial video from within the Hubs environment and familiarize themselves with navigation controls by completing a simple click, drag and drop task. The tutorial video will also inform the participant of their role in the VR environment, which is to act as a site supervisor for a house remodeling project by inspecting each room for safety risks. The exit door to the Job Trailer will be a link to Room 2.

Room 2 will simulate the exterior of a jobsite and contain various scenes and objects for the user to review, interact, and comment on. The exit of this room is located at the garage door, which links to Room 3.

Room 3 begins in the garage, which is new construction, and ends inside the home. This room will also provide various scenarios and objects for the user to observe and comment on. It will also contain a 3D photograph of a real jobsite. The 3D photograph appears as a bubble in which the user will walk into and observe the site with a full 360 degree view. The exit door will link to the final room, Room 4.

In Room 4, the user will be debriefed on the various safety hazards presented in the previous rooms. Also, billboards and navigable pdfs will be displayed for the user to review information about the HBA and the scenarios they were presented in each room.

The Hubs VR Survey will conclude with a link to an exit interview questionnaire survey. The questions are centered around the user's knowledge of the HBA, what HBA benefits they receive and take part in, construction safety, and questions regarding their user experience in the VR environment.

CONCLUSIONS / FUTURE WORK

In Phase I, the authors will collect data from the local HBA and its current members using the described customized VR environment. Survey questions will explore needs and assumptions of safety knowledge, as well as the intended value of HBA membership, the perceived value, and where education plays a part. This data will be used to inform the creation of a novel data collection tool for exploring non-members' beliefs on the value of association membership. Some questions will be sensitive in nature with regards to safety training practices, job site safety practices, and a company's ability to afford membership. The authors will create an online environment to explore non-member needs that will be interactive and provide participants with a safe and anonymous environment to respond to questions and scenario-based casestudies created based on interactions with local HBA leadership and current members.

In Phase II, the authors will use the virtual environment to survey construction workers who are NOT currently members of the local HBA in order to assess the role the association plays in transferring pertinent safety information. After surveying a large population, a small cohort will be invited to join the local HBA with a one-year sponsored by the research. During the year of membership, subsequent surveys will be conducted to determine if changes in responses are evident by participation in the HBA activities. The intent of this phase is to document the value of HBA participation and hopefully inspire these companies to continue participation in the HBA on their own.

In conclusion, the authors feel that a potential method to increase communication and safety knowledge among residential construction firms is to encourage engagement in the local HBAs. In addition, augmenting the HBA experience with aVR survey tool and interactive activities can result in an engaging platform to create a unique safety education experience.

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REFERENCES

Alsharef, A., Bannerjee, S., Jamil Uddin, S. M., Albert, A., Jaselski, E. (2021). "Early Impacts of the COVID-19 Pandemic on the United States Construction Industry," *International Journal of Environmental Research and Public Health.* 18, 1559.

Cheung A.K.L. (2014) "Structured Questionnaires," In: Michalos A.C. (eds) *Encyclopedia of Quality of Life and Well-Being Research* (pp. 6399-6402). Springer. <u>https://doi.org/10.1007/978-94-007-0753-5_2888</u>

Choudhry, R., Fang, D., Lingard, H. (2009). "Measuring Safety Climate of a Construction Company," *Journal of Construction Engineering and Management*. DOI: 10.1061/(ASCE)CO.1943-7862.0000063.

Construction Sector Council, CSC. (2018). *National Occupational Research Agenda for Construction*. <u>https://www.cdc.gov/nora/councils/const/agenda.html</u>

Eiris, R., Gheisari, M., Esmaeili, B. (2018). "PARS: Using Augmented 360-Degree Panoramas of Reality for Construction Safety Training," *International Journal of Environmental Research and Public Health*. 15(11): 2452.

Huang, Y. & Yang, T. (2019). "Exploring On-site Safety Knowledge Transfer in the Construction Industry," *Sustainability*. <u>https://doi.org/10.3390/su11226426</u>

Jazayeri, E., & Dadi, G. B. (2017). "Construction Safety Management Systems and Methods of Safety Performance Measurement: A Review. *Journal of Safety Engineering*, 6(2), 15-28.

Legg, S. J., Olsen K. B., Laird, I. S., and Hasle, P. (2015). "Managing Safety in Small and Medium Enterprises," *Safety Science*. 71: 189-196.

Lin, K. Y., Son, J. W., Roja, E. M. (2011). "A Pilot Study of a 3D Game Environment for Construction Safety Education," *Journal of Information Technology in Construction*. 16, 69-83.

Marin, L. S., C. Roelofs. (2018). "Engaging Small Residential Construction Contractors in Community-Based Participatory Research to Promote Safety", *Annals of Work Exposure and Health*. 62(S1):S72-S80.

Masi, D., Cagno, E. (2015). "Barriers to OHS Interventions in Small and Medium-Sized Enterprises," *Safety Science*. 71, Part C, Janurary 2015: 226-241.

Memari, A. M., Huelman, P. H., Iulo, L. D., Laquatra, J., Martin, C., McCoy, A., Nahmens, I., Williamson, T. (2014). "Residential Building Construction: State-of-the-Art Review," *Journal of Architectural Engineering*. 20(4): B4014005.

Micheli, G. J. L., and Cagno, E. (2010). "Dealing with SMEs as a Whole in OHS Issues: Warnings from Empirical Evidence," *Safety Science*. 48, 729-733.

National Association of Homebuilders (NAHB). (2008). *Residential Construction Fatalities 2003- 2006*. Washington, DC. NAHB, <u>https://superanchor.com/wp-content/uploads/2018/09/NAHB_Fatality_Study.pdf</u>.

NAHBNow. (2020). "DHS Designates Residential Construction as 'Essential Infrastructure Business'," <u>https://nahbnow.com/2020/03/dhs-designates-residential-</u>

construction-as-essential- infrastructure-business/

The National Institute for Occupational Safety and Health (2020). "New Survey Uncovers Construction Safety," <u>https://www.ishn.com/articles/112780-new-survey-uncovers-construction-safety/</u>

Schulte, P. A., Okun, A., Stephenson, C. M., Cooligan, M, Ahlers, H., Gjessing, C., Loos, G., Niemeier, R. W., Sweeney, M. H. (2003). "Information Dissemination and Use: Critical Components in Occupational Safety and Health," *American Journal of Industrial Medicine*. 44: 515-531.

Sørensen, O. H., Hasle, P., Bach, E. (2007). "Working in Small Enterprises – Is There a Special Risk?," *Safety Science* 45, 1044-1059.

Wang, X., Dunston, P.S. (2007). "Design, Strategies, and Issues Towards an Augmented Reality-Based Construction Training Platform. *ITcon*. 12, 363-380.

Site Net Zero Target Contemporegional Architecture – The Barn Haus in Utah

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1. <u>THE BARN HAUS - INTRODUCTION</u>

As a clear, impactful and innovative contribution to sustainability and resilience, the collaborative and interdisciplinary Barn Haus project in Holladay, Utah (Fig. 1, 3, 4) was initiated in 2017 with clients requesting a high-performance, possibly site net zero home for the Salt Lake Valley specific climate. The project outcome shows that resilient, sustainable custom-designed buildings can be developed at high quality within market-rate cost for the location, therefore considerably raising the bar for residential buildings along the Wasatch front and beyond. The goal was reached through application of an integrated process that explored means of passive-to-active house strategies, architectural minimalism, and by focusing decisively on the genius loci in combination with a custom-tailored program and high building performance goals. With the PH (Passive House) approach being an established standard for energy efficient buildings in many parts of the developed world, the standard comes with systemic disadvantages that can be overcome by including Active House strategies (Hegger, Fafflok, Passig, 2013). Especially when staying within a relatively fixed budget, the combination of the two standards help to reach such goal by carefully gauging requirements of both systems against each other, to carefully move the dial towards either more passive or active systems to fulfill the defined comfort and performance requirements.

In the author's function as a professor at the University of Utah's School of Architecture, the project was also taken into the classroom in form of lectures and frequent site visits during the academic years 2018/19 and 2019/20.

2. <u>DESIGN METHOD</u>

2.1 Design philosophy

Albert Einstein once said: "Everything should be made as simple as possible, but not simpler." In today's world, we have lost this approach in many regards, including the ability to concentrate on the essence of things. This applies to architecture, too, and, with few exceptions, is well documented in the built environment with which we surround ourselves in many places. Especially in the field of residential design and construction in the US, architectural design is repeatedly confused with the functional organization of large quantities of spaces, which, at their best, conform to code, but lack spatial, architectural, daylight and especially performative qualities. Often, the results are pricey, poorly performing buildings with low spatial, thermal and indoor air quality and a limited expected lifetime. To find a way back to the essence of good architectural design, the author based the Barn Haus design philosophy on the following four pillars:

- 1. Focusing on the essence of things to omit items unnecessary is key to successful design, sustainability and high performance in architecture and urban design;
- 2. This allows addressing the complexity required in the creation of modern high performance buildings through implementation of an integral design approach with a holistic perspective;
- 3. The *quality* of the detail and its execution determines the level of quality of the overall work;
- 4. Successful architecture and urban design include aspects of both *regional and global* context.



Figure 1: South and entry façade of the Barn Haus in Holladay, Utah

As a result, the Barn Haus is carefully placed into its south-facing slope at the bottom of the Western Rocky Mountains, opening up to the southwest into Salt Lake Valley and offering tremendous views and a perfect solar winter exposure. Located on a former horse pasture, the site findings allowed for an abstract formal and spatial interpretation of Utah's traditional barn outbuildings, creating a strong sense of place and following the Utah *Contemporegional* architectural style defined by the author in previous projects (Rügemer, Carraher, 2015). Based on these regional elements of traditional barn architecture, the building's architectural aesthetic carefully blends with a minimal to modern, contemporary architecture approach. By focusing on formal clarity and reduction in shape and materiality, the solution recalls the straightforward functionality of agricultural buildings, yet clearly establishing the expression of a residence.

2.2 Project goals

To create a case study for the region and its climate zone, the author and clients, at the beginning of the design process, defined the following goals:

- Development of a highly resilient and sustainable residential building;
- Contemporary and minimal architectural design, rooted in the regional context;
- Minimized site impact with a good surface to volume ratio;
- 75% energy-efficient over the 2015 IECC code standard on the Passive Design side and technology optimized to building performance;
- Integrated energy modelling to optimize design, passive strategy and long-term component moisture control;
- Use of robust, durable and fire resistant construction and construction materials, to enhance long-term building resilience and minimize building maintenance;
- Market-transferability;
- Construction cost within local market rate cost.

2.3 Collaborative and integrated project approach at residential scale

The applied collaborative and integrated project approach became crucial for delivering the Barn Haus as a high-performance building. The clients were integral part of every decision throughout the entire process, when they described their key requirements for the design of the house. The author in his role as the architect interpreted those desires and transformed them into architectural, functional and performative solutions, which were then further discussed, evaluated and finally developed. The contractor joined the team during the design development phase, to consult in questions of constructability and economy. Throughout all following phases, the author also worked in close collaboration with the subs, engineers and the local building department, with the overall process coming close to a Design Build process (Fig. 2).



Figure 2: The Barn Haus collaborative project team approach

3. <u>DESIGN & PERFORMANCE</u>

3.1 Site considerations

The integration into its Genius Loci at roughly 5,300' elevation became an important driver for the design process, including all characteristics of existing topography and landscape with its view orientations and consideration of framing the layers of traditional image composition: the foreground (immediate mountain landscape to east and north), the middle ground (the city) and the background (far valley views to south and west). Daylight conditions, and with it the potential for passive solar heat gain, were also important for careful building orientation and the vigilant placement of openings in the building's envelope. More pragmatic aspects, such as minimizing cut-and fill, with the design working *with* the site constraints rather than against it, building access, and all aspects of a passive-to-active high performance defined the framework in which the building was further developed.



Figure 3: The Barn Haus in its context on a south-facing slope of the Rocky Mountains

3.2 **Program and interior**

When approaching the author, the clients brought with them plans for a 5,500 sq.ft. home designed by a local architect for the same location. The design ignored any specific site condition, with the only contribution to sustainability and resilience being a 16-module PV-array on the roof that would barely cover the building's general electrical consumption, not to mention heating and cooling loads. A holistic approach that included a careful re-analysis of the client's program requirements and key considerations for the design of the house resulted in simplification and 30% space reduction of the building without sacrificing the client's spatial or programmatic needs. This strategy instantly saved 30% in embodied energy and materials before the team restarted the design process.

The building mass was then optimized to its external surface area to internal TFA (Treated Floor Area) ratio and divided into the Main House (communal spaces) and the East House, which accommodates more private functions and the bedrooms. Both Houses are connected by the Stair House, which includes the interior vertical circulation articulated as a sculptural Canadian maple staircase. Designed as a functional art piece that appears to be carved out of a solid block of wood, the wood stair is an abstract interpretation of the client

spouse's occupation as a former piano player and opera singer, where the trellis reminds of the strings of a piano and functions as a spatial divider and safety barrier to the corridor. Simultaneously, daylight penetrates the space in a subtle, every-changing and poetic way.

The interior of the Barn Haus follows the client's functional requirements and their daily routines, with each space specifically designed around daylight access and framed views. The communal space of the main house – the Barn Space - includes the kitchen, dining area and living room, which are located above the garage, thus referencing traditional agricultural buildings that often located livestock underneath their living quarters for additional heat gain during the cold seasons (Fig. 4). The Barn Haus interprets this traditional approach into today's modern world, using the off-heat of car engines for additional heating support in the building, and until electric vehicles will entirely replace those. The building will then follow the principle of Werner Sobek's F87 case study house in Berlin (Architizer, 2011), where the house extends its function beyond shelter to become an electric's car "gas station" (Michaely, Schroth, Schuster, Sobek, 2012).



Figure 4: The common living room/dining/kitchen in the Barn Space. The author's Barn Haus table is part of the design of the house, and continues the 'reveal theme' that one can find throughout the building's interior.

The private quarters are separated through the staircase house and a longer corridor to the east. An office space and guest room are located on the same level as the main space, with the master and children bedrooms located more remotely on the top level of the east house. The basement offers an acoustically insulated music and movie room with its own bath and entrance, thus also functioning as an additional guest suite.

The most important, highly dynamic 'material' applied throughout the house is daylight, which has been carefully orchestrated for each space, providing an

amazing, every-changing vibrancy. The interior design focuses on the utilization of very few materials: a neutral, daylight-reflective non-VOC (Volatile Organic Compounds) white paint for all walls and ceilings, and a warm, Canadian maple hardwood for all floors, the staircase, the window frames, and the Barn Haus dining table that occupies the center of the Barn Space. This conscious reduction in materials allows the owners to define their lifestyle through the elements and components that they bring into the building.

3.3 Material choice and indoor environment

In times of severe global climate change, the American Southwest with Utah is especially affected by prolonged periods of drought and extreme temperatures during the summer and fall months. Stark forest and bush fires have become the new 'normal', with the annual fire season starting two months earlier and extending several additional months into the later fall. As a reaction to this real threat, the Barn Haus is protected by a continuous layer of highly durable, maintenance-free and, most importantly, non-combustible materials along its exterior: Ökoskin concrete siding, metal roofing, aluminum exterior window cladding, concrete, stucco and glass. In tandem with a 50-feet fire zone around its periphery, the Barn Haus withstands wildfire hazards better than the standard residential building in the region, adding additional peace of mind to a structure that already offers a highly resilient shelter to its occupants on the energy, performance and thus disaster-survivability side. Even though initially slightly pricier, the chosen materials have a positive impact on the mid-term Return on Investment of the Barn Haus: they are extremely durable and do not need maintenance such as painting or other upkeep, thus also contributing to the building's overall material and embodied energy sustainability. All materials have been carefully selected for a minimized environmental impact and to ensure highest indoor environmental and air quality by avoiding VOCs and offgassing materials, focusing on natural and long-lasting supplies and applications. As part of the PH approach, a Zehnder whole-house ERV (Energy Recovery Ventilation) system with series-connected MERV 7 and 14 filters provides a continuous stream of pre-conditioned, clean and healthy air into the house, blocking PM2.5 pollutants from entering the building during times of severe winter inversion that frequently occur within the Salt Lake Valley (EPA, 2021, Lewis 2014).

3.4 Sustainability and resilience

From the onset the Barn Haus was designed with site-net-zero performance and exceptional sustainability and resilience goals in mind. Starting with simple interventions such as a directly south-facing orientation, simultaneously considering the topography for a reduction in necessary earth movement, the building mass was then optimized towards an external surface area (10,745 sq.ft.) to internal TFA (the net conditioned floor area of 3,240 sq.ft.) ratio of 3.3, which is still within an acceptable ratio for PH performance (Lewis, 2014). As per Passive House Planning Package PHPP (PHIUS, 2021), the building's

envelope components are rated R-45 (exterior walls), R-42 (walls against ground), R-34 (floor slab) and R-60 (roof) respectively. Following the strict PH standard, a 12", double-stud offset wall construction has been applied throughout, filled with 2" closed-cell Icynene along the outer sheathing and 9" cellulose (Blown-In-Blanket) for the remaining cavity; the roof provides a 16" cavity that was filled with 4" of closed-cell Icynene and 12" cellulose BIB, to avoid any moisture issues in the warm roof assembly (Corner, Fillinger, Kwok, 2018). The more complex-than-standard wall and roof assemblies have been simulated in WUFI pro and Ubakus software to ensure the elimination of any possible moisture accumulation over the lifetime of the building.

The radiantly heated and cooled ground floor slabs are thermally separated from the foundation and stem walls and float on a 10" layer of continuous rigid insulation and structural Geofoam; furthermore very careful detailing led to the house being executed with an overall thermal bridge-free construction (Lewis, 2014). In tandem with operable Zola high-performance window and exterior door units, and a highly airtight (0.8ACH₅₀) building enclosure (US DOE, 2019), the Barn Haus was simulated to be an average of 77% efficient over the applicable Utah code standard, which was the 2015 International Energy Conservation Code IECC at time of permitting. This offers a realistic opportunity to offset the remaining energy required with an addition to the 6.3 kWp photovoltaic system (Wikipedia, 2021), to reach site net-zero performance. As build and in operation, the building's performance goals already supersede the AIA sustainable architectural practice position statement and the AIA 2030 commitment, which currently call for a minimum 60% reduction in energy usage from regional baselines.

Based on the performance metrics and 18 months of occupancy experience, the Barn Haus will provide acceptable indoor temperatures and adequate shelter in case of serious emergencies, disasters or local severe weather events. The minimum measured winter temperature without system running was 59°F; the maximum summer temperature without systems was 82°C. These temperatures are certainly outside ASHRAE comfort range, but guarantee occupant survival in case that the systems are completely shut down due to a longer-term possible service interruption. In such case, only the windows would need to be opened occasionally to ensure fresh air exchange. Being designed and constructed with ecological stewardship in mind, the author and clients are confident that the Barn Haus will raise the bar for qualitative, environmentally responsible residential construction along the Wasatch front and beyond.

3.5 Energy systems and system performance

Using simplicity to address complexity, the building's initial 30% reduction in size contributed to a major reduction in embodied and operational energy. By the end of the schematic design process, the stakeholders agreed that the reduction of materials and embodied energy represented a serious step towards carbon reduction, at the same time setting a different bar for the building's day-

to-day energy use due to the reduced amount of conditioned space. For heating and cooling, the Barn Haus is designed for electric-only performance on the HVAC side. A linear, 500 feet horizontally looped geothermal heat-pump system was installed in the foundation excavation, thus not requiring additional excavation or any vertical drilling. The system eliminates a noisy, less comfortable forced air system and exterior compressors, and utilizes the concrete-embedded radiant floor loops for both heating and cooling throughout the house, a strategy that is allowed in residential buildings in Utah due to the region's hot and arid summers. The required, 1 ½" concrete slabs on all upper floors, in tandem with the 4" concrete, insulated ground floor slab provide sufficient thermal mass to minimize temperature undulation throughout any given day. A continuous stream of fresh air is provided by the ERV system, raising the indoor air quality well above required standards.

Utilizing Sefaira energy performance modeling tools, a 69% (cost) to 81% (EUI) saving above IECC 2015 code-standard simulated performance was achieved in the as-build version (Fig. 5). The projected EUI is 8 kBTU/sf²/yr, and projected annual energy consumption is 21,183 kWh, compared to 91,603 kWh for the same building constructed to code standard, which constitutes a 77% improvement (Fig. 6).

1	Baseline Concept	PTHP / Split System	8 ~81%	11,172 -04	16,258 ¥ 80%	\$736 ~69%
2	CODE STANDARD 3,769 R ²	HVAC System Type Fan Coil Units and Central Plant	44 kBTU/tt²/yr	O kWh	81,523 lbCO ₂₀ /yr	\$2,382
			EUI	Renewable Energy G. •	Annual Net CO ₂₄ Em •	Annual Energy Cost •
	Baseline Concept	HVAC System Type	EUI -	Renewable Energy G.	Annual Net CO ₁₆ Em., -	Annual Energy Cost
1	Baseline Concept 3,769 ft ² Conce (1) for (1) for concerned	HVAC System Type PTHP / Split System (System 2)	EUI -	Renewable Energy G	Annual Net CO ₂₆ Em + 16,258 (bCO ₂₆ /yr	Annual Energy Cost •

Figure 5: Sefaira simulated performance comparison of the code-standard version (above) and the as-built Barn Haus baseline

The interpolated numbers of the first 18 months of an ongoing 30-month Post-Occupancy Monitoring (POM) phase show that the occupants used an overall of 23,324 kWh per year, which is 10% above the simulated number. Of that 23,324 kWh, interpolated 8,866.8 kWh came from the 6.3 kWp photovoltaic system installed on the two roofs, which roughly corresponds with the installer's projected annual system performance. This leaves 14,457.6 kWh per year that need to be offset through additional PV panels in the future, which corresponds to an additional 9.45 kWp or 30 additional PV panels. This does not yet include the potential for additional energy savings by optimizing the operational use pattern and take more advantage of the passive character of the house.



Figure 6: Sefaira simulated Total Energy comparison of the code-standard version (left) and the as-built Barn Haus (right), averaging a 77% improvement over a standard building

4. <u>CONCLUSION</u>

Thermal comfort, interior health and market-rate cost goals have been successfully reached with the construction of the Barn Haus. The building's performance will be further monitored until mid-2022, to allow for a final conclusion and the building's feasibility for a 100% site-net-zero energy offset. The clients repeatedly expressed that they love their home and feel it provides them with a resilient, healthy and extremely comfortable and durable shelter for many years to come.

From a more general project development perspective it would be desirable that the integrated development and simulation process applied to the Barn Haus would represent a standard in today's residential building industry, but the reality is still predominantly based on a strong separation between architects. engineers and contractors with their subs. Some firms begin to apply designbuild processes to avoid such separation and to ensure a better work and information flow, which is especially important when coping with the higher quality requirements for high performance buildings. The Barn Haus team had particularly good experiences when simulating the building's energy performance in-house and during the early design stages, which allowed using performance optimization as just another tool to drive the design process. The ongoing inclusion of POM plays an important role to better understand and analyze the impact of specific design and efficiency measures after the building's completion. Furthermore it is an important tool to educate occupants about optimized building use and operations. With the diverse toolsets available on today's marketplace and opportunities to integrate stakeholders from the beginning of a design process, architects are able today to well-integrate such strategies in every design processes, thus pushing the market towards considerably better performing and healthier buildings overall.

REFERENCES

- Hegger, M., Fafflok, C., Hegger, J., Passig, I. (2013). "Aktiv Haus Das Grundlagenwerk," Callwey, Munich, Germany.
- Rügemer, J., Carraher. E. (2015). "*The Girl Scouts of Utah Interlocking Cross-Laminated Timber Summer Cabins*," 31st International PLEA Conference Proceedings, September 9-11, 2015, Bologna, Italy
- Architizer (2011). "F87, Berlin, Germany", https://architizer.com/projects/f87/ Accessed June 22, 2021.
- Michaely, P., Schroth, J., Schuster, H., Sobek, W., Thümmler, T. (2012). "F87: Mein Haus – mein Auto – meine Tankstelle," Greenbuilding 6/2012. Pp. 19-23
- Unites States Environmental Protection Agency (2021). "What is a MERV rating?," <u>https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1</u>. Accessed June 23, 2021.
- Unites States Environmental Protection Agency (2021). "*Particulate Matter (PM2.5) Trends*," <u>https://www.epa.gov/air-trends/particulate-matter-pm25-trends</u>. Accessed June 23, 2021.
- Lewis, S (2014). "PHPP Illustrated A Designers Companion to the Passive House Planning Package," RIBA Publishing, Newcastle Upon Tyne, England. Pp. 12-13, 22-24 and 30-35.
- United States Passive House Institute PHIUS (2021). "Passive House Planning Package PHPP," <u>https://passivehouse.com/04_phpp/04_phpp.htm</u>. Accessed April 5, 2021
- Corner, D., Fillinger, J., Kwok, A (2018). "Passive House Details Solutions for High-Performance Design," Routledge, New York. Pp 258-259
- U.S. Department of Energy (2019). *"Air Leakage Guide. Building Technologies Program, "https://www.energycodes.gov/sites/default/files/documents/BECP* <u>Buidling%20Energy%20Code%20Resource%20Guide%20Air%20Leakage</u> <u>%20Guide_Sept2011_v00_lores.pdf.</u> Accessed May 23, 2021
- Wikipedia (2021). "Nominal power (photovoltaic)", <u>https://en.wikipedia.org/wiki/Nominal_power_(photovoltaic)#Watt-peak</u>. Accessed June 23, 2021.

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Reducing Interior Overheating of Residential Buildings by Passive Cooling Measures

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ABSTRACT

Due to the effects of climate change, summer outdoor temperatures in Canada are rising. Such climatic changes may result in overheating the interior spaces of buildings. This can potentially lead to health issues for building occupants as brought about by heat exhaustion, dehydration, heat strokes and even mortality.

In this paper, the effects of overheating within residential buildings are described. An investigation was completed with the use of the EnergyPlus® simulation tool. Two residential building archetype models were studied: a single family detached home, and an attached row house. The two models were configured for several building envelope construction sets and compared. Two, light and medium-weight constructions were considered in the simulations.

Results for summer thermal comfort conditions confirmed interior overheating issues. Additionally, the effectiveness of several passive cooling strategies were evaluated, such as the effect of the use of building envelope thermal mass, shading, ventilation, and window glazing type.

In this study the climate data of Ottawa, Canada was selected as a location for the determining the likelihood of overheating in homes. A methodology was employed to evaluate overheating in terms of the occupant's thermal comfort that included consideration of the heat stress induced in home occupants.

The results showed that 1) The most effective passive measures to reduce overheating proved to be increased night-time ventilation from opening windows during favorable climatic conditions (i.e. when outside temperature is lower that inside temperature), as well as the use of exterior shading for the fenestration. 2) Significantly less overheating was evident for the attached vs. the detached home. This was due to both, adiabatic conditions and proper orientation for the east and west faces of the attached home such they had no windows. 3) The high performance building tend to overheat to a greater extent than less insulated buildings at studied location.

1 Introduction

Due to climate change effects, summer outdoor temperatures are rising. Globally as well as in Canada, numerous field measurement studies have confirmed the trend of interior overheating (Touchie, et al. 2016; Quinn et al., 2014; Banfill et al., 2013, and Baborska et al., 2017) confirming the urgent need to solve a problem of overheating of building interiors.

The following work is a part of the Climate resilient buildings and core public infrastructure (CRBCPI) project being conducted at the National Research Council Canada (NRC) and focused on overheating in buildings. The goal of the overheating project is to develop guidelines to address the risk to overheating in retrofitted and new buildings from the perspective of thermal comfort and the health of occupants. The evaluation was done with the use of the EnergyPlus® simulation tool on two residential building models, each modelled with several construction sets described in Section 3. The development of the guidelines will help feed future updates to the National Building Code of Canada (NBC). The specific project tasks are to:

- 1. Evaluate building response to climate change;
- 2. Develop and evaluate the effectiveness of selected resilient measures to reduce overheating risk in new and retrofit buildings;
- 3. Develop guidelines and tools for assessing the risk to overheating in buildings and determine the risk to the health of building occupants arising from climate change effects;
- 4. Provide information that would permit revising the NBC to address overheating in buildings.

2 Evaluation Method

Evaluation of overheating will require a metric for thermal comfort or heat stress on home occupants. Laouadi et al. (2020b) have developed a methodology to evaluate overheating in these terms. The methodology uses the transient standard effective temperature index (t-SET) as a heat stress index. The standard effective temperature (SET) defined by (ASHRAE 55, 2017) considers the effect of temperature, relative humidity, air movement velocity and clothing. During exposure to continuous indoor heat events of duration N (days) where occupants can occupy many spaces in which they perform activities during daytime and one space during night-time for sleep, the magnitude (or severity) of overheating (noted as SETH) is expressed by the following relationship:

$$SETH = \sum_{i=1}^{N} (SETH_n + SETH_d)_i$$
(1)

With:

$$SETH_{n} = \sum_{sleep}^{wakeup} (t - SET_{\tau} - t - SET_{n})^{+} \cdot \Delta \tau$$
⁽²⁾

$$SETH_{d} = \sum_{wakeup}^{sleep} (t-SET_{\tau} - t-SET_{d})^{+} \cdot \Delta \tau$$
(3)

Where:

- t-SET_{τ}: hourly value of t-SET of the space being occupied at hour (τ) during day or night time (°C);
- t-SET_n: threshold value of t-SET for a sleeping occupant during night-time (°C);
- t-SET_d: threshold value of t-SET for an active (wakeful) occupant during daytime (°C);
- SETH_d: magnitude of a heat event occurring over a daytime period (°C·h);
- SETH_n: magnitude of a heat event occurring over the preceding night-time period (°C·h);
- SETH: magnitude of overheating (°C·h);

 $\Delta \tau$: calculation time step (h).

The symbol $(^+)$ in equations (2) and (3) indicates that only positive values are considered.

Based on the limiting criterion for body water loss percentage, as specified in ISO 7933:2018, and assuming occupants have 80% rehydration rate (water loss replacement by drinking) overheating is declared when the severity index (SETH) is greater than 230 ± 42 (°C*h).

3 Residential Building Models

The evaluation of overheating of different residential building types was completed using results derived from building simulations. Simulations were conducted using EnergyPlus® software, and simulation models of two types of small residential buildings were developed, and are considered in this paper, based on Natural Resources Canada's (NRCan) building archetypes, namely:

- Single family detached home (SF)

- Row (town) house (RH).

Detailed description of all models is presented in (Bartko et al. 2021a). The geometry of the detached single family home model is shown in Figure 1a) and the one of the attached row house model in Figure 1b). Each model consists of four zones: Attic (unconditioned, un-occupied), first floor (living room zone), second floor (bedroom zones) (conditioned, occupied) and a basement zone (unconditioned, un-occupied). Each zone is represented by a single space with no internal partitions. The living areas of the SF and RH models are 160.4 m² and 221.7 m² respectively. All simulations were carried out for Ottawa, ON using the typical meteorological year (TMY) weather file. The effects of four different construction sets were investigated: old (O), retrofit (R), current (C) and future- net zero (N) construction sets with effective (thermal bridging included) R-values of R10, R24, R18 and R26, respectively, for light weight construction. Old construction was characterised by that built in the 1980s, which corresponds to the largest number of existing buildings built during this period (NRCan, SHEU, 2011).

The parameters investigated related to summer thermal comfort are summarized in Table 1.





Studied parameter	Parameter values							
Building envelope thermal mass (heat capacity)	Light- outside vinyl cladding on wood stud wallMedium- outside brick veneer on wood stud wall							
Building envelope R-value for light (or medium) construction	 Old, R10 (R15) Retrofit, R24 (R28) Current, R18 (R18) Net Zero, R26 (R27) 							
Shading	 Interior blinds (IB) Exterior roller shades / shutters (ES) Reflective interior blinds (RB) Thermochromic glazing (TCE) Electrochromic glazing (ECE) 							
Ventilation	 Mechanical, base case, following NBC requirements (VB) Mechanical, night ventilation, 10 times the base case NBC requirement (VN) Natural, open windows (when indoor temperature is higher than the outside) and the set-point temperature of 26°C (VO) Mixed ventilation, combination of natural (VO) and mechanical (VN) ventilation cases above and the set-point temperature (VN) 							
Window glazing type	 Double clear glazing (DC) Double clear low-E soft glazing (DCEL) Double clear low-E hard glazing (DCEH) Double green low-E soft glazing (DGEL) Triple clear low-E hard glazing (TCEH) Triple clear low-E soft glazing (TCEL) 							
Mechanical Cooling	 Relaxed cooling set-point at 26°C Relaxed cooling set-point at 30°C 							

Table 1: List of investigated parameters

3.1 Air Flow Network

For every building envelope component, air leakage was calculated based on component size. Various air changes per hour were considered for different construction types for both models. For the SF model, the air changes (ACH) at 50Pa of 6.86, 5.34, 2.32 and 1.63 were considered for old, retrofit, current and future construction respectively. For the RH model, the ACH at 50Pa of 7.43, 5.7, 2.8 and 1.96 were considered for old, retrofit, current and future construction respectively. The vertical section diagram for the airflow network (AFN) was identical for both models and is shown in Figure 2. As can be observed, the basement zone is not considered in the AFN.



Figure 2: Vertical connections in the airflow network diagram for both SF and RH models

3.2 Model Calibration

Since the archetype models were developed without known existing structure equivalent, statistical analysis recommended by ASHRAE Guideline 14, such as normalized mean bias error, or root mean square error could not be performed. Instead, heating, cooling and total energy use intensities, for the different home models were compared to several databases such as those available from NRCan and NRC's residential test facility (NRCan SHEU, 2011). This analysis was performed for the single family model only. A very good agreement between the model calibration results and reference information was obtained, as shown in Table 2.

Fnergy	Constru	ction model		NRCan	NRCan
Intensity kWh/m ²	Old	Current	NRC (current)	data- base (old)	(SHEU, 2011) (old)
Cooling	8.74	9.05	4.57	5.0	N/A
Heating	175.3	50.8	73.4	228.4	108-125
Total	214.2	96.8	N/A	282	147-175

 Table 2: Model calibration results.

4 SF Model Simulation Results

The extended analysis of the SF model is presented in (Bartko et al. 2021b). The results revealed that interiors do overheat for all construction types and that the most efficient passive measures to reduce overheating were increased natural ventilation (VO) (cross ventilation night-flush) when the outdoor temperature is lower than the indoor temperature; and the most efficient overheating prevention measure is the installation of external vertical shading devices (ES) such as, screen shadings or shutters.

5 RH Model Simulation Results

5.1 Severity of Overheating

Two diagrams of severity of overheating are presented in Figure 3. The left diagram shows results for the severity of overheating for each of the four models of various construction types and a case with basic ventilation (VB) satisfying the NBC requirements. The steep increase in severity of overheating for highly insulated assemblies can be attributed to poorer capability to dissipate the heat, as well as lower heat convection losses due to increased airtightness of building envelope components in newer high R assemblies. Its severity to overheating is very significant, since even a healthy person feels fatigue and other symptoms after a couple of days (corresponding to severity above 100°C•h) of exposure to temperatures above thermal comfort levels. It is obvious that overheating in hundreds or thousands of °C•h occurring in residential buildings is unacceptable.

In the diagram on the right of Figure 3b the results of the same construction types are presented for the case with increased air change rates. The night flush cross ventilation (VO, windows open during the night when outdoor temperature drops below 26°C) proves a very efficient means for heat dissipation and the values for the severity of overheating are much more favourable.

5.2 Effect of Thermal Mass

Both, the left diagram in Figure 3a with VB case and the VO case in the right diagram in Figure 3b show that a difference in heat capacity for light and medium assemblies show a negligible effect of thermal mass on overheating.

5.3 Effect of Various R-value Assemblies

Another fact that is evident from Figure 3 is that adding thermal insulation to walls and roofs worsens the overheating problem as can be observed on current and net zero home construction.

Figure 4 shows a comparison of energy consumptions for heating and cooling for all construction types. Heating energy on the top diagram shows extremes for old, poorly insulated vs. NZE, super insulated construction types with a higher than six-fold difference. The differences in cooling energies (bottom diagram) is much smaller with the lowest value obtained for retrofit construction.

It should be noted that R-value in itself was not a part of the parametric study. Any unexpected irregularities in the results could be due to differences in mechanical systems, glazing types and airtightness levels applied with various different construction types.

5.4 Effect of Shading

Interior blinds, interior reflective blinds and vertical exterior shading devices were modelled. In addition, the effect of thermochromic and electrochromic glazing types were investigated in the shading category.

As is apparent in Figure 5, the most effective means to prevent overheating from the use of shading devises is use of an opaque vertical exterior screen. Both glazing types (TCE and ECE) also achieved a significant decrease in severity of overheating when compared to interior shading. The comparison was done considering basic ventilation case (VB) and the light construction assembly; the results for medium construction show very similar trends.

5.5 Effect of Ventilation

The increased mechanical ventilation (VN) was achieved by turning the exhaust fans at night-time from 10:00pm to 9:00am with increased flow rate within the capacity of standard bathroom and kitchen fans. A 10-fold flow rate of the standard ventilation rates specified in the NBC were applied. As can be observed in Figure 6, the desired effect of bringing the severity of overheating to lower levels was achieved.

The most significant decrease in severity of overheating however is accomplished by



Figure 3: Severity of overheating for different construction types and thermal mass a) for basic code required ventilation (VB), and b) for night flush ventilation (VO)



Figure 4: Heating and cooling energy consumption for different construction types of the light thermal mass envelope



Figure 5: Effects of various shading types for different construction types of the light thermal mass envelope with basic ventilation type



Figure 6: Effects of increased ventilation on severity of overheating of the light thermal mass envelope



Figure 7: Effects of glazing type on severity of overheating

increased natural, night-flush ventilation (VO) simply by opening windows during the times, when exterior temperatures are lower than interior ones. Opening windows at these times was deemed the single most effective measure to reduce overheating in buildings. Comparable results were obtained for a mixed mode (VM) ventilation; however, additional positive effect was not very significant. One can consider this be offset by increased electricity consumptions by fans.

5.6 Effect of Glazing

Several double and triple glazing types having both hard and soft Low-E coatings were examined.

The comparison is difficult to make, since not all glazing types were modelled for all construction types. For instance, windows with triple glazing (TCEH and TCEL) were not considered for old, retrofit or current construction. Similarly, plain double glazing is no longer being used today, and thus was omitted for the retrofit, current and net zero construction cases.

It can be seen from Figure 7, that the double green glazing with low-E coating (DGEL), and having a low value (0.3) of solar heat gain coefficient (SHGC), seems to provide the greatest effect in reducing the severity of overheating.

The comparison of results was done for the light construction assembly; results for medium construction assembly show very similar trends.

5.7 Effect of Building Orientation

One of the RH models (with light mass, current construction set and interior blinds) was additionally modelled with 90° rotation (E-W orientation). Heating and cooling energy consumptions increased by approximately 2 % (from 11.74 MWh to 12.05 MWh) and by approximately 25 % (from 1.44 MWh to 1.83 MWh), respectively. The severity of overheating increased significantly from 883 °C·h to 3975 °C·h.

Ultimately, considering interior overheating, the E-W orientation seems considerably less advantageous than N-S orientation.

6 Results Comparison and Behavior of the Two Models

In general, the attached RH home model performed better i.e. overheated less than detached SF home model. The Table 3 compares the result values for current light thermal mass construction. The severity of overheating for the RH model is lower for all studied parameters. Some parameters show larger than 50% decrease, some are nearly identical (99%). It should be noted however, that this comparison is simplified, since neither geometries, nor home sizes were identical.

Studied r	aramatar	Severity of Ov	Difference,		
Studied p		SF model	RH model	% of SF model	
Thermal	Light	3890	1901	48.9	
mass	Medium	3872	1738	44.9	
R v	alue	3890	1901	48.9	
Shadir	ng (ES)	424	384	90.6	
Ventilati	ion (VO)	113	96	84.9	
Glazing	(DGEL)	1678	1314	78.3	
Cooling,	@ 30°C	264	261	98.8	

Table 3: Results comparison for SF and RH model performances.

7 Conclusions

Several passive measures to reduce the risk of overheating in residential buildings in summer were evaluated. These will help feed updates to the future Canadian energy and building codes.

For both evaluated model (SF and RH), the measure with the highest impact on the overheating in summer is increased natural ventilation (cross ventilation night-flush) when the outdoor temperature is lower than the indoor temperature. This method for passive heat dissipation can easily and effectively be applied in locations having a low risk of contamination of the outdoor air. Unlike, for instance, in areas influenced by increased occurrences of wild fires, such as western Canada, western USA, southern Europe, etc. this measure could not be applied. In these areas, the most effective overheating prevention measure is the installation of external vertical shading devices such as, screen shadings or shutters. Increased mechanical ventilation and the use of advanced glazing (electrochromic and thermochromic) were also helpful in decreasing the severity of overheating. The effect of thermal mass difference, as well as several glazing types was not very significant. Increased R-value of the highly insulated assemblies proved counterproductive and increased the severity of overheating significantly, particularly if the indoor space was not ventilated. This is due to preventing a heat flow through thick layers of thermal insulation as well as due to the increased airtightness of building envelopes in modern buildings. The E-W orientation of the RH model considerably increased severity of overheating and cooling loads.

Lastly, significantly less overheating was evident for the attached, row house vs. the detached, single family home. This was due to adiabatic conditions of the east and west faces of the attached home and absence of windows in these critically oriented walls.

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References

- ASHRAE 55, (2017) *Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA.
- ASHRAE. (1998). Standard Method for Determining and Expressing the Heat Transfer and Total Optical Properties of Fenestration Products, Public Draft of Standard 142P.
- Baborska-Marozny, M, F. Stevenson, M. Grudzinska. 2017. Overheating in retrofitted flats: occupant practices, learning and interventions. *Building and Research*. 45: 1-2, 40-59.
- Banfill, P.F.G., D.P. Jenkins, S.Patidar, M. Gul, G.F. Menzies, G.J. Gibson. 2013. Towards an overheating risk tool for building design. Structural Survey. 31:4, 253-266.
- Bartko M., A. Laouadi, M. Lacasse. 2021a. Development of Archetype Models of Residential Buildings for Interior Overheating Evaluation. March 2021
- Bartko M., A. Laouadi, M. Lacasse. 2021b. Effect of Selected Passive Cooling Measures on Overheating in Residential Buildings in Canada. *Proceedings of the Building Simulations 2021 Conference*. September 1-3, 2021, Bruges, Belgium.
- CMHC: Canadian Wood-Frame House Construction, 1988
- CMHC: Canadian Wood-Frame House Construction, 2013
- Gaur A. et al. (2019) Climate data to undertake hygrothermal and whole building simulations under projected climate change influences for 11 Canadian cities. *MDPI*, May 2019.
- ISO 7933, Ergonomics of the thermal environment Analytical determination and interpretation of heat stress using the predicted heat strain model, 2018.
- Laouadi, A. et al. (2020a) Development of reference summer weather years for analysis of overheating risk in buildings. *Journal of Building Performance Simulation*. February 2020.
- Laouadi, A. et al. (2020b) A new method of evaluation of overheating in buildings. *Energy and Buildings*, July 2020.
- Laouadi, A. et al. (2018) Climate resilience of buildings, Overheating in buildings- literature review.
- NRC. (2017). *National Energy Code of Canada for Buildings*. Ottawa, ON: National Research Council of Canada.
- NRC. (2015). *National Building Code of Canada*. Ottawa, ON: National Research Council of Canada.
- NRCan, (2011). Survey of Households Energy Use
- Quinn, A., J.D. Tamerius, M. Perzanowski, J.S. Jacobson, I. Goldstein, L. Acosta, J. Shaman. 2014. Predicting indoor heat exposure risk during extreme heat events. *Science of the Total Environment*. 490: 686-693.
- RDH: Deep Building Enclosure Energy Retrofit Study, Multi-Unit Residential Building Deep Energy Retrofit Study- Enclosure Retrofit, 2017.
- Touchie M., E. Tzekova, J. Siegel, B. Purcell, J. Morier. 2016. Evaluate Summertime Overheating in Multi-Unit Residential Buildings Using Surveys and In-Suite Monitoring. Proceedings of the thermal Performance of the Exterior Envelopes of Whole Buildings XIII International Conference, ASHRAE.

Comparing Affordable, Durable and Energy Efficient Wall Retrofit Systems

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ABSTRACT

With funding from the Department of Energy's Building Technologies Office, the Pacific Northwest National Laboratory, along with the Oak Ridge National Laboratory and the University of Minnesota, just completed a three-year project which compares 14 wall retrofit systems and 2 base-case iterations using both field research and modeling. In addition to comparing the three core criteria of affordability, durability, and energy savings potential, the ease-of-construction and the wide-scale applicability of the solutions were also considered. Wall retrofit systems chosen for this study included options that retained, covered, or completely replaced the existing cladding, as well as walls that were prefabricated or new innovations. The goal was to provide broad review of a range of attributes to determine which wall retrofit systems were the most suitable for various applications. In cold and very cold climates five wall upgrades were found to provide payback of 13 years or less with IRRs ranging from 12% to 42%. Moisture performance improvements to two wall upgrades and cost compression for several more warrant further study. Three of the tested walls are prototypes. This presentation will describe the project scope, team, experimental plan, and project outcomes. This abstract is part of the "Durability Issues Associated with Building Retrofits" session.

BACKGROUND

<u>Project Scope</u> - Homes built before 1992, when the U.S. Department of Energy's (DOE) Building Energy Codes Program was established, represent approximately 68% of the residential building stock in the country (Livingston et al. 2014; U.S. Census Bureau 2017). Up to 43% of these homes have little to no insulation in the walls (National Renewable Energy Laboratory 2019) and have very high air leakage rates. The path toward resolving existing thermal, moisture, and infiltration issues is often fraught with technological, financial, and social challenges.

In 2018, DOE's Building Technologies Office awarded funding for a 3-year project to identify reliable, cost-effective, high-performing wall configurations for energy retrofits and to characterize the viable market, analyze economic opportunities, and help identify and overcome barriers associated with adoption.

<u>Project Team</u> - This project included experimental and simulation studies, and market analysis and techno-economic modeling to examine and characterize wall upgrades of residential enclosures that include both traditional and innovative solutions. All research teams participated in research plan development, literature review, industry expert meetings, and review and documentation. Specific organizations and staff are listed in Table 1, with roles and expertise:

Pacific Northwest energy modeling, e	National Lab - Project mgmt, economic analysis, lead authorship	Oak Ridge National Lab - Hygrothermal simulation and analysis					
Cheryn Metzger	Co-PI, Project Manager	Andrè Desjarlais Project Management					
Jian Zhang	Co-PI, Energy Modeling	Anthony Aldykiewicz Hygrothermal Modeling					
Philip Jenson	Assistant Project Manager						
Chrissi Antonopoulos	Techno-Economic Analysis	University of Minnesota - In situ installation, monitoring, and constructability analysis at					
Sumitrra Ganguli	Techno-Economic Analysis	University of Minnesota's Cloquet Residential Research Facility (CRRF).					
Travis Ashley	Data Analysis/Management	Pat Huelman Project Mgmt					
Harshil Nagda	Energy Modeling	Garret Mosiman Field Research Lead					
Tyler Pilet	Energy Modeling, Documentation	Rolf Jacobson Field Research Support					
Patti Gunderson	Review, Documentation	Fatih Evren Data Acquisition					

Table 1. Project Team Expertise, Staff and Roles

RESEARCH PLAN

The flowchart below (Figure 1) outlines the project's multi-disciplinary approach.



Figure 1. Project Flowchart

<u>Literature Review</u> - A comprehensive literature review was conducted in early 2019 to explore various innovative insulation materials and products, context and background for the planned experiment, simulation methods, and techno-economic analysis, including anticipating the end-use needs of the project's final conclusions and recommendations by constituents—builders and building owners (Antonopoulos, Metzger, et al. 2019).

The literature review provides an overview of the thermal and moisture performance of typical wall assemblies, identifies relevant research, and summarizes current practices for exterior wall retrofits for existing homes, focusing on retrofit applications to the exterior side of a wall assembly. Retrofit wall assemblies applied over existing siding for reduced installation costs were of particular interest.

Findings from the literature review provided context for the experimental plan, including a range of wall retrofit assemblies and innovative materials and methods being developed or tested by others. Click on this link to access the full report: Wall Upgrades for Residential Deep Energy Retrofits: A Literature Review

<u>Advisory Committee</u> - Researchers engaged with leading thermal enclosure experts from industry, academia, national laboratories, state and federal programs, and other research organizations. In the first advisory committee meeting (April 19, 2019, Arlington, VA), 27 experts and the project team identified and characterized candidate wall retrofit assemblies of interest.

These leading researchers and innovators shared information and experience, collaborated on the development of the research methodology, identified test wall criteria, and reviewed results. The group's two primary categories of interest and the five most important issues for each were as follows:

- 1. <u>The most important criteria</u>: air tightness; constructability; labor cost, control layer options and complexity; installation time
- 2. <u>Priority components or materials for testing</u>: exterior rigid insulation; European panels, InSoFast foam panel with plastic struts; injectable spray foam; nail base retrofit insulation panels (RIPs).

Results from the first advisory committee meeting are published in an expert meeting report (Antonopoulos, Baechler, et al. 2019). Reports were not published for four subsequent advisory committee meetings. Click on this link to access the full report: Wall Upgrades for Residential Deep Energy Retrofits: Expert Meeting Report

<u>Wall Upgrade Selection Criteria</u> - The voting exercise resulted in the following decision criteria for the test wall matrix:

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

Further consultation with DOE determined that "wide-scale applicability" should be included as a criterion. The project's original scope was also expanded to include some walls with thermal performance more modest than the traditional "deep" energy retrofit, and to include a wide range of solutions that retained, covered, or completely replaced the existing cladding.

<u>Wall Upgrade Systems</u> - The team chose the following retrofit wall assemblies for in situ testing and constructability observation at the CRRF. (Table 2)

ID	PHASE 1 WALL DESCRIPTION	ID	PHASE 2 WALL DESCRIPTION
А	Baseline 1 – Typ uninsulated, circa 1950	Ι	Baseline 2 – Typical uninsulated, circa 1950
В	Drill-&-Fill Cellulose (dense-pack)	J	Drill-&-Fill Fiberglass (proprietary FG, high-dens)
С	Injected Cavity Foam (proprietary cc-spu)	K	Fiberglass Batt + Int Polyiso
D	Pre-fab Ext EPS (panel w/struts)	L	Drill-&-Fill FG + Ext Polyiso
Е	Drill-&-fill Cellulose + Ext XPS	М	Pre-fab Ext EPS/EIFS Panel System
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	Ν	Pre-fab Ext PU/Vinyl Block System
G	Exterior Mineral Fiber Board	0	Drill-&-Fill FG + Ext FG Board
Н	Exterior gEPS Structural Panel System	Р	FG Batt + XPS + OSB (Thermal Brk Shear Wall)

Table 2 Identifiers (ID) and Descriptions of Test Wall Configurations

RESULTS

<u>Test Wall Performance and Constructability</u> - A prototype of each wall upgrade configuration was installed and instrumented on a test building in climate zone 7 (CZ-7) at the CRRF by University of Minnesota researchers. Data gathered during the in situ testing then were used to validate energy and moisture models for simulating performance of the test assemblies in other climate zones.

The exercise of building each base-case wall and the 14 test wall assemblies provided insight into the degree of difficulty that novel—or even just slightly unusual—approaches may represent. The 4- x 7-ft walls for the test building were geometrically simple and straightforward compared to the complexities of an entire house, with windows and doors, mechanical penetrations, inside and outside corners, and connections to foundations and soffits. The number of operations involved in the installation process is a telling metric—each layer that can perform multiple duties saves the crew time, effort and even distraction. Prefabricated products shift some labor tasks to a controlled, off-site setting and may also incorporate means of fastening and measuring (Walls D, F, M and N) to provide a degree of predictability and efficiency that could possibly offset their cost premiums.

Wall thickness is an important issue. Even for the test building, thicker walls required more attention to detail at top and bottom and edge connections. This is likely to compound greatly in real-world conditions. Walls that provide higher R-values without substantially increasing the thickness seem to provide advantages. On the other hand, wall products that cannot easily be field modified create challenges. A prefabricated system that incorporates necessary air and water control for a new wall upgrade that is installed over the top of the existing building's finish may have an advantage; however, drill and fill approaches (B, C, J) were easy and straightforward.

<u>Hygrothermal Modeling Results</u> - Hygrothermal simulations using WUFI Pro (Version 6.4) were validated against experimental data and then carried out in all eight climate zones to understand the impact of the retrofit systems on moisture performance/durability. The mold index was calculated in accordance with standard ANSI/ASHRAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE 2016) to determine moisture durability for each assembly. Mold indices range from 0 to 6; values of 3 and above indicate moisture vulnerability.

The resulting mold index was below 3 for most walls in most climate zones; B (drilland-fill cellulose) and J (drill-and-fill fiberglass) had mold indices above 3 for northern exposures in Subarctic, Very Cold and Marine climates. Untreated cellulose fill would be considered moisture vulnerable for Cold and Mixed Humid, as well.

The other two walls using drill-and-fill cellulose performed well. Wall E included an exterior layer of EPS continuous insulation, maintaining higher temperatures within the cavity which reduces condensation. Wall K included a 1-in. layer of polyisocyanurate on the interior side of the wall; the foil facing has very low permeability. The last drill-and-fill wall (C)used closed cell injected foam, with good moisture performance due to the foam's relatively low permeability.

<u>Energy Modeling Results</u> – Experimental results were used to calibrate a THERM model of each wall assembly, which was then applied to an entire building using EnergyPlus (U.S. Department of Energy 2021; Vidanovic et al. 2021). A residential prototype building was used to extrapolate energy savings in each U.S. climate zone. The prototype single-family building using the most frequent building characteristics for existing U.S. homes (e.g., attic insulation level, window specifications, foundation insulation, etc.) were extracted from ResStock data and simulated to represent a typical home constructed in the mid-1950s.



Figure 2. Annual Total Energy Cost & Savings, Cold and Very Cold Climates

Energy modeling results showed that locations with the highest potential for retrofit savings are those which are heating-dominated (i.e., Cold and Very Cold climate designations) with savings due to the wall retrofits alone (using regional pricing)

ranging from 21% to 38% for energy use intensity (EUI) and 18% to 31% for energy cost savings. (Figure 2)

<u>Economic Results</u> - Labor and Material costs were estimated for the 14 prototype walls in all climate zones and combined with energy modeling results to calculate Internal Rate of Return (IRR) and Simple Payback (Figure 3) for two cold climate cities: Chicago, Illinois and Burlington, Vermont.



Figure 3. Internal Rate of Return (%) and Simple Payback (years) for Chicago and Burlington, Ordered by Installation Cost (\$/ft²) of the Wall Upgrades

Test walls in Figure 3 are ordered from least to most expensive. Five of the studied wall upgrades can be built for between \$1.90 and \$6.30 per square foot of enclosure. These same walls provide strong, double-digit IRRs and Simple Payback periods of less than 13 years in cold climates. Among the wall upgrades in this study, lower cost wall upgrades pay back faster, despite producing modest energy savings. The cost of labor dominates total cost (66% to 82%) for all but three walls, and walls with higher labor cost vs total cost ratios are strong candidates for future cost compression.

A local cost estimator and RS Means Cost data both informed the pricing, with review and adjustment from the research team and advisory committee. In some cases, the manufacturer provided a projected unit cost that reflects the necessary profit margin if the wall were to be widely adopted.

PROJECT SUMMARY

Up to 30% of existing homes in the United States have no cavity insulation and leaky construction. The wall upgrades studied in this project provide many energy saving options while increasing occupant comfort and building durability. Table 3 provides a range of qualitative and quantitative metrics for assessing the full range of test wall upgrade configurations for two cities in the climate zone of most concern here—Cold. Darker colors indicate better results, lighter colors are less good.

		Constructability, Performance						Economics Chicago				Economics Burlington				
ID	Name	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Assembly R-Value (eff)	Energy Cost Savings, %	Cost \$/sf Wall	IRR, %	Simple Payback	Energy Cost Savings, %	Cost \$/sf Wall	IRR, %	Simple Payback
В	Drill-&-Fill Cellulose (dense- pack)	1	2	1	1	0	4C 5 6 7 8	14.2	18	\$2	22	5	18	\$2	36	3
С	Injected Cavity Foam (proprietary cc-spu)	X	2	2	1	0		19.5	22	\$6	7	13	22	\$6	12	8
D	Pre-fab Ext EPS (panel w/struts)	3	3	1	2	5.3		24.8	29	\$20	0	31	30	\$21	3	19
Е	Drill-&-fill Cellulose + Ext XPS	1	5	3	3	2.5		28.4	30	\$19	0	28	31	\$19	4	17
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	X	4	3	2	0.5		25.5	29	\$14	2	22	31	\$14	6	13
G	Exterior Mineral Fiber Board	3	3	2	3	5.3		22.9	29	\$18	1	27	30	\$18	4	16
Н	Exterior gEPS Structural Panel System	3	4	3	2	7		28.5	30	\$22	-1	32	31	\$22	3	20
J	Drill-&-Fill Fiberglass (proprietary FG, high- dens)	2	2	1	1	0	4C 7 8	16.5	21	\$2	25	4	22	\$2	42	2

Table 3.	Observation,	Simulation	and Anal	ysis Re	esults for	CZ-5 and	CZ-6
	,						

		(Constr	uctab	oility,	Perfo	rman	ce		Econo Chio	omics cago			Econ Burli	omics ngton	
ID	Name	Materials Acquisition	# Operations	Speed of Installation	Ease of Installation	Added thickness, in.	Moisture Risk by CZ	Assembly R-Value (eff)	Energy Cost Savings, %	Cost \$/sf Wall	IRR, %	Simple Payback	Energy Cost Savings, %	Cost \$/sf Wall	IRR, %	Simple Payback
к	Fiberglass Batt + Int Polyiso	1	4	2	3	1		20.6	20	\$5	9	10	21	\$5	16	6
L	Drill-&-Fill FG + Ext Polyiso	1	5	3	3	1.5		22.8	29	\$14	2	22	30	\$15	6	13
М	Pre-fab Ext EPS/EIFS Panel System	4	3	2	2	5.8		27.2	30	\$45	-5	67	31	\$45	-2	41
N	Pre-fab Ext PU/Vinyl Block System	X	2	1	2	4		27.6	29	\$5	13	8	31	\$5	22	5
0	Drill-&-Fill FG + Ext FG Board	3	4	2	3	3.3		25.2	29	\$17	1	25	31	\$17	5	15
Р	FG Batt + XPS + OSB (Thermal Break Shear Wall)	1	6	4	4	0.8		18.9	28	\$16	1	25	29	\$16	5	15

The construction assessments were made by the research team at the University of Minnesota who installed the 4-ft x 7-ft wall upgrades. Their experience with only two iterations of a simple geometry was not indicative of installation speed or ease under the challenges of real-world conditions. Still, the team's training and experience is excellent context for the thought exercise—a real-world opportunity to see, feel, work with and compare the materials and methods.

Comparing the constructability metrics side-by-side against pricing, energy savings, and moisture performance allows a global perspective akin to what a contractorhomeowner team requires for informed decision making. While it's intuitive that the best energy performers are also likely to be among the most expensive, careful examination of all outcomes allows discernment between superficially similar options in the "middle of the pack" as well as the context to "mix and match".

Five of the tested wall upgrades can be installed for under \$6.50 /sf of wall:

- B Drill-and-Fill Cellulose (high density)
- J Drill-and-Fill Fiberglass

- K Fiberglass Batt + Int Polyiso
- N Pre-fab Ext PU/Vinyl Block System
- C Injected Cavity Foam (proprietary cc-spu)

While the first two offer excellent return on investment and are the most affordable (under \$2/ft² of wall area) as well as among the fastest to install, they are moisture vulnerable in certain climates—extra attention to the interior vapor retarder may eat away at some of their simplicity, speed or cost advantages in those locations. All five methods leave the exterior siding in place, although walls B, C, and J require that a few courses of siding be removed for access to each stud cavity for filling with insulation. Wall N leaves siding in place and builds up the new prefab wall in front of the old wall. Wall K leaves the siding untouched because all work is done from inside of the house. Walls B, J, and C presume the existing home's stud cavities are completely empty; drill-and-fill is not an option when walls are already filled with insulation, no matter how inadequate.

These five methods all provide energy savings although not all of them bring the existing building up to the current prescriptive energy code R-minimums. In addition to first costs, investment metrics drive whether a builder recommends—or a homeowner chooses—a particular retrofit. In cold and very cold climates the five top wall upgrades listed above all provide payback of 13 years or less, and IRRs ranging from 12% to 42% in cold climates.

Three of the remaining tested wall upgrades are prototypical – accurately pricing both labor and materials is challenging. But both IRR and Simple Payback are very sensitive to first-cost, so improvements that translate to labor or product cost savings are likely to have a strong positive effect. Wall N is a prototype, prefabricated system of vinyl-covered foam blocks stacked together snugly with a tongue-and-groove profile using custom hangers and channels. The final effect looks very much like traditional vinyl siding. This system is a good example of the challenges of pricing products which are not yet marketed and available. If the ease of installation noted by the University of Minnesota team translates well to whole buildings, and if the pricing the developer anticipates at scale holds, this wall is a good performer. Two other innovative wall upgrades appear ripe for market growth/introduction. Wall D (Pre-fab Ext EPS [panel w/struts]) is new to the market and Wall F (Drill-&-fill Cellulose + VIP/Vinyl Siding) is not yet commercially available. Both received high marks from the UMN installation team.

These test walls were designed for cold and very cold climates; some of their performance may be wasted in milder conditions. Most are easily modifiable to reduce both R-value and cost, incrementally—retrofits do not necessarily need to be "deep" or invasive to significantly improve energy performance.

The overarching issue is that in today's market, first-costs are too large, and projected annual energy cost savings too small, to make the time and trouble of the most intensive—and expensive—wall upgrades the first and easiest answer for the typical homeowner. Rising fuel prices and the pressures of global warming may change some
of the economic inputs. But this research confirms that even modest interventions can make a substantial difference, and careful planning can ensure good performance as well as good return on investment.

RESEARCH LIMITATIONS AND FUTURE STUDY

The costing exercise was complicated by COVID-19 supply chain disruptions and a year-long gap between Phase 1 and Phase 2. For newer, innovative systems, installers don't have the hands-on experience to bid labor commensurate with the expected effort—the product's novel nature can invoke industry conservatism. Additionally, the ultimate unit price for pre-market prototypes is genuinely unknown.

Wall upgrades can be labor-complex and expensive. Finding additional advantages is key, such as coordinating with other improvement projects like re-siding, window replacement, or remodeling. Another opportunity is to add a new performance goal; these approaches can ameliorate the high first cost of these major undertakings. Although some of the tested walls provided added benefits such as new siding (Walls D, E, F, G, H, L, M, N, O, P), improved fire resistance (Wall G), or improved shear resistance (Wall P), none of these advantages are reflected in the pricing comparisons. Future work could quantify monetary and other benefits for decision-makers.

The walls in this study were configured for cold and very cold climates, with performance and economic analysis for the test matrix extended to all other climates. Tuning thermal and moisture performance to the specific needs of other climate zones would be warranted.

Complete details for all energy simulation, hygrothermal modeling, and economic assumptions are included in the full project report, to be published in early 2022: *Wall Upgrades for Energy Retrofits: A Techno-Economic Study*, C. Antonopulos, et al.

REFERENCES

- Antonopoulos, C. A., Baechler, M. C., Metzger, C. E., & Zhang, J. (2019). Wall Upgrades for Residential Deep Energy Retrofits: Expert Meeting Report.
- Antonopoulos, C. A., Metzger, C. E., Zhang, J., Ganguli, S., Baechler, M. C., Nagda, H., & Desjarlais, A. O. (2019). Wall Upgrades for Residential Deep Energy Retrofits: A Literature Review.
- ASHRAE. (2016). ANSI/ASHRAE Standard 160-2016: Criteria for Moisture-Control Design Analysis in Buildings. ASHRAE.
- Livingston, O., Elliott, D., Cole, P., & Bartlett, R. (2014). *Building Energy Codes Program : National Benefits Assessment* (Issue March).
- National Renewable Energy Laboratory. (2019). *ResStock*. Data Viewer: National Baseline (EFS V2).
- U.S. Census Bureau. (2017). *American FactFinder: Selected Housing Characteristics*. 2013-2017 American Community Survey 5-Yeas Estimates.
- U.S. Department of Energy. (2021). EnergyPlus Engineering Reference.
- Vidanovic, D. S., Curcija, D. C., Salonvaara, M., & Pallin, S. (2021). *THERM 8 Technical Documentation*.

Hygrothermal simulation of exterior retrofits in a cold climate

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Abstract

This work presents results from moisture modeling as part of a project undertaken by Pacific Northwest National Laboratory and its research partners, the University of Minnesota, and the Oak Ridge National Laboratory. The research goal is to identify exterior wall retrofit systems for cold climates that are low cost, energy-efficient, and do not result in moisture durability problems. A base case wall was identified representing a typical wood frame construction, circa 1950. Retrofit options were selected based on input from industry, academia, and published work and seven options were constructed and installed at the University of Minnesota's cold weather exposure facility in Cloquet, MN. Measurements were carried out during winter months and the data was used for model validation. Hygrothermal simulations were then carried out using WUFI (Version 6.4) in accordance with standard ANSI/ASHRAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings. Simulations were run out to three years and results show that the exterior retrofits improve thermal performance and do not negatively impact moisture durability of the existing wall.

Introduction

Residential homes account for just under 12 Quads of energy consumed in the US. That represents just over 22 percent of the total energy and approximately 20 percent of greenhouse gas emissions (U.S. Energy Information Administration, 2021). Energy codes have addressed energy consumption in new construction by increasing the level of insulation, implementing continuous insulation to reduce thermal bridging, and addressing air leakage by tightening the building enclosure (International Energy Conservation Code, 2018). However, more than 65 percent of the single detached residential structures were built prior to the Department of Energy's establishment of the Building Energy Codes Program in 1992 (American Housing Survey, 2019). It's expected that more than half of those homes have poorly insulated or even uninsulated building enclosures (Antonopoulus, et al., 2019).

Efforts have been made to reduce energy from the older building stock through programs like the Department of Energy's Weatherization Programs (Tonn, Rose, & Hawkins, 2018) and local utility incentive programs, e.g., Mass Save (The RCS Network, 2021). In Europe, studies have shown that the challenge to implement or deploy deep energy retrofits is cost. There's certainly interest in energy reduction, but the cost needs to be comparable to standard major renovations (D'Oca, et al., 2018). Both in the US and Europe, there is a realization that to reduce energy consumption from the residential building stock, there must be a greater effort to reduce the energy consumption from the older housing

inventory. Retrofits are crucial to realizing the energy savings potential of the opaque envelope because nearly two thirds of the buildings that exist today will still be standing in 2050 (Architecture 2030, 2021). In the Netherlands, Energiesprong (Energiesprong Foundation, The Netherlands, 2021) was established to develop a novel approach to facilitate energy retrofit for the existing affordable housing stock. Based on Energiesprong's success, similar programs have emerged in the United States. REALIZE (RMI, 2021) and RetrofitNY (NYSERDA, 2021) are attempts to implement the Energiesprong model for deep energy retrofit. They are currently funding projects specifically related to the development of scalable retrofit solutions for the older residential building stock. The effort, in part, is being driven by legislation to reduce greenhouse gas emissions. For example, New York passed legislation to achieve a carbon-free grid by 2040 (NY State Senate, 2018). The New York State Energy Research and Development Authority (NYSERDA) realized that to achieve this goal, the energy consumption from older housing must be addressed. Hence, the genesis of RetrofitNY.

To make low performing buildings more energy-efficient, a deep energy retrofit (DER) is required. In a report published by the American Council for an Energy-Efficient Economy, a DER for residential buildings is expected to achieve a reduction in energy consumption of at least 50% (Cluett & Amann, 2014). DERs improve the overall efficiency of a structure by adding insulation, reducing air leakage, resizing, or deploying more efficient HVAC systems, addressing plug loads and lighting, and incorporating sources of renewable energy.

In recognition for the need to improve the energy performance or existing housing stock, the Department of Energy (DOE) invested just over \$70 million to develop technologies to construct high performance buildings and to facilitate energy retrofits for the existing housing stock by leveraging modular and prefabrication technologies (Facility Executive, 2020). DOE established a web site to provide more details about the program and projects (The Department of Energy, 2021).

One of the challenges with building envelope energy improvements is durability. Increasing the insulation value of the envelope and reducing air leakage will impact moisture transmission through and condensation within the envelope. In northern climates, making the envelope tighter significantly reduces the drying potential. Increased insulation coupled with a reduction in drying potential brings along the risk or can potentially increase the risk of moisture durability problems if not designed and installed correctly. These problems can manifest themselves in the form of mold and degradation of building components, e.g., rot and corrosion. For example, when first introduced into residential construction sealed exterior insulation finish systems resulted in significant moisture damage of the building envelope because of moisture accumulation behind the insulation or between the insulation and the exterior sheathing (Sullivan, 1996). Water penetration coupled with a reduction in drying potential resulted in significant degradation of the building envelope. One approach to help better understand what impact these types of improvements will have on the durability of the building envelope is to carry out hygrothermal simulations (Desjarlais, Karagiozis, & Aoki-Kramer, 2001). Hygrothermal simulations were used to understand what caused early failure of EIFS systems and what to do to mitigate future problems. Simple modifications such as a drainage plane behind the expanded polystyrene insulation was sufficient to prevent moisture accumulation on the exterior sheathing without compromising the energy benefits of exterior insulation provided by EIFS construction.

Over the last 40 years, moisture engineering has heavily relied on experimental approaches to resolve moisture performance issues. Hundreds of research investigations employing laboratory and field

monitoring have been performed in both North America and Europe (Hens, 1996) (Trechsel, 1994). However, the majority of our current design guidelines have essentially been generated by past experimental analysis.

The development of hygrothermal models began in earnest in the 1990s with the initial emphasis being placed on the performance of building envelope systems. Numerous large-scale building envelope failures associated with water intrusion drove this development. The authors were heavily involved in the model development to predict moisture performance in building materials under real climatic conditions based on physical principles. The main advantage of modeling is that, if the system has been carefully characterized, the long-term hygrothermal performance of the system under different climatic conditions, effect of changes in the interior conditions and the effect of water leakage scenarios can be predicted.

The model accounts for night sky radiation, as this can be an important thermal and moisture load in various climates around the world. Provided there is enough weather data to account for this, this feature allows one to consider surface wetting during the night. The model also contains algorithms for modeling the effect of wind-driven rain as a function of height. Finally, interior conditions of the building are set or can vary depending on time of year.

The model is an excellent educational tool for understanding the complex interactions during the transport of heat and moisture in construction assemblies. The visual design allows one to understand the complex effects that nonlinear material properties play in the transport of moisture.

The models used in this project is a transient, one-dimensional heat and moisture transfer model that can be used to assess the hygrothermal behavior of a construction (Fraunhofer Institute for Building Physics, 2021). This model can be developed in both cartesian and cylindrical coordinates. The necessary input data include the composition of the examined component, its orientation and inclination, as well as the initial conditions and duration. The material parameters and the climatic conditions can be selected from the embedded databases, or the actual data can be input if their hygrothermal properties have been measured.

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

WUFI® is one of the commonly used building industry hygrothermal models and is one of the most advanced hygrothermal models for coupled mass and heat transport analysis (Fraunhofer Institute for Building Physics, 2021). WUFI® is an acronym for Wärme Und Feuchte Instationär which, translated, means heat and moisture transiency. It is based on a state-of-the-art understanding of physics regarding sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is also well documented and has been validated by many comparisons between calculated and field performance data (Holm & Künzel, 1999), (Künzel H. M., 1995), (Künzel, Kießl, & Krus, 1995), (Künzel & Kießl, 1996).

The model requires material properties. A materials database that is part of the program includes a full range of building and insulation materials commonly used in building industry. Materials can easily be added to the database as required. The model also requires hourly weather data, such as temperature, relative humidity, wind speed and orientation, driving rain, and solar radiation, which are employed in the hygrothermal calculations. These data are available in a database for a wide range of global climatic zones or specific climate data can be added if needed.

Experimental approach

Eight wall assemblies were constructed and installed at the University of Minnesota's outdoor test facility in Cloquet, MN (Figure 1). The test facility was made up of four bays with north and south orientations. Pairs of each assembly type were constructed and installed at each orientation for a total of 16 wall panels. Figure 1 shows the different panels installed facing south. The same wall panels and installation were repeated on the north side. The material layers that make up the eight assemblies are listed in Table 1. Wall A represents the base case wall, i.e., a typical wood frame construction, circa 1950. The wall is made up of exterior cladding, inland western red cedar, spruce board exterior sheathing and gypsum drywall as the interior sheathing. The stud cavity is uninsulated. Wall B introduced cellulose insulation into the stud cavity, 3.5 inches thick. Spray polyurethane foam is used to insulate the stud cavity and represents wall C. For walls D, G, and H, exterior insulation was added directly on wall A's exterior cladding. Wall D incorporates expanded polystyrene with special grooves and channels on both sides to facilitate the removal of liquid water and facilitate drying. Wall G adds mineral insulation board on the exterior. Wall H uses expanded polystyrene impregnated with graphite to improve thermal performance. Walls E and F removed the exterior cladding and replaced the weather resistive barrier, added exterior insulation and cavity insulation. Wall E adds extruded polystyrene insulation and Wall F uses an insulated composite cladding made up of vacuum insulation panels mounted behind vinyl siding.

To determine the moisture durability of the constructions in Table 1, hygrothermal simulations were carried out using WUFI (Version 6.4). As a first step, field data from the test panels (wall assembly) and facility were collected over a two-month period. Data included weather data (temperature, relative humidity, wind speed and direction, rain, and solar loads). From the test panels, temperature, relative humidity, moisture content and heat flux were measured. The data was then used to validate the model for the test period. In addition, thermal and moisture transport properties of the building materials used in the construction of the test panels were measured and compared to the material properties in the WUFI data base. Adjustments were made accordingly.

Once the model was validated, hygrothermal simulations of all the wall assemblies were carried out for a cold climate as specified by the Department of Energy (Office of Energy Efficiency and Renewable Energy, 2021). The selected city & state used for the simulation was Boston, Massachusetts, representing climate zone 5.

Simulations were carried out for northern and southern exposures in accordance with standard ANSI/ASHRAE 160-2016, Criteria for Moisture-Control Design Analysis in Buildings. Simulations were run for three years. The initial moisture content for all the materials in the assembly were based on an equilibrium relative humidity of 80% in accordance with the standard for retrofits. The boundary conditions and surface coefficients are given in Table 2.

The mold index was used to determine the overall durability of the wall assembly. The mold index is a measure of a building materials susceptibility to microbial growth and based on the work of Viitanen and Ojanen (Viitanen & Ojanen, 2007). The calculation was later incorporated into ASHRAE 160 and WUFI Pro. Table 3 provides guidance regarding the mold index measures. ASHRAE 160 makes a distinction between materials that are moisture durable and those that are susceptible to mold growth. ASHRAE 160 states that to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the mold index, calculated in accordance with the standard, shall not exceed a value of three (3.0).

Results and Discussion

Before carrying out hygrothermal simulations using WUFI, the thermal conductivities of the materials used to construct the eight wall assemblies were measured and compared to the thermal conductivity of the materials in WUFI's data base. The thermal conductivities were measured in accordance with ASTM C518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. Figure 2 is a chart that comparing the measured values to those in WUFI's database. From the chart it's clear that there's good agreement between the two datasets. As a result, most of the material properties from the WUFI data base were used for the hygrothermal simulations. Modifications were made to the OSB, cement siding and gypsum wall board.

Before simulations were carried out on the assemblies, a validation study was carried out to compare measured values to those calculated using WUFI. The validation study was carried out using data obtained from field measurements including some weather data. The exterior temperature, relative humidity and solar irradiance were measured. The exterior temperature and relative humidity are shown in Figure 3 and the solar irradiance for the north and south orientations are in Figure 4. The solar irradiance was plotted on the same scale to highlight differences in solar loads between the north and south orientations. Rain load, wind speed and direction were obtained from Weather Underground (Weather Underground, 2021).

The interior temperature and relative humidity were monitored in each bay and shown in Figure 5. The results were similar across all four bays and averaged to generate one set of interior temperature and relative humidity conditions used for all wall assemblies, Figure 6. The validation study was carried out using two months of field data, from April to May. Figure 7 shows a cross section of the base case wall with the location and identification of sensors used to measure temperature, relative humidity, heat flux and moisture content. The validation study was carried out for temperature and relative humidity only and for locations that had both temperature and relative humidity sensors. For the base case, Wall A, positions 2, 3, 4, and 5 satisfy that criterion. Positions 3, 4, and 5 are in the same location in the wall assembly, behind or on the interior side of the exterior sheathing. The difference between them is the vertical position in the wall assembly. Position 3 is that the top of the wall, position 4 in the middle and

position 5, the bottom. Since the hygrothermal simulation is one dimensional, it does not account for position in the vertical direction. A two-dimensional analysis would be required to account for vertical position in the wall assembly. Rather than treat each position individually, the average of all three were calculated and then used to compare to the simulation. Figure 8 shows the temperature and relative humidity for the measured and calculated values for positions 2 and 3, north orientation. The same results are presented in Figure 9 for the base wall, south orientation. Measurements were also compared to simulations for all retrofits. Results from Wall G (Figure 10) will be presented. The wall constructions for the Base Wall and Wall G generated using WUFI together with the finite element mesh are shown in Figure 11. The most notable difference between the Base Wall and Wall G are measurement positions exterior to the original cladding, i.e., the inland western red cedar, positions 7 and 8 due to the addition of retrofit elements. Figure 12 and Figure 13 show the north orientation temperatures and relative humidity's for the measured and simulated values. The results from the south orientation are shown in Figure 14 and Figure 15. There's good agreement between the measured and simulated values for all positions. As the sensor moves towards the exterior of the wall, the amplitude of the transients is not captured as well by the simulation, position 8. WUFI does not account for temperature dependent sorption which typically causes larger hourly variations with significant changes in temperature such as on the exterior walls or roofs (Salonvaara, Karagiozis, & Desjarlais, 2013). These calculations were carried out for all wall assemblies. Results show good agreement between the predicted relative humidity and temperature compared to the measured values, in most cases.

To measure the quality of the prediction the mean absolute error (MAE) was calculated for each simulation. The mean absolute error is given by the following equation:

$$MAE = \frac{\sum_{i=1}^{n} |y_i - x_i|}{n}$$

Where y_i is the result from the simulation, x_i is the measured value, and n is the number of observations. The variation between measured and simulated values was less pronounced for the north orientation compared to the south. The results for all the wall assemblies are given in Figure 16 and Figure 17. For the north (Figure 16), the mean absolute errors for temperature and relative humidity were between 0.7 and 13.3°F and 0.6 and 21.3 percent, respectively. The variation in mean absolute errors for temperature and relative humidity for the south orientation (Figure 17) were 0.5 and 13.0°F and 0.6 and 27.4 percent, respectively. The largest mean absolute errors were associated with relative humidity and temperature measurements close to the exterior portion of the wall. The large mean average errors were associated with the magnitude of temperature and relative humidity transients. Figure 13 shows the measured and predicted values for wall assembly G, position 8, illustrating the difference in transients between the two values. Though, the WUFI model could predict the transients, the magnitude was smaller, on average, by approximately 10°F and 23 percent RH at exterior points in the wall. This was surprising, since one would expect better agreement as comparisons were made closer to the interior and/or exterior boundaries of the wall. The measured transients in relative humidity at exterior wall positions were higher compared to the exterior values obtained from the weather data. The reason, in part, could be a metrology issue rather than a difference between simulation and measured values. Despite that difference, overall, agreement between the predicted and measured values were good. This is consistent with other studies and supports the use of WUFI as a tool for hygrothermal simulations (Fraunhofer Institute for Building Physics, 2021).

The mold index was calculated for all surfaces except for the weather resistive barriers. Figure 18 and Figure 19 shows the mold index as a function of time for each of the material surfaces for the Base Wall and Wall G. The maximum mold index from the time dependent measurements for all assemblies is shown in Table 4 as a function of orientations, north and south. Except for Wall B, all retrofit solutions are moisture durable based on the mold index criterion. For the north orientation Wall B has a mold index value greater than three for the cold climate zone. The results were consistent for the south orientation. For this assembly, the issue is the cellulose insulation. The maximum mold index was calculated for the exterior side of the cellulose insulation. The mold index calculation requires that the material be classified as sensitive or resistant based on experimental studies (Viitanen & Ojanen, 2007). In this analysis, the cellulose insulation was treated as being very sensitive or susceptible to mold growth. Today, manufacturers treat these materials with additives to prevent mold growth, resist insects and improve fire performance. Cellulose insulation materials are being tested for susceptibility to mold growth in accordance with ASTM C1338, Standard Test Method for Determining Fungi Resistance of Insulation Materials and Facings. Testing is carried out in a culture medium containing fungous spores at 95 % relative humidity and 28°C for days. Lowering the level of sensitivity would improve the performance and result in a decrease in the mold index to less than three. In this case, a classification of sensitive was used because there was no data to support a lower classification. The standard does provide users the flexibility to select a sensitivity class based on test data for the materials. If the material has been tested it can be given a classification consistent with its performance. A mold index can then be calculated from the hygrothermal simulation data for that material.

Conclusion

The moisture durability of energy retrofits was analyzed using hygrothermal simulations. Eight wall assemblies, including a base case wall, was analyzed for moisture durability problems. Seven different retrofit solutions were incorporated or implemented based on expert advice. The retrofits were analyzed and, with few exceptions, were moisture durable in a cold climate zone. The hygrothermal model was validated using experimental data showing good agreement between the simulated and measured values. There was better agreement between the simulated and measured temperature compared to relative humidity. The overall behavior of relative humidity was captured; however, the magnitude was greater for the measured values compared to the results from the simulation. The moisture durability of retrofit wall assemblies as measured by the mold index met the criterion of ASHRAE 160 with values less than three in most cases. Except for Wall B, all retrofit solutions were moisture durable with a mold index less than three. Results were consistent for the south orientation. The addition of these types of retrofits, in theory, can reduce energy consumption of residential homes without compromising the durability based on field measurements and one dimensional hygrothermal simulations in cold climates.

References

American Housing Survey. (2019). American Housing Survey (AHS). United States Census Bureau.

- Antonopoulus, C. A., Metzger, C. E., Zhang, J. M., Ganguli, S., Baechler, M. C., Nagda, H. U., & Desjarlais,
 A. O. (2019). Upgrades for Residential Deep Energy Retrofits: A Literature Review. United States:
 N. p. doi:10.2172/1544550
- Architecture 2030. (2021). Architecture 2030, Actions for Zero Cabon Buildings. Retrieved from https://architecture2030.org/existing-building-actions/
- Cluett, R., & Amann, J. (2014). *Residential Deep Energy Retrofits*. Washington, D.C.: American Council for Energy Efficient Economy.
- Desjarlais, A. O., Karagiozis, A. N., & Aoki-Kramer, M. A. (2001). Wall Moisture Problems in Seattle. *Performance of Exterior Envelopes of Whole Buildings VIII*. Clearwater Beach, Florida, USA,: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- D'Oca, S., Ferrante, A., Pernetti, R., Gralka, A., Sebastian, R., & op't Veld, P. (2018). Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects. *Buildings*, 8(174), 1-25. doi:10.3390
- Energiesprong Foundation, The Netherlands. (2021). *Energiesprong*. Retrieved from https://energiesprong.org/
- European Commission. (2010, May 19). Energy Performance of Buildings Directive. *Directive* 2010/31/EU.
- Facility Executive. (2020, February 13). *DOE Invests \$74M In Building And Construction Technologies*. Retrieved from Facility Executive, Creating Intelligent Buildings.
- Fraunhofer Institute for Building Physics. (2021). WUFI. Retrieved from https://wufi.de/en/
- Fraunhofer Institute for Building Physics. (2021). *WUFI Literature*. Retrieved from WUFI: https://wufi.de/en/literature/
- Hens, H. (1996). Modeling, Final Report, IEA-Annex 24, Task 1, ACCO. Leuven.
- Holm, A., & Künzel, H. M. (1999). Combined effect of temperature and humidity on the deterioration process of insulation materials in ETICS. *Proceedings of the 5th Symposium on Building Physics in the Nordic Countries*, 2, pp. 677-684. Goteborg.
- International Energy Conservation Code. (2018). 2018 International Energy Conservation Code (IECC). International Code Council.
- Künzel, H. M. (1995). Simultaneous heat and moisture transport in building components —One and two-dimensional calculations using simple parameters. Fraunhofer IBP. Fraunhofer IRB Verlag Stuttgart.
- Künzel, H. M., & Kießl, K. (1996). Drying of brick walls after impregnation. *Internationale Zeitschrift fur Bauinstandsetzen 2H.2,S.*, 87-100.

- Künzel, H. M., Kießl, K., & Krus, M. (1995). Moisture in exposed building components. *Proceedings of the International Symposium on Moisture Problems in Building Walls*, (pp. 258-266). Porto.
- MORE-CONNECT. (2021). MORE-CONNECT. Retrieved from https://www.more-connect.eu/
- NY State Senate. (2018, July 18). NY State Senate Bill S6599. *Climate Leadership and Community Protection Act.* NY State Senate.
- NYSERDA. (2021). *Retrofit NY*. Retrieved from https://www.nyserda.ny.gov/All%20Programs/Programs/RetrofitNY
- Office of Energy Efficiency and Renewable Energy. (2021). *Climate Zones*. Retrieved from https://www.energy.gov/eere/buildings/climate-zones
- RMI. (2021). RMI Realize. Retrieved from https://rmi.org/our-work/buildings/realize/
- Salonvaara, M., Karagiozis, A., & Desjarlais, A. (2013). Moisture Performance of Sealed Attics in Climate Zones 1 to 4. Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference. Clearwater: ASHRAE.
- Sullivan, A. C. (1996). Improving EIFS performance. Architecture, 85(5), 251.
- The Department of Energy. (2021). *Office of Energy Efficiency and Renewable Energy*. Retrieved from Advanced Building Construction Initiative.
- The RCS Network. (2021). *mass save Residential Rebates and Incentives*. Retrieved from https://www.masssave.com/en/saving/residential-rebates
- Tonn, B., Rose, E., & Hawkins, B. (2018). U.S. Department of Energy's Weatherization Assistance Program: Impact Results. *Energy Policy*, 118, 279-290.
- Trechsel, H. R. (1994). *Moisture Control in Buildings*. Philadelphia: American Society for Testing and Materials.
- U.S. Energy Information Administration. (2021). *Monthly Energy Review, May 2021*. Washington, D.C.: U.S. Department of Energy.
- Viitanen, H. A., & Ojanen, T. (2007). Improved model to predict mold growth in building materials. *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Building X.* Clearwater, Florida.
- Weather Underground. (2021). Retrieved from https://www.wunderground.com/

Figures



Figure 1. Wall panels in Cloquet, MN. Four panels are in each bay, two on the north side and two on the south orientation.

Table 1. Wall A is the base case wall. Walls B thru H are the energy or retrofit improvements. All the layers shaded blue represent additions/improvements to the base case wall. For walls B and C the stud cavity was filled with insulation. For walls D, G, and H, exterior insulation was added directly on wall A's exterior cladding. Walls E and F removed the exterior cladding and replaced the weather resistive barrier, added exterior insulation and cavity insulation.

Layers	Wall A	Wall B	Wall C	Wall D	Wall E	Wall F	Wall G	Wall H
1								26 gauge Classic Rib Metal Roofing Panel (White)
2								1"x4" (¼"x3-½") SPF Boards at Studs
3				Double 5" Lap Vinyl Siding (White)			cement siding 5/16"x8.25" (White)	2-1/8" graphite impregnated eps insulation board
4				2-½" eps panel w/ integrated furring & grooves on both sides			1"x4" (%"x3-%") SPF Boards at Studs	2-1/8" graphite impregnated eps insulation board
5				2" eps panel w/ integrated furring & grooves on wrb side			2" mineral wool insulation board, 8 pcf	fully adhered weather resistive barrier
6				Spun bonded polyolefin house wrap			2" mineral wool insulation board, 8 pcf	1-1/2" of osb (two %" panels)
7				5/8" Semi-rigid Fiberglass Panel	Double 5" Lap Vinyl Siding (White)		Vapor Permeable Brush Applied Membrane	5/8" Semi-rigid Fiberglass Panel
8	Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)	1"x4" (%"x3-½") SPF Boards at Studs with %" XPS In-fill		Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)	Oil-based Primer; Latex Vapor Retarder Paint; Latex Top Coat; (White)
9	1"x8" (¼"x7-¼") Inland Western Red Cedar	1"x8" (¼"x7-¼") Inland Western Red Cedar	1"x8" (%"x7-%") Inland Western Red Cedar	1"x8" (%"x7-%") Inland Western Red Cedar	2 inches of XPS	Vacuum Insulated Panel Mounted to Vinyl Lap Siding (Brown)	1"x8" (%"x7-%") Inland Western Red Cedar	1"x8" (%"x7-%") Inland Western Red Cedar
10	#30 Roofing Felt	#30 Roofing Felt	#30 Roofing Felt	#30 Roofing Felt	Spun bonded polyolefin house wrap	Spun bonded polyolefin house wrap	#30 Roofing Felt	#30 Roofing Felt
11	1"x6" (¾"x5-½") Spruce/Pine Boards	1"x6" (¾"x5-½") Spruce/Pine Boards	1"x6" (%"x5-%") Spruce/Pine Boards	1"x6" (¼"x5-½") Spruce/Pine Boards	1"x6" (¼"x5-½") Spruce/Pine Boards	1"x6" (¾"x5-½") Spruce/Pine Boards	1"x6" (%"x5-½") Spruce/Pine Boards	1"x6" (%"x5-½") Spruce/Pine Boards
12	3-½" Air Space	blown in cellulose, 3-½" at 3.5- 4.0 lbs/cf	Injected Closed-cell Spray Polyurethane Foam (CT)	3-½" Air Space	blown in cellulose, 3-½" at 3.5- 4.0 lbs/cf	blown in cellulose, 3-½" at 3.5- 4.0 lbs/cf	3-½" Air Space	3-½" Air Space
13	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board	5/8" Gypsum Board
14	Latex Vapor Retarder Primer (White)	Latex Vapor Retarder Primer (White)	Latex Vapor Retarder Primer (White)	Latex Vapor Retarder Primer (White)	Latex Vapor Retarder Primer (White)			



Figure 2. Measured thermal conductivity compared to the thermal conductivities in the WUFI material data base.

Table 2. The boundary conditions and surface transfer coefficients used in the WUFI simulations.

Boundary conditions					
Exterior weather data	ASHRAE Year 2				
Indoor climate	ASHRAE 160 (heating only)				
Surface transfer coefficients					
Exterior	Latex paint 1 (16.4 perm)				
Interior	Latex paint 2 (4.9 perm)				

Table 3. Mold index and the accompanying description of the growth rate based on microscopic and visual inspection of the surface. The mold index is based on the work of Viitanen and T. Ojanen (Viitanen & Ojanen, 2007).

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



Figure 3. Measured exterior temperature and relative humidity in Cloquet, MN.





Figure 4. Measured solar irradiance in Cloquet, MN, north and south orientations.



Figure 5. Measured interior temperature and relative humidity of each of the bays in the Cloquet, MN, test facility.



Figure 6. The average temperature and relative humidity of all four bays.



Figure 7. The cross section of the base case wall, *A*, showing the positions of the temperature, relative humidity, heat flux and moisture pin sensor locations.



Figure 8. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 2 and 3, north orientation, Wall A, base wall.



Figure 9. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 2 and 3, south orientation, Wall A, base wall.



Figure 10. The cross section of the retrofit wall, G, showing the positions of the temperature, relative humidity, heat flux and moisture pin sensor locations.



Figure 11. The wall constructions for the Base Wall (a) and Wall G (b) generated using WUFI together with the finite element mesh, materials, and material thicknesses. The materials designated (ORNL) were modified. The measured thermal conductivities in Figure 2 were used to replace the values in the WUFI material data base.



Figure 12. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 2 and 3, north orientation, Wall G.



Figure 13. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 6, 7, and 8, north orientation, Wall G.



Figure 14. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 2 and 3, south orientation, Wall G.



Figure 15. Comparison between measured (MEAS) and simulated (SIM) temperatures and relative humidity's at positions 6, 7, and 8, south orientation, Wall G.



Figure 16. The mean absolute error between measured and calculated temperatures and relative humidity's for all wall assemblies, north orientation.



Figure 17. The mean absolute error between measured and calculated temperatures and relative humidity's for all wall assemblies, south orientation.



Figure 18. Mold index calculation for Wall A, base case. The mold index was calculated for the exterior and interior surfaces of the western red cedar siding, the spruce board sheathing, and the interior gypsum board.



Figure 19. Mold index calculation for Wall G, retrofit wall with exterior insulation. The mold index was calculated for the exterior and interior surfaces of the cement siding, mineral wool insulation board, western red cedar siding (base wall), spruce board exterior sheathing, and interior gypsum board.

Table 4. Maximum mold index for wall assemblies A thru H for north and south orientations. Green indicates mold index less than 3 and red indicates values equal to or greater than 3.

	lth	гţ
Wall	Sol	No No
А	0.5	0.8
В	3.2	3.5
С	0.0	0.1
D	0.0	0.1
Е	0.4	0.5
F	0.2	0.3
G	0.0	0.0
Н	1.1	1.1

Insitu Testing for PNNL/ORNL/UMN Deep Wall Insulation Upgrade Project Patrick H. Huelman¹, Garrett Mosiman², Fatih Evren³, Rolf Jacobson⁴

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1. ABSTRACT

Over the course of two years, the University of Minnesota (UMN) conducted in-situ experiments to validate the energy and hygrothermal performance of multiple insulation upgrade methods for existing uninsulated wood-frame walls. This work was carried out at the Cloquet Residential Research Facility (CRRF) located in northeast Minnesota with funding and support from the Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL). Fourteen different wall upgrade treatments were select for this study. Each upgrade along with the "base case" walls were tested at the same boundary conditions with both a north and south orientation. The first seven wall upgrades were monitored for two winters allowing comparison to the previous year as well as a direct comparison to the seven new wall upgrades constructed and monitored in the second year.

The base case wall represents typical 1950s uninsulated frame construction with 2"x4"studs at 16" centers, 1"x6" board sheathing, building paper, and cedar lap siding. A heavy 5/8" gypsum board was used on the interior to represent an older drywall or plaster finish. Vapor retarder coatings were applied to the siding and interior gypsum board to simulate multiple coats of oil-based paint. This paper describes the research set-up, tested assemblies, sensors, data acquisition protocols, and insights into constructability of the fourteen wall upgrades.

2. INTRODUCTION

In the United States, 39% of total energy is consumed by the building sector and approximately one-half of that total is attributed to residential buildings (EIA 2018). Homes built before widespread energy codes represent approximately 68% of residential building stock in the country often have significant air leakage, inadequate insulation, and inefficient windows. Homes with little to no air sealing or insulation have heating and cooling losses that can account for a substantial portion of utility bills. Done correctly deep energy retrofits can significantly increase the energy performance of a home's thermal envelope, decrease indoor pollutants, increase homeowner comfort, and improve durability, thus extending the useful life of the building. In support of DOE's move toward transformational wholebuilding upgrades and enclosure solutions, PNNL, ORNL, and the UMN partnered and collaborated with leading building science researchers to characterize the technical and economic barriers to facade retrofits. This effort was designed to identify market-viable solutions that could be used to transform existing homes. The project, comprised of an experimental study, simulation study (Aldykiewizc, et al: 2022), techno-economic study, and market analysis (Antonopoulos, et al: 2022), was undertaken to examine comprehensive energy retrofits of residential enclosures that include both traditional and innovative wall upgrades that would result in durable, energy efficient, and marketable retrofit strategies.

The experimental portion of this project was carried out by the UMN at the Cloquet Residential Research Facility (CRRF). This research building (Figure 1) is located on the Cloquet Forestry Center near Cloquet, Minnesota which is approximately 20 miles west of Duluth and in Climate Zone 7 (Very Cold). The CRRF was constructed by the UMN in 1997 with funding from Saint Gobain and CertainTeed Corporation to evaluate long-term, coldclimate performance of full-scale building enclosure assemblies.



Figure 1. Cloquet Residential Research Facility

The CRRF building is oriented along an east-west axis to maximize its northern and southern exposures. It sits on a full basement with 12 independent above-grade test bays protected by two end guard bays (Figure 1). These test bays are also thermally isolated from the two basement test bays. The eight test bays (1 to 4 and 9 to 12) having both north and south exposures were selected to conduct insitu testing of the wall energy upgrades for this project.

3. OVERALL APPROACH

This project was conducted in two phases. Phase 1 was conducted in Bays 1 through 4 and Phase 2 used Bays 9 through 12. Each test bay has a north and south facing wall opening that is approximately 8' wide by 7' high. Based on previous work at the CRRF, these test openings were divided in half to support two different test panels. Each test panel was mirrored on both the north and south orientation. The test panels are approximately 4' wide by 7' high. Each panel was carefully sealed into the building rough opening (Figure 2). The test panel has three wall cavities at approximately 16" on center to represent older wood-frame construction. The center cavity of each test panel was a true 16" on center and was designated as the test cavity (Figure 3). All of the monitoring sensors were placed in this center test section. The wall cavities on each side of the test cavity serve as guard cavities.

A. Base-Case Wall Preparation

Once the team had determined the base-case wall for in-situ testing, the UMN team built 16 identical test walls for each phase. The exterior finish was selected to represent an older house with several coats of oil-based paints. The interior finish was selected to represent an older home with heavy drywall or plaster and several coats of paint.



Figure 2. Exterior view of the Cloquet Residential Research Facility test bays.

B. Data Acquisition System (DAS)

The DAS for the in-situ experiment was built around the Campbell Scientific CR-1000X datalogger system. Each test cavity had between 15 and 20 sensors depending on the wall treatment. The sensor types and models installed in wall assemblies are in Table 1. The primary sensor array was located along a line through the wall section traversing the center of the width and height of the test cavity. In addition to the center line sensor array, there were secondary temperature and relative humidity sensors on the interior surface of the sheathing located approximately 6 inches from the top and bottom of the test cavity.

Table 1. Sensors Installed in the Wall Assembly for Performance Data Collection

Sensor Type	Sensor Model
Temperature	Omega Type-T thermocouples
Relative Humidity	Honeywell HIH-4000
Heat Flux	FluxTeq PHFS-09e
Moisture Content	Brass nails (shaft coated with enamel paint)

In general, there was a temperature sensor on the interior and exterior surfaces of the drywall, interior and exterior surfaces of the sheathing, and the exterior surface of the siding. A relative humidity sensor was placed on the cavity-side surface of the drywall along with the interior and exterior surfaces of the sheathing. A heat flux plate was located on the interior surface of the drywall. The insulated moisture content pins were inserted from the cavity side to measure the moisture content of the interior and exterior surfaces of the pine sheathing as well as the middle of the cedar siding. In the cases where a cavity insulation was to be installed a protective cap was placed over the moisture content pins. All sensor wires were run horizontally through a sealed opening into the guard cavity and then out to the test bay modules through a sealed block (Figure 3).

The DAS also collected interior and exterior boundary conditions. The interior temperature and relative humidity were measured in each test bay and recorded on the DAS. In addition, the exterior temperature, humidity, wind, and precipitation conditions were gathered from a local weather station. Pyranometers were used to measure horizontal solar radiation along with the vertical solar radiation on both the north and south wall exposures.

C. Air Tightness Calibration

It is well documented that air leakage can have a major impact on the thermal and moisture performance of a wall system. So, it was critical that each of the 32 base-case walls that represents the preexisting condition have a similar overall air leakage rate across the test cavity. To accomplish this, the inner drywall panels employed a gasket seal at all four edges and between the test cavity and guard cavities. Thisconcentrated interior-side leakage through a single electrical outlet box placed in the test cavity. Once the base-case test panels were completed, installed, and reached equilibrium with the controlled indoor conditions, the team performed an air leakage test using a TEC Micro Leakage Meter. Each test wall was measured with a 50 Pascal (Pa) pressure difference between the test bay and the outdoors using the empty electrical cut-out in the drywall panel. Using these baseline test results the tighest wall was set as the airtightness target. Then airtight gasketed electrical boxes were installed with a customized orifice to match the leakage of the target wall. This ensured the starting conditions of each test configuration were uniform.





4. WALL CONSTRUCTION

Performance criteria and other key research goals were developed based on input from industry experts and the literature review. The team chose 14 wall retrofit wall treatments along with two baseline walls for in-situ testing at the Cloquet Residential Research Facility (CRRF). All walls are structured using 2"x4" (nominal) studs that are 16" on center with gypsum board on the interior.

A. General Construction Notes

This section includes a construction description and assessment for each wall treatment. For wall treatments which added new exterior insulation and finishes over the top of the existing siding most solutions included a new air and water barrier (WRB = weather resistive barrier, FAM = fully-adhered membrane, or LAM = liquid applied membrane) over the existing cladding along with a compressible low-density fiberglass board installed over the old cladding prior to the wall upgrade installation. This layer was added to offer some leveling assistance and support for the new layers, suppress vertical convection and wind wash, and provide an opportunity for water to drain if it got behind the new treatment at windows, doors, and other wall penetrations. Most of the drill-&-fill approaches required the removal and replacement of one or more courses of the existing siding and the repair of the existing building paper over the holes used for installing the insulation.

B. Description of Selected Wall Upgrade Treatments

- Wall A: Base Case Wall #1 (Figure 4): As this is the base-case wall, no construction assessment is provided.



Figure 4. Wall A – Base Case

- Wall B: Drill-&-Fill Cellulose (Figure 5): A qualified installer drilled these wall cavities from the exterior and filled with cellulose at a density between 3.5 to 4.0 lb./c.f. This is a fairly standard application today and with an experienced crew it should be very straightforward. Trained crews with proper equipment for this type of application are widely available, allowing for competitive pricing and fast installation. This drill-and-fill process was also used for Wall E and Wall F.



Figure 5. Wall B – Drill-&-fill cellulose.

- Wall C: Injected Cavity Foam (Figure 6): This wall upgrade uses a proprietary low-rise, closed-cell polyurethane foam installed from the interior. The liquid foam was injected through very small holes in the drywall for each cavity and infrared imaging was used to ensure the cavities were completely filled. This treatment requires a trained crew with specialized equipment and this proprietary product is not yet widely available. However, the install for this wall upgrade was relatively fast and easily accomplished. Some repair of the interior finishes would be necessary.



Figure 6. Wall C – Injected cavity foam.

- Wall D: Pre-fab Ext EPS (Figure 7): This wall treatment used a commercially available prefabricated EPS insulation product that includes built-in drainage capabilities and an embedded structural ladder. A low-density fiberglass panel was installed to fill the air channels that would be created between the existing lapped siding and the rigid EPS board. This was covered by a housewrap-type WRB to provide a new air and water control layer. The first 2" EPS panel was installed to the existing wall using the integral fastening ladder followed by a second 2¹/₂" panel fastened to the previous panel using the integral fastening ladder. Uniform ladder spacing made it easy to connect the two panels and install the siding. This proprietary product is commercially available, though not necessarily in all regions. While this treatment is straightforward, it does require several steps.



Figure 7. Wall D – Prefabricated Exterior EPS.

- Wall E: Drill-&-fill Cellulose + Ext XPS (Figure 8): A layer of continuous exterior insulation was added to the dense-pack cellulose described in Wall B. The cedar lap siding and building paper were removed and a housewrap-type WRB was installed as a new air and water control layer. This was followed by a 2" layer of XPS insulation installed with 1"x4" furring strips securely fastened to framing. A 3/4" XPS insulation was placed between the furring strips to support the vinyl siding. This well-vetted treatment was quite simple and easy to install though it involves several steps and layers, including removal of the existing siding.



Figure 8. Wall E – Drill-and-fill cellulose plus exterior XPS.

- Wall F: Drill-&-Fill Cellulose + VIP/Vinyl Siding (Figure 9): Similar to Wall E, this wall treatment started with dense-pack cellulose. Siding and building paper were removed and a housewrap-type WRB was installed as a new air and water control layer. Then vinyl siding sections with an integrated vacuum insulated panel (VIP) were installed with appropriate fasteners to the sheathing. Compared to separate layers of rigid foam insulation and siding the installation of this treatment was simple and straightforward. The VIPs are 18" long by 12" high to match the height of double-six siding. However, a VIP cannot be cut or punctured without losing the vacuum. When the panel size does not fit the wall section, a piece of rigid insulation of the same thickness and size can replace the VIP.



Figure 9. Wall F – Drill-and-fill cellulose plus prefabricated VIP/vinyl siding.

- Wall G: Exterior Mineral Fiberboard (Figure 10): This wall upgrade started with the application of a vapor permeable liquid applied membrane (LAM) over the existing lapped siding to provide a more robust water control layer. A 2" thick mineral wool panel was installed with minimal cap nails. A half-height panel of the second layer of 2" mineral wool is installed at the bottom to ensure staggered seams and then 1"x4" furring strips were fastened to the framing at the bottom only which holds both insulation layers in place. The remaining second layer of 2" mineral wool panels were slid behind the furring strips all the way to the top of the wall where the furring strips were adjusted to be straight and plumb and secured to the framing with screws. Fiber-cement siding was secured to the furring strips using normal installation techniques. The installation of this treatment is pretty straightforward, but has several layers and steps.



Figure 10. Wall G – Exterior mineral fiberboard.

- Wall H: Exterior gEPS Structural Panel System (Figure 11): This wall upgrade was envisioned to be an off-site fabricated panel custom-fit to the specification and measurements of the existing building and then brought to the site to be hung onto the existing wall using a preinstalled engineered clip system. However, this panel is not commercially available, so the wall was built on-site in layers over the existing wall. A structural OSB sheet was fastened with screws to the wall framing and covered with a fully-adhered membrane (FAM). The first layer of 2-1/8" graphite impregnated EPS (gEPS) was installed with minimal cap nails. Then a second layer of 2-1/8" gEPS was installed with 1"x4" furring strips securely fastened to the OSB panel. Finally, metal panel siding was installed on the furring strips. The stiffness of the OSB panel made it easy to install the compressible fiberglass panel over the existing siding. While there are several layers, installation was quite straightforward.



Figure 11. Wall H - Exterior gEPS structural panel system.

- Wall I: Base-Case Wall #2 (Figure 4): This is a second base case wall.

- Wall J: Drill-&-Fill High-Density Fiberglass (Figure 12): A qualified installer drilled and filled this wall with a blown-in fiberglass from the exterior at approximately 1.5 lb./c.f. similar to what would be done in the weatherization and retrofit market. This is a standard application today. Trained crews with proper equipment are widely available allowing for competitive pricing and fast installation. This same process was used in Wall L and Wall O.



Figure 12. Wall J – Drill-&-fill high-density fiberglass.

- Wall K: Fiberglass Batt + Int Polyiso (Figure 13): This wall was selected as an upgrade that could be installed by the homeowner during an interior remodel. The interior drywall was removed and an unfaced R-13 fiberglass batt was installed in the existing cavity. Then a 1" foil-faced polyisocyanurate foam insulation board was installed over the studs on the room side. The foam board was sealed to the existing framing and penetrations to reduce air infiltration. New drywall was installed using longer drywall screws to provide adequate purchase to framing through the 1" foam. Installation was relatively smooth and fast.



Figure 13. Wall K – Fiberglass batt with interior foil-faced polyisocyanurate.

- Wall L: Drill-&-Fill FG + Ext Polyiso Figure 14): This wall upgrade starts with drill and fill fiberglass like Wall J, but the existing siding and building paper were removed and the holes in the sheathing for the blown-in fiberglass were sealed. A housewrap-type WRB was applied followed by a layer of 1" foil-faced polyisocyanurate. 1"x4" furring strips were placed over the foam and fastened to the studs. Then a prefinished wood composite lap siding was secured to the furring strips. Siding removal and the remaining two operations are not complicated, but requires multiple steps. Ideally the exterior furring strips should be fastened to the framing. With only 1" of insulation that is pretty easily achieved.



Figure 14. Wall L – Drill-&-fill fiberglass with exterior foil-faced polyisocyanurate.

- Wall M: Pre-fab Ext EPS/EIFS Panel System (Figure 15): This wall upgrade is a 6-in. thick panel of EPS foam finished on all six sides with a stucco material. The building's existing siding and building paper were removed and two coats of liquid-applied membrane (LAM) was applied. Sheathing seams and nail holes were filled with a compatible sealant. The prefinished EIFS panel was fixed in place using a gun-grade adhesive. As a prefabricated system, this should be fairly easy and straightforward. Once prepped, the installation of the panel was straightforward and very quick.



Figure 15. Wall M – Prefabricated exterior EPS/EIFS panel system.

- Wall N: Pre-fab Ext PU/Vinyl Block System (Figure 16): This prefabricated system of foam blocks faced with vinyl siding did not require removal of the existing siding. A housewrap-type WRB was installed over the top and sealed to serve as a new air and back-up water control layer. Installation begins at the bottom with a metal starter strip and drip edge. Each lightweight block engages the previous course in tongue-and groove fashion and the assembly is screwed to the framing through the upper flange. The sides and top used a cap strip that resembles a deep J-channel. The installation of this system was generally very efficient. The finished look resembles typical vinyl siding.



Figure 16. Wall N – Prefabricated exterior polyurethane block system.

- Wall O: Drill-&-Fill FG + Ext FG Board (Figure 17): This wall upgrade starts with the dense-pack cellulose installed as described in Wall J. The siding was replaced, but touch up was not required, and a housewrap-type WRB was secured at the top and draped over the siding. The 2" semi-rigid fiberglass boards were installed starting at the bottom and temporarily secured using two cap nails per piece. Then 1"x 4" furring strips were installed over the panels and fastened to framing. A fiber cement siding was secured to the furring strips. The installation of this treatment is pretty straightforward but does have multiple layers and steps.



Figure 17. Wall O – Drill-&-fill fiberglass with exterior fiberglass board.

- Wall P: FG Batt + XPS + OSB (Figure 18): This thermal break shear wall upgrade was developed to provide a combined structural and thermal upgrade to an existing home. The first step was to remove existing siding, building paper, and sheathing. Next, an unfaced R-13 fiberglass batt was installed in the existing cavity followed by a 1" XPS board insulation installed over the studs. Then a ³/₄-in. OSB sheet is installed over the XPS and fastened securely to the studs as a shear plate. A housewrap-type WRB was installed followed by a typical installation of vinyl siding. This wall treatment is a bit involved but improves both structural and energy performance. Once the siding and sheathing were removed, the remainder of the installation was pretty straightforward though time consuming.



Figure 18. Wall P - Fiberglass batt with XPS (sheathing is removed and replaced).

C. Constructability Assessment

The UMN team provided a qualitative assessment for five constructability attributes for each of the wall treatments: 1) ease of material acquisition, 2) simplicity and ease of installation, 3) overall speed of installation, 4) number of discrete operations, and 5) added wall thickness. - Material Acquisition: This focused on the availability of the material, a trained contractor, or installation equipment at the time of the project. It ranged from being readily available in the local market, to product that were available from limited building material supply outlets or manufacturers, to some novel products that were not available in the market at that time. - Simplicity and Ease of Installation: This included the level of skill required and the availability of equipment that might be needed to properly install the wall upgrade. Some wall upgrades were very simple and straightforward, while others required multiple steps or were more complex to execute. If a crane or lift is required for installation this increases complexity, which can be overcome by process savings with other aspects of the wall system. - Overall Speed of Installation: This is a fairly intuitive metric to assess the comparative speed of the installation of the wall upgrade for these test panels. While related to simplicity and ease, there are some walls that might be simple enough, but require several operations or different contractors to complete the overall process. Speeds ranged from very fast to quite slow or uncertain. This subjective assessment was based on building and installing the test walls and did not take into account complexities associated with whole-house projects. - Number of Operations: This metric was used to indicate the number of unique steps, layers, or processes required to complete each wall upgrade. In general, an operation is limited to a single trade (though a trade may do multiple operations) and represents a particular layer or a clear chronological step from one type of operation to another. However, in the case of the drill and fill cavity insulation, the siding removal (first step) and siding replacement (last step) are counted as a single operation since the same skill or trade would be used for both. Likewise, multi-layer insulation wall upgrades are counted as a single operation since they would be done at the same time by the same trade. However, not all operations are similar in complexity or time. For instance, the installation of a house wrap or a fiberglass batt might be much simpler and quicker than the installation of two layers of insulation that are overlaid and fastened with furring strips.

- Added Wall Thickness: When discussing wall upgrades a common concern is how the additional thickness can be integrated with existing features such as windows and overhangs. The added thickness is simply the thickness of the final treatment minus the thickness of the base case wall. This thickness is generally added to the exterior of the wall. However, for Wall K the insulation was added to the interior.

D. Constructability Summary

It is critical to understand that these qualitative and relative assessments are based on the experience of the UMN team in building and installing each of these wall upgrades on a 4' x 7' base-case wall. This assessment only represents these small, clean wall segments without openings, corners, or other architectural elements. No attempt has been made to assess how these wall upgrades would scale up to a whole house installation. Furthermore, because each wall upgrade was only built twice (one north and one south exposure) it is not clear how the learning curve with time and experience might impact the assessment provided. Presumably an actual bid from a contractor would include those considerations. Table 2 aggregates some of the most important logistical features perceived to affect adoption. Darker colors indicate clear advantages or positive outcomes; paler colors indicate greater challenges.

ID	Description	Material Acquisition	Installation Ease	Installation Speed	# of Operations	Added Thickness
В	Drill-&-Fill Cellulose (dense-pack)	readily available to contractor	very easy; straightforward	very fast	2	0
С	Injected Cavity Foam (proprietary oc-spu)	not currently available	moderately easy	very fast	2	0
D	Pre-fab Ext EPS (panel w/struts)	available at some BMS*	very easy; straightforward	somewhat fast	3	5.25"+
Е	Drill-&-fill Cellulose + Ext XPS	readily available to contractor	several layers or steps	somewhat slow	5	2.5"
F	Drill-&-fill Cellulose + VIP/Vinyl Siding	not currently available	several layers or steps	somewhat fast	4	0.5
G	Exterior Mineral Fiber Board	available at some BMS*	moderately easy	somewhat slow	3	5.25"+
Н	Ext. gEPS Structural Panel System	available at some BMS*	several layers or steps	somewhat fast	4	7"
J	Drill-&-Fill Fiberglass (proprietary, high-dens)	available at most BMS*	very easy; straightforward	very fast	2	0
K	Fiberglass Batt + Int Polyiso	readily available to contractor	moderately easy	somewhat slow	4	1"
L	Drill-&-Fill FG + Ext Polyiso	readily available to contractor	several layers or steps	somewhat slow	5	1.5"
М	Pre-fab Ext EPS/EIFs Panel System	available from manufacturer	moderately easy	somewhat fast	3	5.75"
N	Pre-fab Ext PU/Vinyl Block System	not currently available	very easy; straightforward	somewhat fast	2	4"
0	Drill-&-Fill FG + Ext FG Board	available at some BMS*	moderately easy	somewhat slow	4	3.25"
Р	FG Batt + XPS + OSB (thermal break shear)	readily available to contractor	moderately difficult	quite slow	6	0.75"

Table 2. Qualitative Constructability Assessments of Each Test Wall

* BMS refers to Building Materials Supply outlets such as big-box DIY chains or larger local lumberyards ⁺ Two layers of exterior insulation for colder climates; a single layer may be adequate for warmer climates

5. CONCLUSIONS

The exercise of building the 14 test wall treatments over a base-case wall provided insight into the relative degree of difficulty that novel or even just slightly unusual approaches may represent. The number of operations involved in the installation process is a telling metric. Each layer that can perform multiple duties saves the crew time, effort, and disruption. The

test panels for this study were geometrically simple and straightforward compared to the complexities of an entire house with windows and doors, service penetrations, inside and outside corners, and connections to foundations and soffits. Prefabricated products that incorporate a means of premeasuring and fastening (Walls D, F, H, M, and N) provide a degree of predictability and efficiency that could offset at least a portion of their cost premiums. On the other hand, wall products that cannot be easily modified in the field can create challenges. The team recognizes that wall thickness is an important factor. Even for the test building, thicker walls required more attention to detail at the top and bottom and edge connections. This is likely to be compounded greatly in real-world conditions. Walls which provide higher R-values without substantially increasing the thickness would provide substantial advantages.

The research team had anticipated that wall configurations which left the existing exterior finish in place would always be advantageous. However, this was not necessarily the case, because oftentimes new air and water control layers were necessary. The solution of a compressible fiberglass panel seemed to work well, but definitely increased the time. Alternate methods need to be explored for dealing with the interface between existing cladding and the wall upgrade for time and cost savings. A prefabricated system that incorporates necessary air and water control may be advantageous. Drill and fill approaches were remarkably straightforward, resulting in speed and cost advantages. Their limited thermal improvement still captures the bulk of available savings. Adding continuous exterior insulation can improve the wall's R-value and moisture and mold performance by shifting the condensation point to the outer side of the wall, but this comes at a substantial upcharge.

In closing, it is important to note that treatments with minimal intervention or that leave existing exterior finishes in place assumes there is no longstanding moisture damage. Contractors who choose these routes may decide to establish a reliable method of confirming the condition of the existing structure and materials before recommending these methods.

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7. REFERENCES

- Aldykiewicz, Antonio, Andre Desjarlais, Patrick Huelman and Garrett Mosiman. Hygrothermal Simulation of Exterior Retrofits in a Cold Climate. Residential Building Design and Construction Conference, Penn State, PA. 2022.

- Antonopouolos, Chrissi, Patti Gunderson, Tyler Pilet, Sumitrra Ganguli, Jian Zhang, Travis Ashley, Patrick Huelman, Antonio Aldykiewicz, Garrett Mosiman, Harshil Nagda, Cheryn Metzger, Andre Desjarlais and Rolf Jacobson. Comparing Affordable, Durable and Energy Efficient Wall Retrofit Systems. Residential Building Design and Construction Conference, Penn State, PA. 2022.

Structural Evaluation of a proposed concrete 3D printed Habitat in remote Alaska

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Abstract

A recent study was carried out at Penn State to evaluate the feasibility of using the technology of 3D concrete printing (3DCP) to build small habitats in remote areas of Alaska that need to consider permafrost in their design. This paper is focused on evaluating the structural performance of a designed habitat for 3DCP considering some of the applicable loads such as gravity, wind, snow, and earthquake. Four conceptual designs were developed for the superstructure that would rely on compressive stresses to resist the applied loads. Such a constraint would define a dome shaped structure where the compressive stresses resulting from application of the loads can be resisted by the concrete without the use of steel rebar reinforcement. Given the permafrost condition as another constraint, where heat transfer from the superstructure to the supporting soil should be prevented, the most plausible solution would be to elevate the structure on piles, requiring a valled transition from the superstructure to columns supported on piles. Alternatively, a slab on grade system with sufficient thermal insulation between the slab and underlying soil may also be designed to satisfy the constraint.

One of the main objectives of this paper is to discuss the finite element modeling of one of the four superstructure concepts assumed to be elevated on wooden piles. The loading conditions considered include earthquake effects in high seismic region, wind effects, and snow load. The dominant loading condition is earthquake loading, which causes excessive overturning effect because of the position of the center of mass above ground, subjecting piles to uplift forces. Another main objective of the paper is to discuss design of the transition element from printed reinforced concrete columns to wooden piles through specially designed joints that allow adjusting the elevation of columns in case of permafrost-related pile settlement. The results of structural capacity determination for various elements along the load path are discussed to illustrate satisfactory performance under the considered loading conditions.

1. Introduction

Residential design construction in Alaska comprises a set of challenges such as harsh environmental conditions that result from frozen soil, excessive snow and wind actions, and yearly temperature gradients that goes from -35F in winter to 65F in summer. Moreover, over 40% of Alaska's communities are located in rural areas with lack of road and sanitary infrastructures, which stresses the importance of efficient and sustainable construction. This project explores the application of concrete 3D printing as a solution to build affordable and sustainable housing since it avoids the use of formwork, reduces construction time and labor requirements, and increases design flexibility.

When designing concrete structures for 3D printing, several constraints should be addressed in the early design stages. Such constraints are a consequence of system, structural, and material issues. The first type of constraints are system-oriented and concern the printing envelope and motion limitations. Structural constraints concern geometric aspects of the design such as the maximum overhang angle, which should be at least 60 degrees [2], and the adequate number of beads per layer. Finally, early-age material behavior can be described in terms of rheology, deformability, and tensile strength (over the course of several hours), which should be accounted for when designing the shape and simulating structural behavior. Toolpath design is another issue of the 3D printing process that should be optimized to minimize travel length while ensuring that the layers at the bottom acquire enough strength to withstand subsequent layers on top.

2. Conceptual design of the Habitat

The preliminary design of a house for Alaska culminated in a system comprised of the following elements (Figure 1): foundation, substructure/vaulted grounding, slab, walls, and roof. A parametric definition of the structure was developed to allow a quick exploration of possible design alterations such as changing the height, curvature, footprint, openings, and foundation shape in response to structural, aesthetic, or functional requirements.



Figure 1. Perspective view of the solution: (a) model of solution showing the different parts of the 3D printed monolithic structure (piles, substructure, slab, walls, and roof); (b) preview of the printed structure.

When designing structures for permafrost regions in Alaska, pile foundations are a popular solution because of avoiding thawing of the permafrost, transferring loads to a stiffer soil, and the ease of building when elevated from the ground surface which reduces heat transfer from the structure to the supporting frozen ground (permafrost layer) and allows circulation of cold air below the structure.

The substructure is the part of the structure that creates an isolating air cavity between the inhabitable structure and the ground surface underlain by active and permafrost layers, something like a crawl space. It consists of a set of cross-vaulted shapes supported on the wooden or steel piles. The goal of the design is to enable as much airflow as possible through the cross vaults, while still transferring structural loads of the floor slab above down into the individual piles below. These geometric tradeoffs have been analyzed, and the constraints for the needed height to create sufficient ventilation, while limiting the height to reduce lateral seismic induced forces in the columns have been considered. Furthermore, considering the height needed for the curved arch shape of the supporting columns, the result has been to minimize the height of the pile above ground surface to about 1.0 ft, with the rest of the height for ventilation provided by the printed columns for a total open space height of about 4.5 ft above the ground surface.

One design option for the substructure consists of a heterogeneous solution where the exterior shell is 3D printed, and the interior core results from pouring light-weight concrete with lightweight-expended clay and cork granules replacing sand aggregates. The initial 4.5 ft of the substructure were designed with counterweight, which is represented by filling the area with 3D printed concrete. This avoids overturning effects while printing the columns.

3. Structural analysis of conceptual 3D Printed Concrete Housing Structure

3.1.1. Material Properties

As a starting note, Abaqus has no built-in system of units, which means that a structure should be modeled with consistent units, such as described in the Abaqus manual [4]. For this project we will be working in feet (ft) as the base unit. This structure was modeled using timber for the piles, with a 1 feet length above ground (below ground length is not considered for the analysis, as the pile is assumed fixed at the ground surface), and concrete for the superstructure, which includes the vaulted substructure and the wall-shell system. For concrete, a compressive strength of 2500 psi was adopted, and damage plasticity constitutive model as the one described in [5] was applied to study the behavior in a non-elastic way, and a density of 4.66 slug/ft³ (150lb/ft³) was used.

3.1.2. Boundary conditions

To model the boundary condition of the piles at the ground surface, we assume piles are fixed, which with the assumption of frozen ground is a reasonable conservative assumption for modeling. However, the adjustable jack system that would be located between top of each pile and bottom of printed concrete column will be assumed to act as a frictionless pin and modeled using pinned conditions. Therefore, pinned conditions were assigned to the bottom of each column. It should be pointed out that at this stage, we conservatively assume there is one such adjustable jack under each column. For a more refined evaluation and minimizing the cost, we will study the need for a jack under each column, and if justified, we can place such jacks under selected columns.
3.1.3. Loading

Four types of loads are considered in the load combinations for this analysis, namely, self-weight, snow, seismic and wind load. The respective load combinations are presented below, where D stands for Deadload, S for snow, E for Earthquake load, and W for Wind load.

- \blacktriangleright 0.9*D*+1.0*E* (Seismic)
- ▶ 1.2*D*+1.0*W* (Wind)
- > 1.2D+1.6S+0.5W (Snow)

3.1.3.1. Seismic Load Calculations, E

For the quantification of seismic loads, since there is the possibility of building in a remote area in the state of Alaska, a conservative approach of considering the region with largest ground acceleration was taken, which would be in the surrounding area of Valdez.

Since we will be dealing with a structural system that has no steel rebar reinforcement in the main body of the structure, and only in the cast concrete part of the columns, we conservatively assume the structure has no ductility, and that the response will be expected to be mostly elastic, which led us to adopt an R (response amplification factor) value of 1.0. In addition, we assume a risk category of II, and site class category D. Table 1 summarizes the seismic parameters.

	1 abit 1. 5ti	inc parameters.	
Ie (importance factor)	1	R (response amplification factor)	1
Sds (g)	1.333	S _{D1} (g)	1.133

From the Abaqus model, the fundamental period of the structure was found to be 0.0218 seconds, which is an indicator of a very stiff system, further justifying the assumption to use an R value equal to 1.0. Finally, the Seismic Response coefficient (C_s) can be determined from Equation (1).

$$C_s = \frac{S_{DS}}{(R/I_e)} = 1.333$$
 (1)

The value for Cs is between the lower and upper limits values that are, respectively, defined in Equations (2) and (3) from ASCE 7-16 (ASCE 2016), which in this case would be respectively 0.0587 and 51.97.

$$C_{s,min} = 0.044 S_{DS} I_e \tag{2}$$

$$C_{s,max} = \frac{S_{D1}}{T \left(\frac{R}{I_e} \right)}$$
(3)

For this initial assessment of the seismic loads, since there are no irregularities, and the height of the structure is lower than 160ft, we adopt the Equivalent Lateral Force Method, which requires the determination of the base shear. It is recognized that the structure can also be assumed to be a non-building structure because of its conical shape (lack of a diaphragm to distribute seismic induced loads to lateral load resisting systems. However, this assumption is not considered in this paper. The equivalent lateral force method serves as a simplified method to replace dynamic load effects by an equivalent static distributed lateral load at each floor of a building, which serves the purpose at this stage of the project.

The only step left to determine the base shear is the evaluation of the seismic weight, which in this case corresponds to the weight of the structure. The weight is obtained from the product of the volume with the density of concrete, resulting in a weight of 82,870 lbf, or 82.87 kips. The base shear is then calculated using Equation (4). It should be noted that in this scenario, the base shear obtained from ELFM is conservative as it exceeds the value from the expression in ASCE 7-16 (chapter 15) for rigid non-building structures: $V = 0.30S_{DS}WI_e = 33.14^k$.

Base shear =
$$C_s * Seismic Weight = 1.333 * 82.87^k = 110.49^k$$
 (4)

For the Abaqus modeling, the horizontal forces are applied at two levels, namely: (i) the slab above the substructure, with a force of 23.32 kips, which would be reflected upon an applied pressure of 3239 psf; (ii) the Shell + Wall system, with a force of 87.17 kips. The quantification of the described forces is shown in Table 2, and the application in the model in Figure 2.

Level	h _i (ft)	h (ft)	wi (kips)	w*h ^k	Cvx	Fi (kips)	Area of application (ft ²)	Pressure (psf)
Shell + Walls	10	15	45.97	689.51	0.79	87.17	15.03	5799
Slab	5	5	36.90	184.50	0.21	23.32	7.20	3239
		Total	82.87	874	1	110.49		
		Base	110.49				-	

Table 2. Equivalent Lateral force method results for Model D.

3.1.3.2. Wind Load Calculations, W

a. Wind Load Parameters

For the wind load calculation, the largest basic wind speed (V) of 150 mph in the Alaska region was adopted conservatively. In addition, the house is assumed to be in a flat, unobstructed area, including unbroken ice, corresponding to Exposure Category D. For the gust effect factor, since the fundamental period is 0.0218 seconds, the fundamental frequency is much larger than 1 Hz. Therefore, the building is considered rigid for wind calculation and the gust factor (G) is assumed to be 0.85.

b. Velocity Pressure, qz and qh

Since the height above ground is smaller than 15ft, and exposure category is D, the velocity pressure coefficients K_z and K_h are both equal to 1.03 (ASCE7-16). These coefficients are used to determine the velocity pressure coefficients q_z and q_h (Equation 4 and 5), which leads to the forces applied on the house. The wind directionality factor, K_d , and the topographic factor, K_{zt} , were assumed to be respectively 0.85 and 1.0.

$$q_z = 0.00256K_z K_{zt} K_d V^2 = 50.43 \ psf \tag{4}$$

$$q_h = 0.00256K_h K_{zt} K_d V^2 = 50.43 \, psf$$

c. Wind Loads

The remaining parameter to calculate wind loads is the pressure coefficient, C_p , which is equal to 0.8 for the windward wall, or the wall the directly receives wind, and -0.5 for the leeward wall, or the opposite wall to the windward wall. Having calculated the velocity pressure, gust factor, we can determine the wind load for the windward and leeward walls (Equation 6).

$$q_z G C_p = 34.30 \ psf$$

$$q_h G C_p = -20.17 \ psf$$
(6)

(5)

d. Wind Load Scenarios

Load scenarios for wind (see Figure 2b and 2c) can be summarized into fours types (Figure 3), where two of those consider torsion effects. In Abaqus, the torsion effect was introduced by applying an equivalent pressure load in opposite faces (see Figure 6).



Figure 2. (a) Combination of seismic load and gravity load with seismic load applied as pressure to the slab and to part of the face of the wall; (b) Equivalent torsional pressure applied to the house model for Load cases 2 and 4; (c) Load case 4 (wind load) representation.



Figure 3. Wind load scenarios (top view).

3.1.3.3. Snow Load Calculations, S

Snow loads should be an expected load in the design of roofing systems and should be assumed to act on the horizontal projection of the surface in question. In the case of both model D or model B (respectively a pointed cross-vault, and a pointed cloister vault sliced around 70% of its height), we have a roof that is geometrically defined from a pointed barrel vault. According to ASCE 7-16, barrel vault roofs shall have a slope factor, C_s , equal to 1.0 (Section 7.4.4 ASCE7-16). As a result, the sloped roof balanced snow load, p_{s_i} is equal to:

$$p_s = C_s p_f = p_f = 0.7 C_e C_t I_s p_g = 86.24 \, psf \tag{7}$$

Where,

- \succ *c_e* is the exposure factor, which is 0.70 in Alaska.
- \succ c_t is the thermal factor, which is 1.1 in structures kept just above freezing
- > I_s is the importance factor, and equal to 1.0
- > p_g is the ground snow load, which is equal 160 psf in Valdez, Alaska.

Due to the large inclination of roof, which is close the 70 degrees along its height, there is no need to calculate unbalanced roof loads (Section 7.6.2. of ASCE7-16) due to the influence wind loads on the snow distribution on the roof. The load scenario in Abaqus for snow load combination, includes deadload, and 0.5 times wind load, which in this case involved the wind load case 3 (see Figure 2 that consists of loads in both windward and leeward walls, since it controls wind load design for the columns.

3.1.4. Meshing

For this stage, a coarser mesh with 0.7ft size elements was adopted, and as a result of the complex geometry of the concrete shell and vaulted substructure, 10-node quadratic tetrahedral elements (C3D10), which has 4 integration points, was chosen for the simulation.

3.1.5. Results

a. Seismic Load Case: 0.9D + 1.0E

Starting with the seismic load case, the maximum displacement obtained from the model was 1.332E-03 feet, or 0.016 inches (Figure 4). However, for this structure, the set of elements that could represent more problems would be the substructure columns, namely the base, where the cross-section is smaller, which will provide most of the system's flexibility.



Figure 4. (a) Meshed structure; (b) Deformation under seismic load; (c) Displacement field in the structure To evaluate and design the base of the columns, we want to work with stress resultants, such as forces and moments, which is also provided by Abaqus by performing section cut at the desirable height, which in this case is the base of the columns. The force and moment components at the level of the base of the substructure columns are presented respectively in Figures 5(a) and (b). The gravity load (F_z) corresponds to approximately 0.9 times the weight of the structure (0.9 * 82,870lb = 74,583 lb), whose difference is due to vertical load caused by overturning effect of the seismic loading on the grounding columns. The Fx force of around 93.77 kips, which is mainly from the Equivalent lateral forces, will control the shear design of the columns. Three columns were identified as having the larger difference in the results as far as the forces and moments are concerned, which will serve as the representative elements of the analysis.



Figure 5. Force components (lbf) and (b) Moment components (lbf-ft) at column base for Seismic loading.

From the force (shear in two orthogonal horizontal directions and axial force) and moment components for columns 2B, 1A, and 4A, the first observation is that as expected, exterior columns have considerably more axial load than the interior columns, and this can be explained by two reasons: first, the overturning effect of the equivalent seismic load in the building results in vertical forces, which will be maximum in compression in alignment 1, and maximum in tension in alignment 4; secondly, the shell and wall system is placed on the perimeter of the structure, which results in the perimeter columns sustaining most of its weight. The second observation is that the columns in alignment 4, such as the case of column 4A, are under tension, which is explained by the fact that the tensile force from the overturning effect of the equivalent seismic horizontal forces were larger than the compressive force that resulted from the deadload. As a result, the connection of the columns in alignment 4 should be designed to have enough pullout strength. Third, interior columns are subjected to larger shear forces, which is a result of having a larger tributary area, which leads to larger stiffness in the system interior column-grounding, thus absorbing more percentage of the lateral forces. Finally, moments are very small ($M_{x,max} = 4.591$ ft-k), which is due to assigning pinned connections to the base of the columns. A summary of the forces and moments is shown in Table 8. Wind Load Case: 1.2 + 1.0W.

The main takeaway from this analysis is that cases 1 and 3 result in higher shear at the base of the columns. Column 1A will be considered for the analysis since it experiences the larger shear force. The next step consists of verifying the satisfactory performance of the column and connection to the adjustable jack under the applied forces, which can be illustrated by evaluating the capacities vs. the demands.

b. Snow Load Case: 1.2D + 1.6S + 0.5W

The results for the snow load combination are presented in the section on Additional Finite Element analysis Results, where a maximum displacement of 3.107E-04 feet was obtained close to the top of the roof, as expected. Since the wind load is applied at half of the value, a lower shear was obtained in comparison with the other load combinations. It can be concluded that the snow combination does not control the design of the columns.

3.1.6. Column and Connection Design

The analysis described in the previous section allowed the determination of the forces and moments in the columns of interest. A summary of the forces and moments used to evaluate the safety and, if needed, to redesign the members, is in Table 3. With this information, it will be possible to verify the column for shear capacity, design the needed reinforcement in the columns, and determine if the connection between column and adjustable jack is adequate.

Table 3. Forces and Moments for interest columns in Model D.

	Colur	nn		Forces and Moments			
Load combination	Designation	Type of Column	N (k)	V _x (k)	V _y (k)	M _x (ft-k)	My (ft-k)
	2B	Interior	4.00	8.57	0.05	0.08	4.59
Seismic: 0.9D+1.0E	1A	Exterior	20.96	5.04	1.47	0.91	2.83
	4A	Exterior	-13.76	4.72	0.04	1.37	3.74
Wind Load 1: 1.2D+1.0W	1A	Exterior	14.51	1.82	1.40	0.26	0.15
Wind Load 3: 1.2D+1.0W	1A	Exterior	13.10	1.68	1.03	0.46	0.17
Snow: 1.2D+1.6S+0.5W	1A	Exterior	11.18	1.32	0.94	0.32	0.04

3.2. Shear capacity check for base of columns and reinforcement solution

The shear capacity can be calculated conservatively by using expression (22.5.5.1) from ACI318-14, which would be valid for non-prestressed members without (conservatively) axial force, where V_c is the shear strength, f_c ' the compressive strength of concrete, and b and a are the dimensions of the section. For this scenario, we are only (conservatively) considering the cast concrete area, whose dimension would be the difference of 14.4 inches (1.2ft) with 3 beads of printed of concrete on each side, resulting in an area of 7.32 x 7.32 inches.

$$V_c = 2\sqrt{f'_c} ba = 2 * \sqrt{2500} * 7.32 * 7.32 = 5358 \ lb = 5.358 \ k \tag{8}$$

The shear capacity of 5.36k is not enough for the Column 2B in the case of the seismic load, whose shear force is equal to 8.57k. To check this criterion, the section should be upsized to 16.5 inches, which will provide a cast concrete area of 9.40x9.40 inches. This way, the new shear capacity will be enough to withstand shear from the seismic load case.

$$V_{c.upsized} = 2\sqrt{f_c'}ba = 2 * \sqrt{2500} * 9.40 * 9.40 = 8836 \, lb = 8.836 \, k \tag{9}$$

In terms of reinforcement solution, a shear reinforcement solution of No.3 @ 6 inches will be adopted to create the rebar cage to be placed within the printed shell of the column and along the height of the columns, while 4 No. 5 rebars will be used as longitudinal column reinforcement, which will work as a minimum reinforcement, since the moments are approximately zero at the bottom of the columns. A detail of the cross-section of the base of the column, including reinforcement is present in Figure 6.

3.2.1. Shear Stud Design

In the current design, shear studs are used to connect concrete to serve as a way to propagate loads to the saddle jack bracket. The main verification for the shear stud is usually nominal strength in terms of shear. However, in the seismic load scenario, the columns in alignment 4 end up being under tension, which require an additional check concerning pullout strength of the studs.

3.2.2. Nominal shear strength of single steel stud, Q_n

The value of the nominal shear strength of single steel stud is given in *Specification* Section I8.2a of AISC, and is defined in Equation (10), where, A_{sa} is the cross-sectional area of the shank of the stud, R_g and R_p are reduction factors to account for experimental test results, which are considered as equal to 1.0, and Fu is the minimum specified tensile strength of the stud. A ³/₄² stud will be considered at this stage.

$$Q_n = 0.5A_{sa}\sqrt{f_c'E_c} \le R_g R_p A_{sa} F_u \tag{10}$$

$$<=>0.5 * 0.4417 * \sqrt{2.5 * 2880} = 18.35k \le 1 * 1 * 0.4417 * 65 = 28.71k$$

The nominal shear strength of each shear stud is equal to 18.35 kips, which provides enough strength for the shear demand, since the largest shear in a column will be column 2B for the seismic load scenario, which has 8.57 kips distributed by 4 studs, corresponding to 2.142 kips, which is substantially lower than the value obtained in Equation (10).

3.2.3. Pullout strength, Npn

In the case of an excessive tensile force in a concrete column, the anchoring shear stud may tend to pull out, but because the stud head, it tend to break a cone out of the concrete as its failure mode. In particular, under combined shear and the tensile force in concrete column resulting from earthquake, cracking of concrete occurs, which may lead to even lower resistance against the pullout of the shear stud. To estimate pullout strength, ACI318-08 establishes an expression that depends on the shear stud head bearing area, or A_{brg} , compressive strength of concrete, and a pullout cracking modification factor, $\psi_{c,p}$ (Equation 11). A $\frac{3}{4}$ '' stud has head bearing diameter of 1.25'', resulting in an area of 1.23 in², and a pullout modification factor equal to 1.0 if the concrete is conservatively assumed as cracked.

$$N_{pn} = 8A_{brg}f'_c \psi_{c,p} = 24.60k \ (per \ stud) \tag{11}$$

This pullout strength is enough to sustain the tensile load of 3.44 kips (or 13.76/4) kips in each stud of column 4A under seismic load.

3.2.4. Bolt Connecting Saddle Bracket and Steel Pan

In order to assure load transmission from the steel pan to the saddle bracket jack, four bolts will be distributed around the base of the column. At this stage, let us assume a $\frac{1}{2}$ A307 bolt of 60ksi steel. This element will be subjected to combined tension and shear in the columns from alignment 4 when subjected to seismic loads. The quantification of combined shear-tension is obtained from AISC and involves the calculation of a modified tensile stress, F_{nt} that includes effects of shearing stress (Equation 12).

$$F'_{nt} = 1.3F_{nt} - \frac{F_{nt}}{\sigma F_{rv}} f_{rv} \le F_{nt}$$
⁽¹²⁾

Where F_{nt} is the nominal tensile stress when only tension occurs, F_{nv} is the nominal shear stress when only shear stress occurs, and φ is equal to 0.75 for LRFD. For a ½'A307 bolt, F_{nt} is equal to 45 ksi, F_{nv} is 27 ksi, and f_{rv} is equal to 1.18^k/0.196in², which leads to a F_{nt} value of 45.12 ksi. Since it must be lower than F_{nt} , we will adopt $F_{nt} = F_{nt} = 45$ ksi.

Following the calculation of the modified tensile stress, we can obtain the modified tensile strength, R_n .

$$R_n = F'_n A_b = 45 * 0.196 = 8.84k \ (per \ bolt) > \frac{N}{4} = \frac{13.76k}{4} = 3.44k \ (per \ bolt)$$
(13)

This confirms that a solution with 4 bolts of 1/2" diameter and 65 ksi steel strength assures safety of the connection.

3.2.5. Adjustment Screw Design

The adjustable screw will be subjected to the total axial and shear load from the corresponding column. Therefore, a similar verification to the one performed for the bolt can be made for the adjustable screw. In the case of column 4A, a tensile force of 13.76kips, and shear force of 4.717 kips should be resisted by the adjustable screw.

Assuming a 1.5" bolt of Grade 8.8, F_{nt} and F_{nv} will be, respectively, equal to 90ksi and 54ksi, thus resulting in F_{nt} value of 111.07ksi, which surpasses 90ksi. Therefore, 90ksi will be used as the value of F_{nt} . Finally, the modified tensile strength, R_n , is obtained from the product of 90ksi with the area of the shank of the 1.5" bolt, resulting in a strength of 159 kips, which significantly exceeds the axial force of 13.76 kips transmitted to the adjustable screw. Finally, a complete detail of the connection detail and column is shown in Figure 19.



Figure 6. Cross-section and connection detail for the base of the column.

4. Early-age structural analysis of a substructure module for printing

To test the printability of the habitat, a module of substructure will be printed to answer the following questions:

- Are the assigned constraints enough to assure printability of the vaulted shape? If not, what effects are we not considering?
- ✤ Are the printing results in accordance with the FEA simulations?
- ✤ Is dimensional accuracy verified?

A module of the substructure is presented in Figure 7(a) and (b) and results from the combining three columns: column A (corner column), column B (perimeter column), and column C (interior column).

4.1. Column A – 3D model, toolpath and structural analysis

Column A was designed considering overhangs larger than 60 degrees, and a printing time per layer larger than 34 seconds, which avoids the need to consider material deformation in both vertical and horizontal directions. This guarantees that the printability requirements are met. In addition, a FEA analysis was performed using material information from different authors, such as [6,7], and results on possible modes of failure will be compared with printed column.



Figure 7. (a) 3D model fo the Substructure; (b) Definition of the module to print; (c) and (d) Column A – toolpath.



Figure 8. Toolpath at three different level of Column A: (i) counterweight; (ii) Hollow shell after counterweight; (iii)Top of perimeter wall.

A linear elastic analysis on column A was performed using *Karamba3D* which a Grasshopper plug-in. Based on the toolpath length at each level, the mechanical properties of the material were determined considering the yield stress expression from [6], and the compressive strength and modulus of elasticity evolution over time (Figure 9). The analysis was only performed in the structure after the counterweight region (Figure 10a). The printed column is presented in Figure 10b.



Figure 9. Mechanical properties at each layer.



Figure 10. (a) FEA on column A; (b) Printed column.

5. Conclusions and future work

This paper describes the FEA analysis of one of four shelter designs being considered for 3D printing in the permafrost regions of Alaska. The design is characterized by a substructure raised from the ground formed by a series of small domes that rest on piles to isolate the house from the permafrost soil, preventing it from thawing, and a superstructure with a dome-shaped structure to enable the continuous printing of the shelter from the foundation to the roof. The FEA analysis shows that the proposed design would be able to withstand the loads associated with wind, snow, and earthquakes. The earthquake load produced larger forces at the bottom of the substructure and governed the design. In terms of printing stage, early-age mechanical properties should be quantified to perform a FEA in a layer by layer basis to predict whether plastic collapse, or the collapse of printed layer because of the weight of new printed layers. Preliminary printing tests of the foundation confirmed the printability of the envisioned substructure domed shapes. Future work will be concerned with the determination of the rheological and strength properties of concrete in the fresh state to develop a simulator of structural behavior during printing, when concrete has not set completely.

References

- [1] T. McFadden, Design Manual for New Foundations on Permafrost. North Pole, Alaska, 2000.
- [2] K. Park, J. Duarte, S. Nazarian, A.M. Memari, BIM for parametric problem formulation, optioneering, and 4D simulation of 3D-printed Martian habitat : A case study of NASA 's 3D Printed Habitat Challenge, (2020).
- [3] G. Duarte, N. Brown, A. Memari, J.P. Duarte, Learning from historical structures under compression for concrete 3D printing construction, J. Build. Eng. 43 (2021) 103009. https://doi.org/10.1016/j.jobe.2021.103009.
- [4] M. Smith, ABAQUS/Standard User's Manual, Version 6.9. Dassault Systèmes Simulia Corp., (2009).
- [5] M. Hafezolghorani, F. Hejazi, R. Vaghei, M.S. Bin Jaafar, K. Karimzade, Simplified damage plasticity model for concrete, Struct. Eng. Int. 27 (2017) 68–78. https://doi.org/10.2749/101686616X1081.
- [6] R.J.M. Wolfs, F.P. Bos, T.A.M. Salet, Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing, Cem. Concr. Res. 106 (2018) 103–116. https://doi.org/10.1016/j.cemconres.2018.02.001.
- [7] R. Jayathilakage, P. Rajeev, J. Sanjayan, Yield stress criteria to assess the buildability of 3D concrete printing, Constr. Build. Mater. 240 (2020) 117989. https://doi.org/10.1016/j.conbuildmat.2019.117989.

A comparison of thermal insulation strategies for 3D printed concrete structures in cold regions

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ABSTRACT

While large-scale 3D concrete printing has shown promise, it poses many building science challenges when proposed for housing. Among these challenges is ensuring adequate insulation throughout the building envelope, especially for irregular geometries or in extreme climates that require a substantial thermal barrier. This project investigates several possible configurations for insulation placement in 3D printed concrete structures. It assesses each option for its ability to feasibly provide required insulation levels in extremely cold climates such as northern Alaska. The design possibilities include: (1) sprayed foam on the inside of a single concrete shell, which could have variable thickness when transitioning from wall to roof; (2) sprayed foam on the exterior of a single concrete shell; and (3) foam placed inside the cavity formed by a double concrete shell, with several geometric strategies for structurally connecting the two shells while reducing thermal bridging between the two. The thermal performance and architectural pros and cons for each option are discussed. The paper also examines the insulation types and specifications for the options of pile foundation and slab-on-grade design of the structure.

INTRODUCTION

Residential applications of 3D printed concrete have the potential to improve on conventional construction methods in terms of cost, speed, and customizability of forms (Bos et al., 2016; Duarte et al., 2021). However, 3D printing technology poses many challenges for placing components of the building envelope and systems. In

extreme environments, thermal insulation is of particular concern since concrete itself does not offer sufficient thermal resistance to meet building codes. Furthermore, in permafrost regions, heat transfer between the building and the soil beneath should be prevented to avoid thawing of the frozen ground, which can lead to settlement. Insulation in conventional, rectilinear construction usually consists of rigid, flat foam boards, batts, rolls, or loose-fill materials placed into cavities and in between structural members. A continuously printed concrete structure requires a custom solution instead, especially since the irregular building shapes afforded by 3D printing may lead to significant curvature and gradual transitions between walls and roofs. Sprayed foam offers the flexibility necessary for curved concrete structures, but where exactly this foam should be applied within the assembly is an open question, as it affects many aspects of the architecture. In addition, strategies to prevent heat transfer between the structure and foundation depends on whether the building is elevated and supported on piles or a multipoint system, or it is slab-on-grade. For pile supported buildings, thermosyphons or thermopiles are commonly used. For a slab-on-grade construction system, the suggested approach is to provide rigid insulation layer between sand and gravel layers below the slab.

This paper provides a preliminary investigation of potential thermal barrier options in the design of concrete structures, with an emphasis on walls and roofs. It first reviews existing methods for insulation in extreme environments and proposed insulation strategies for continuously printed structures. It then lays out the methodology for an initial assessment of the feasibility, which includes basic thermal conductivity calculations and preliminary modeling of heat transfer through the wall. The paper next presents the results of this investigation before discussing the architectural implications of each choice. Solving the insulation "problem" is part of a broader research project to establish a feasible design and construction approach for 3D-printed houses in extreme environments. Determining a proper insulation strategy has significant implications for the rest of the design, since the insulation thicknesses required to prevent heat loss affect the construction sequence, built structural performance, and architectural utility of the space.

LITERATURE REVIEW

Insulation needs in extreme environments

While the content in this paper may be relevant to many cold regions, this study focuses on the state of Alaska as an example. The environment in Alaska necessitates careful consideration of the envelope and its performance. Most of Alaska's territory is classified under the Koppen designation Dfc, which is Subarctic. The Subarctic climate is characterized by long, very cold winters and short, cool summers. It is generally found at latitudes from around 50 degrees to 70 degrees. However, Alaska also contains some Tundra areas, in addition to more mild continental regions. In the colder subregions, a central issue is thermally separating the conditioned indoor space from the foundation through an open crawlspace to avoid thawing the permafrost. While thermal separation for the floor has significant implications for the structural design, it also relates to the livability of the house. The surface temperature of the floor is of particular concern in Arctic climates, since it is where occupants work, play, and relax. Insulation that isolates the foundation from the living space will also be evaluated in terms of its ability to keep the floor surface temperature as close to the ambient temperature as possible. This will reduce thermal discomfort from radiation and stratification of cold air near the floor.

the walls and roof have stringent insulation In addition to floor. the requirements. For Alaska climate, the required R-values range from around R-20 for above grade walls to around R-50 for roofs, depending on the geographic location. In traditional rectilinear construction, such values could be achieved through a variety of methods including rigid foam insulation, thick fiberglass batts, insulated concrete forms (ICFs), structurally insulated panels (SIPs), or dense-packed fiberglass or cellulose. The geometries produced by 3D printing may require different strategies due to their curvature and often gradual transitions between what is considered a wall and what is a roof. The construction method is also less clear—since a 3D-printed wall or roof is gradually constructed by robots, it may be advantageous to add insulation during this process, or all at once at the end, once the structure has been firmly established. This paper considers both possibilities, drawing from existing knowledge about the application of insulation.

Existing insulation strategies for 3D printed buildings

Insulation in 3D printed buildings is an area of ongoing interest. Pessoa et al., (2021) provide an overview of insulation technologies applied by researchers involving 3D printing, which can be both printed itself or applied later. Implemented technologies include formwork that stays in place, hard polystyrene, rock wool, or liquid polyurethane that is applied in the middle of a load-bearing wall to fill all voids in the space (3D Printing Media Network, 2019; Gosselin et al., 2016; Sun et al., 2021). For example, Kaszynka built a wall with mineral woold and polyurethane foam between printed layers (Kaszynka et al., 2019). In the project *Gaia*, the company WASP filled inner vertical cavities of a 3D printed building with rice husks (Valente et al., 2019).

Other strategies involve combining concrete with another material, either as a functionally graded material (Craveiro et al., 2020) or a heterogenous mixture. One example is the integration of aerogels into the cement itself, which increases thermal resistance (Baghban, 2019). Lightweight extrudable foamed concrete, which also has improved rheological properties, also has improved thermal properties (Falliano et al., 2018). Several others have also experimented with adding cork to the concrete (Gama et al., 2019). Within these materials-focused research examples, several have found significant improvements in the thermal properties compared to conventional concrete. For example, Mohammad et al., (2020) report a reduction in thermal conductivity by 62%. However, the scale of insulation needs in extreme climates is substantially higher—an improvement of 20- or 30-fold might be required to reach building codes.

As a result, none of these strategies have fully solved the needs of custom 3D printed structures in extreme environments. Some are in temperate environments and do not have the adequate thickness to meet the significant R-values needed in places such as Alaska, while others are unsuited to gradual transitions between wall and roof. This paper identifies some strategies that could be useful when both are present.

METHODOLOGY

Description of prototypical 3D printed house

This paper considers insulation solutions for 3D-printable structural forms that have been proposed for housing in Alaska. Such forms include the roof geometries shown in Figure 1, which can be coupled with different options for grounding shown in Figure 2. The examples shown below provide approximately 150 ft² (14 m²) of living space and would thus likely be combined with adjacent domes side-by-side or with printed connectors. However, the forms themselves could be scaled depending on the constraints of the printing system being used. Ideally an insulation solution would be flexible enough to work for any such geometry, regardless of its curvature and relationship between vertical and horizontal structural elements. The main elements in need of customized insulation are the walls and roof, which will be described next.



Figure 1. Potential structural options in need of insulation





Transitions between wall and roof

Traditionally, walls are the vertical elements that enclose an interior space. Because of the vaulted shape of the roof geometries under consideration, the printed walls can be short, before they transition into the roof. Two possibilities are considered for the structure of the walls: solid (single shell) or hollow (double shell) (Figure 3). The former may use homogeneous concrete or functionally graded concrete with insulative "layers" with an increased grade of lightweight (with the potential benefits mentioned), and the insulative aggregates printed on the exterior side of the wall. The latter has the advantage of being lighter, using less material, and having improved insulation

properties, but it makes printing of the vaulted roof on the top more challenging. The hollow cavities maybe filled with insulation foam or granules, but this hybrid solution complicates construction. Further study will permit to identify the most appropriate solution weighing in structural, thermal, printing, and construction considerations.

In the possible configurations above, the walls transition to the roof at a lower point than in traditional construction. A vaulted or domed structure for the roof permits 3D printing of the whole structure, avoidance of formwork, simpler construction, and a sealed-enclosure environment by decreasing the number of joints. Like the remaining parts of the structure, the roof may be printed using ordinary concrete or lightweight concrete, which could be homogeneous or potentially functionally graded, with the grade of lightweight aggregates increasing toward the top for improved structural performance.



Figure 3. Possible single- and double-shell concrete printed geometries. (A) shows a single layer wall while (B) shows a double layer wall.

Insulation details

Such a structural configuration leaves several potential options for insulation. In addition to single layers of conventional materials, functionally graded materials may offer the possibility of integrating cork or other lightweight substances such as Styrofoam balls into the concrete. Hempcrete or other composite materials might also be considered. Combining concrete with other materials may also improve other properties and attributes of the design in different domains. For example, making the structure lighter favorably affects foundation design and seismic design, while functionally graded materials could improve thermal resistance or lower the carbon footprint, thus being more environmentally friendly.

However, since concrete itself generates less than R-1 per inch depending on density, other insulating materials will be required beyond graded materials containing concrete. One possibility is spray foam, which can adhere to custom shapes and offer R-values of up to 7 per inch for closed-cell foams. Spray foams made from materials such as polyurethane or polyisocyanurate offer significant benefits for 3D printed buildings at this scale in cold climates, since high R-values are required to fit into small

available volumes, and their material and mechanical properties provide some flexibility during application. However, many of these materials are extremely carbon intensive. As more environmentally friendly materials with high R-values are developed and improved, such as cellulose-based composite foams, they should be given strong consideration. It should be noted that further research is required to determine when during the process foam insulation should be applied, as there are both advantages and challenges to application during or after printing.

Another option entirely is to print double walls and even roofs, which creates some structural advantages, and then fill the voids/cells with insulative materials. Such a double wall solution would behave analogously to a structurally insulated panel but will follow the concrete shape rather than the usual modular form of a panel system. In this method, special care would be given to potential thermal bridging, subject to how the two layers are connected to ensure structural load transfer. Depending on final geometries, some options might also be combined—for example, some of the flat portions could contain rigid insulation to save on costs if a continuous thermal barrier can be maintained. Basic details of each assembly type are provided in Figure 4.





It is worth noting that in the double-shell configuration, structural requirements dictate that the two shells are connected at various points. In typical Contour-Crafting-style 3D printing, the outer and inner face of the walls are printed along with a zig-zag interior pattern that connects the two. While this satisfies many structural requirements, such significant material connection between the inner and outer concrete shells would effectively negate much of the insulation's benefit. As part of this research, we considered potential geometries for providing structural benefits while lessening thermal bridging (Figure 5). The effective R-values of these solutions are calculated and modelled in the next section, along with the details from Figure 5.



Figure 5. Possibilities for structural connection between inner and outer printed shells

RESULTS

Preliminary R-value calculations for the assembly concepts are provided in Table 1 below. The estimated R-values can also be compared to historical requirements for ceilings and walls for Alaskan climate zones (Table 2). Especially for the insulation-inside configuration, the spray foam could be thickened as the wall transitions into a ceiling where necessary. For the double shell configuration, this transition could also be made but will be accomplished through a combination of decreasing the shell layers and widening the gap. In addition, the parallel path method was used to calculate R-values for a range of double-wall sections like the one in Figure 6. Structural connections from the concrete reduced the R-value considerably, often below R-10. These results are not included because of their high degree of uncertainty without further modeling and testing, but the exercise made it clear that such an assembly requires additional design efforts to mitigate this bridging.

Tables 1. Calculated overall insulation for single and double walls

	Material	R-value / inch	R-value	Thickness	R-Value Total
		(Range)	(Used)	in	Deg F x ft ² x hr / BTU
	Air film (inside)				0.68
	Interior Finish				
1 -	Spray Foam	5 to 7	6.25	4.72	29.50
Single	Concrete	0.07 to 0.52	0.21	7	1.47
Shell	Exterior Finish				0.50
	Air film (outside)				0.17
	Total				32.3
	Air film (inside)				0.68
	Interior Finish				
	Concrete		0.21	4.72	0.99
2 - Double shell	Spray Foam	5 to 7	6.25	4.72	29.50
	Concrete	0.07 to 0.52	0.21	4.72	0.99
	Exterior Finish				0.50
	Air film (outside)				0.17
	Total				32.8

Tables 2. Alaska Insulation Requirements (Seifert, 2000)

Alaska Insulation Code Requirements	Ceiling	Wall
Regions 1-3 (Southeast, southcentral, Interior southwest)	38	18-25
Region 4 (Northwest)	38	30
Region 5 (Arctic Slope)	52	35

DISCUSSION

After reviewing the R-values of these assemblies, several observations can be made.

Extreme climates require substantial insulation thickness, often beyond what is possible through modifying the concrete material itself. While initially considering a number of functionally graded materials, it became clear that although FGMs have significant architectural benefits, their thermal benefits alone do not achieve stringent code-based requirements. The most effective strategy for building assemblies is thus to find an extremely insulative material per thickness, such as closed-cell foam, and apply it ways that can follow the shape of a concrete printed building.

Reducing thermal bridging will be an important design consideration in any *assembly that holds insulation inside a cavity.* Having an inner and outer concrete shell in the structural assembly can have many advantages, similar to historical structures that share this geometry. Interior concrete finishes might also be attractive from an architectural perspective. However, any insulation solution for extreme environments with this condition must think of creative ways to thermally break connections between the inner and outer shell. Otherwise, these connections transmit so much heat loss that they fall below code requirements.

Single-layer foam insulation is likely the best option in terms of R-value and ease of application, but it can have architectural consequences. Such a solution must consider how continuous the insulation can be after penetrations to the concrete and other building systems are installed, especially if on the interior. It is also possible to place insulation on the outside of the main shell, which could similarly reduce thermal bridges compared to double-wall solutions. However, having insulation exposed outside the concrete might require additional material layers to adequately protect the foam from the elements or provide an acceptable architectural finish. Further study is required to fully develop this detail.

CONCLUSIONS

This paper reviews potential insulation strategies for use in 3D concrete printed buildings in extreme climates, proposes possible geometries for this insulation, and provides preliminary hand calculations regarding the R-values of these assemblies. These efforts are only a starting point for developing a fully integrated thermal strategy in 3D printed buildings. Furthermore, insulation is just one of many challenges facing 3D printed buildings in extremely cold climates—significant issues in controlling temperatures and managing the material during and after printing must also be resolved. However, insulation challenges are a significant issue given the stringent performance requirements and lack of space. Future work in this area includes additional detail development, computational heat transfer simulations of potential assemblies, and then mockups of prototypes and physical evaluation of the heat loss of various specimens. Nevertheless, the numbers in this paper set the limits on potential insulation strategies and point towards potential areas for improvement.

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REFERENCES

- 3D Printing Media Network, 2019. Apis cor 3D prints first on-site house in Russia in one day for \$10,134 [WWW Document]. URL https://www.3dprintingmedia.network/apis-cor-3d-prints-first-site-house-russia-one-day-10134/
- Baghban, M.H., 2019. Thermal insulating cementitious composite containing aerogel and phosphate-based binder. IOP Conference Series: Materials Science and Engineering 609, 062024. https://doi.org/10.1088/1757-899X/609/6/062024

- Bos, F., Wolfs, R., Ahmed, Z., Salet, T., 2016. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. 11, 209–225. https://doi.org/10.1080/17452759.2016.1209867
- Craveiro, F., Nazarian, S., Bartolo, H., Bartolo, P.J., Pinto Duarte, J., 2020. An automated system for 3D printing functionally graded concrete-based materials. Additive Manufacturing 33, 101146. https://doi.org/10.1016/J.ADDMA.2020.101146
- Duarte, G., Brown, N., Memari, A., Duarte, J.P., 2021. Learning from historical structures under compression for concrete 3D printing construction. Journal of Building Engineering 43, 103009. https://doi.org/10.1016/J.JOBE.2021.103009
- Falliano, D., Gugliandolo, E., De Domenico, D., Ricciardi, G., 2018. Experimental Investigation on the Mechanical Strength and Thermal Conductivity of Extrudable Foamed Concrete and Preliminary Views on Its Potential Application in 3D Printed Multilayer Insulating Panels. RILEM Bookseries 19, 277–286. https://doi.org/10.1007/978-3-319-99519-9 26
- Gama, N., Ferreira, A., Barros-Timmons, A., 2019. 3D printed cork/polyurethane composite foams. Materials & Design 179, 107905. https://doi.org/10.1016/J.MATDES.2019.107905
- Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., Morel, P., 2016. Large-scale 3D printing of ultra-high performance concrete a new processing route for architects and builders. Materials & Design 100, 102–109. https://doi.org/10.1016/J.MATDES.2016.03.097
- Kaszynka, M., Olczyk, N., Techman, M., Skibicki, S., Zielinski, A., Filipowicz, K., Wroblewski, T., Hoffmann, M., 2019. Thermal-Humidity Parameters of 3D Printed Wall. IOP Conference Series: Materials Science and Engineering 471, 082018. https://doi.org/10.1088/1757-899X/471/8/082018
- Mohammad, M., Masad, E., Seers, T., Al-Ghamdi, S.G., 2020. High-Performance Light-Weight Concrete for 3D Printing. RILEM Bookseries 28, 459–467. https://doi.org/10.1007/978-3-030-49916-7_47
- Pessoa, S., Guimarães, A.S., Lucas, S.S., Simões, N., 2021. 3D printing in the construction industry A systematic review of the thermal performance in buildings. Renewable and Sustainable Energy Reviews 141, 110794. https://doi.org/10.1016/J.RSER.2021.110794
- Seifert, R., 2000. Special Considerations for Building in Alaska.
- Sun, J., Xiao, J., Li, Z., Feng, X., 2021. Experimental study on the thermal performance of a 3D printed concrete prototype building. Energy and Buildings 241, 110965. https://doi.org/10.1016/J.ENBUILD.2021.110965
- Valente, M., Sibai, A., Sambucci, M., 2019. Extrusion-Based Additive Manufacturing of Concrete Products: Revolutionizing and Remodeling the Construction Industry. Journal of Composites Science 2019, Vol. 3, Page 88 3, 88. https://doi.org/10.3390/JCS3030088

A parametric investigation of canopy heat islands mitigation strategies: A case study of a new residential development master plan of a U.S. north-eastern city

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ABSTRACT

According to the 2018 United Nations World Urbanization Prospects, 68 percent of the world's population will live in urban areas by 2050. This upstream urbanization causes changes in local weather, air quality, and climate. The "urban heat island" (UHI), which conventionally refers to the difference in temperature between urban and corresponding rural or suburban areas, is one of the most well-documented phenomena of urban climate change caused by urbanization. UHI effects are now a global concern and have been observed in cities of all sizes and locations. The negative effects of UHI on human welfare are being studied worldwide; however, selecting geographically appropriate UHI mitigation strategies at the early design stages is of great interest and benefit to architects, engineers, and urban planners.

This study investigates the impact of various mitigation strategies on the intensity of UHI inside the canopy level of a new development master plan in a north-eastern city in the United States. A sensitivity analysis was conducted by using a large number of inputs in the Urban Weather Generator (UWG) model, an urban climate prediction tool. The UHI-induced weather data were produced in EPW format under various scenarios of UHI mitigation strategies and compared to reveal the impact of studied variables on the UHI intensity over a 5-day simulation period. The analyses proved that the greatest reduction in UHI intensity after the greenery coverage ratio (grass and trees) can be expected from reducing pavement thickness. Although increasing surface albedo and roof vegetation are well-known mitigation strategies, alterations to surface albedo and adding green roofs were among the least influential factors investigated in this specific location and climate zone.

The findings of this study are useful for climate-sensitive design purposes and will open up the discussion for considering geographically appropriate UHI mitigation policies by designers and policymakers. The methodology provides an architect and planneraccessible framework for evaluating new construction or potential interventions to mitigate the UHI effects.

INTRODUCTION

Today, urban areas house 55 percent of the world's population, a figure that is expected to rise to 68 percent (i.e., two out of every three people) by 2050. According to

projections, "urbanization," or the gradual shift in human population residence from rural to urban areas, combined with global population growth, could add another 2.5 billion people to urban areas by 2050 (United Nations, 2018). Given the enormous and growing proportion of the world's population that lives in cities, as well as the disproportionate share of resources consumed by these urban dwellers, particularly in the global North, towns and their inhabitants are key drivers of global environmental change (Grimmond, 2007). The well-studied "urban heat island" (UHI) effect, which is one of the most visible anthropogenic interventions on climate, causes urban agglomerations to be typically warmer than their surrounding rural areas (Oke, 1967). Heat islands keep their typical characteristics within different places; however, the intensity and timing vary at each location (Vettorato & Prosperi, 2011). Due to differences in land cover and surface characteristics inside each urban area, the urban thermal environment differs accordingly (Hart & Sailor, 2009). Oke (1995) classified UHI into four types based on the height at which it can be measured: subsurface urban heat island, surface urban heat island, canopy layer urban heat island, and boundary layer urban heat island. The canopy layer urban heat island (UHI_{UCL}), which is the air layer from the ground to about the roof level and is the zone of human occupation, is the most commonly studied of the four types of UHI. The UHI_{UCL} is strongly influenced by time (of day and year) and weather (wind, cloud), and its effects are a global concern and have been observed in cities regardless of their locations and size. The negative impacts of UHI_{UCL} on human welfare have been broadly confirmed during the past decades by studies, e.g., Clarke, 1972; Meier, 2006; Grimmond, 2007; and Akbari & Kolokosta, 2016.

The conventional method for measuring any city's heat islands is to collect and compare air temperatures at screen height (one to two meters above ground) of "urban" and "rural" in two or more fixed sites and/or from mobile temperature surveys (Stewart & Oke, 2012). However, measuring the effects of heat islands on regional climate requires a significant amount of effort and advanced instruments that are not accessible to all scholars. The lack of broad investigation in this realm is more evident when it comes to evaluating the effectiveness of different design strategies in reducing these impacts. particularly caused by a new master plan which is still under development. That is where modeling becomes necessary. Heat island modeling tools are used both to understand heat island intensities and to estimate how effective will be the various mitigation measures to tackle the phenomenon. Computational Fluid Dynamics (CFD) based models and Surface Energy Balances (SEB) models are known as two main models to investigate the heat island's effects on individual buildings, a single street or neighborhood, or an entire urban region. Typically, these models and tools require expert knowledge of climatology, an enormous number of inputs, and a high amount of computational time, which makes them undesirable for examining the phenomenon's impacts during the building design process.

To fill this gap, Bueno Unzeta (2012) developed the Urban Weather Generator (UWG) to estimate the UHI effect in the urban canopy layer and generate neighborhood-specific weather files using meteorological data measured at weather stations located in an open area outside the city. The UWG model transfers meteorological data from an open-air weather station to a specific urban location. At the same time, it incorporates the effects of the built environment on original weather data. The UWG

uses EnergyPlus; a Building Energy Model (Crawley et al., 2001), and the Town Energy Balance model (Masson, 2000).

The model's primary inputs are classified according to their role in modifying the urban environment, i.e., urban form and urban function. Although the effectiveness of inputs on results varies, it is clear that urban form parameters (those associated with changes in surface albedo and emissivity) and urban function parameters (those associated with changes in anthropogenic heat generation) are critical factors in quantifying canopy heat islands using the UWG model (Figure 1). The third set of inputs is derived from the reference site and will be fed into the model in the form of weather data such as Typical Meteorological Year (TMY) data in EPW format.



Figure 1. List of required inputs to the UWG model based on urban feature classification, Source: Authors

The UWG model has been tested for Toulouse, France, Basel, Switzerland, and Singapore. The original version of the model is in beta, and the Ladybug tools team (Ladybug, 2019) recently released Dragonfly, an architect-friendly and open-source UWG interface.

The UHI is caused primarily by reduced evapotranspiration from vegetation cover and highly solar-absorbing materials in urban areas. There is a rich body of research on the efficacy of individual heat island mitigation strategies, but few on the hierarchies and second-order effects of potential interventions. The cooling effects of different UHI mitigation strategies have been widely investigated with a focus on metropolitan areas, in Los Angeles by Rosenfeld, et al., 1998, Tokyo by Ca, et al., 1998, Honk Kong by Tong et al., 2005, and Phoenix by Cow & Brazel, 2012, to name a few. Although vast research effort has been dedicated to UHI effects and its mitigation strategies in Metropolitan and densely populated urban areas, very few studies exist on UHI impacts in low-rise and less-populated urban areas. Moreover, investigating the increased temperature caused by a new master plan and potential solutions at the early design stages is of great interest and benefit to architects, engineers, and urban planners. To this purpose, a parametric approach is proposed in his study to, 1- estimate hourly heat islands inside the canopy level of a new development master plan of a U.S. northeastern city, State College, PA, 2- provide a computationally optimized list of intervention arrangements and placements to tackle the potential problem of UHI.

METHODOLOGY

Case Study

Pine Hall Traditional Town Development (TTD) was selected as a cases study. TTD Masterplan is proposed to convert an area of 137.7 acres (2,500 by 2,400 feet) of land with almost 95% covered by trees and grass to a residential /commercial development located in Ferguson Township, Pennsylvania. The master plan proposed site coverage of 14% for new construction including 30% public and 70% residential building. The new tree coverage rate is 6% and 50% for grass coverage. The average height for residential buildings is 20 feet and 10 feet for commercial/public developments. The remaining 30% are man-made, heat-absorbent surfaces like sidewalks, parking lots, and car roads (Figure 2).



Figure 2. The Proposed TTD Master Plan, adapted after Township of Ferguson, PA

Workflow

Figure 3 depicts the entire workflow of this study, which included five major steps. The first step was to create a 3-D model of the master plan using advanced and parametric architectural tools. To do so, shapefile and CAD data were imported into Rhinoceros 3-D using Meerkat (Lowe, 2014), a GIS data-parsing plug-in, and Grasshopper (Mcneel, 2009). The Centre Region Council of Governments (COG)



Figure 3. Workflow of the UHI estimation and mitigation strategies (Source: Authors)

provided the authors with CAD data for the proposed master plan, and a detailed process of 3-D model creation is explained by Hashemi et al., 2018.

Buildings and site properties were added to the model after the 3-D model was created and incorporated into the UWG model to ensure the accuracy of the UHI simulation. Energy-related properties of commercial and residential buildings were extracted for climate zone 5A (Cold) from the US Department of Energy's Commercial Reference Buildings (Standard 90.1, version 2019, new construction) and Residential Prototype Buildings Models (International Energy Conservation Code, version 2018), respectively. The DOE reference buildings (Deru et al., 2011) represent realistic building characteristics and construction practices.

According to the Local Climate Zones (LCZ) developed by (Stewart & Oke, 2012), the TTD master plan is classified as LCZ 6-Open low-rise and its size was acceptable as each LCZ should have a minimum diameter of 400–1,000 m (i.e., a radius of 200–500 m) to make sure that its internal boundary layer lies entirely within the zone.

The LCZ classification scheme consists of 10 built and 7 land cover types and each of the 17 basic types is associated with typical value ranges for a set of key urban parameters. The reliability and validity of the system were demonstrated in several studies done in cities from various climatic zones e.g., Singapore (Ng, 2015); Colombo, Sri Lanka (Perera & Emmanuel, 2018); Presidente Prudente, Brazil (Dos Dantos Cardoso & De Costa Trindade Amorim, 2018); Phoenix, U.S. (Middel et al., 2014); and Dublin, Ireland (Alexander & Mills, 2014).

Based on the LCZs dataset sheets, the site's anthropogenic heat flux was considered to be 25 (W/m^2) due to fuel combustion and human activity (transportation, space cooling/heating, industrial processes, and human metabolism). Furthermore, the LCZ data sheets were used to calculate terrain roughness class, surface admittance, and albedo. The inputs for the proposed buildings, sidewalks, and traffic developments provided to the UWG to simulate UHI intensities are listed in Table 1.

Category	Inputs	Inputs Value
Building Typology	Floor to Floor Height	3 m
(Residential-70%)	Glazing Ratio	0.18
	Solar Heat Gain Coefficient (SHGC)	0.33
	Wall Albedo	0.21
	Roof Albedo	0.22
	Roof Vegetation Coverage	0.0%
Building Typology	Floor to Floor Height	4 m
(Commerciar-30 %)	Glazing Ratio	0.65
	Solar Heat Gain Coefficient (SHGC)	0.39
	Wall Albedo	0.21
	Roof Albedo	0.22
	Roof Vegetation Coverage	0.0%
Pavement	Albedo	0.1
Parameters	Thickness	0.5 m
Traffic Parameters	Sensible Heat flux	4 W/m ²

Table	1.	The	inputs	to	the	UWG Model
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Figure 4 shows the finished baked model, which includes the properties of buildings and the site as a result of step 2.



Figure 4. Pine Hall Traditional Town Development (TTD), Ferguson Township, Centre County, Pennsylvania (3-D illustration by Authors)

The typical weather data recorded by State College-Penn State University were used as the reference weather data in step 4. For a calendar year, the hourly temperatures inside the TTD's canopy level were simulated. The UHI intensity is defined as the difference between the simulated and reference temperatures. Figure 5 depicts the hourly simulated temperatures vs the reference temperatures for four days, namely January 14, May 31, July 25, and September 14, representing the Winter, Spring, Summer, and Fall seasons, respectively (the mentioned days showed the highest UHI intensities compared to other days of their seasons).



Figure 5. Simulated TTD's air temperature vs reference temperature on four days from four different seasons

Finally, a sensitivity analysis was performed to assess the efficacy of various UHI reduction measures. Changes in albedo, green roof, pavement thickness, solar heat gain

coefficient, glazing ratio, grass and tree coverage on the UHI intensity on five consecutive days in September when the highest UHI intensities were found are depicted in Figure 6. The hourly canopy temperature has a characteristic regime that is most apparent over dry surfaces, on calm, clear nights (Heisler & Brazel, 2010). To reveal the efficacy of different mitigation strategies, the amount of decreased temperature at the same time (8 pm) in five consecutive days of September with clear sky cover and low wind speed are compared.

One more round of the simulation was done to study a scenario of mitigation strategies, in which all mitigation techniques with sensible impacts on UHI reduction were gathered into one group called "All" in Figure 6.



Figure 6. Effectiveness of different mitigation strategies on UHI intensities at the same hour (8:00 pm) during 5 consecutive days in September

RESULT & DISCUSSIONS

To model the UHI intensities inside the canopy level of a new master plan development proposed for Ferguson Township, Centre County, PA, a parametric approach was introduced. A sensitivity analysis was also conducted to evaluate the effects of a list of well-known mitigation techniques on UHI intensities separately, as well as the optimal scenario including all the strategies together. The key finding of this study is the evaluation of the cooling capacity of well-known UHI mitigation strategies during 5 consecutive days in a month (September) when a higher average of UHI intensities compared to other months were recorded. The average temperature during the day and night was compared using weather data from a suburban region and weather data generated by the TTD master plan's UWG model. Under the impacts of UHI, the average daytime temperature climbed by 3.01 percent, while the average nighttime temperature increased by 17.45 percent, for a total rise of 7.8 percent for the full year.

The highest maximum UHI intensity of 5.4 °C was reported during the Winter (January 14 at 4:00 a.m.), 7.8 °C during the Spring (May 31 at 6:00 a.m.), 8.2 °C during the Summer (July 25 at 9:00 a.m.), and 9.7 °C during the Fall (September 14 at 7:00 am). To investigate the impacts of the well-known mitigates strategies on reducing the UHI intensities, 11 scenarios of design (10 scenarios from individual strategies and one for all the strategies combined) including higher albedo for building walls and roofs, added green roofs, decreased pavement thickness, increased pavement thermal conductivity, higher solar heat gain coefficient, lower glazing ratio, and more grass and trees coverage were tested. The sensitivity analyses were run for a consecutive five days in September at the same time (8:00 pm) right after the sunset when the UHI intensities are high.

The analyses proved that the greatest reduction in UHI intensities caused by the individual strategies can be expected up to 1.2, 1, and 0.9 °C by 20%, 15%, and 10% increase to tree coverage, respectively. Followed by reducing pavement thickness from 0.5 m to 0.2 m, the UHI magnitude can decrease up to 0.6 °C. Even though increasing surface albedo and green roofs are well-known mitigation strategies, alterations to surface albedo and adding green roofs to the all-proposed buildings were among the least influential factors studied in this specific location and climate zone. Furthermore, modifying the thermal properties of pavements and windows area had a relatively insignificant impact on the UHI intensities inside the canopy level of the proposed master plan. For the last scenario called "All" in figure 6, all the effective strategies proved in the former scenarios were combined into one case, and simulation was run to indicate the efficiency levels of UHI mitigation strategies altogether. In this case, higher albedo for roof and walls, lower thickness and higher thermal conductivity of pavement, 10% increase in the grass, and 20% more trees were assumed and added to the model. For 5 consecutive days at 8:00 pm, the reduced temperature caused by the "All" scenario exceeds 1.4 °C and reaches 1.6 °C. Note that in this study, limitations such as local building codes, cost, and mutual compatibility of design strategies have not been considered for the individual scenarios and the "All" scenario as well. Also, the thermal properties of the proposed building, commercial and residential buildings, were extracted from the DOE reference buildings due to the lack of detailed information on the proposed buildings in the master plan.

CONCLUSION & FUTURE WORKS

The results of this study show that UHI-induced temperatures can climb by up to 10 degrees Celsius inside the canopy level of a low-rise master plan development. Also, the efficacy of well-known mitigation methods like increased albedos and green roofs might vary depending on the climate zone and site characteristics of design development. In addition, analyzing the influence of various methods early in the design process can assist planners and architects in expanding on lesser-known

strategies such as pavement thickness, which have larger benefits on UHI reduction and result in more effective climate-sensitive design.

Building energy simulations (heating and cooling loads) and outdoor thermal comfort can be used for the proposed master plan to better understand the effects of UHI. Furthermore, the same research might be carried out for other climate zones, particularly warmer ones, to expose the possible effects of alternative mitigation measures and design scenarios.

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REFERENCES

- Akbari, Hashem, & Kolokotsa, D. (2016). Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings*, *133*, 834–842. https://doi.org/10.1016/j.enbuild.2016.09.067
- Alexander, P. J., & Mills, G. (2014). Local climate classification and Dublin's urban heat island. *Atmosphere*, 5(4), 755–774. <u>https://doi.org/10.3390/atmos5040755</u>
- Bueno Unzeta, B. (2012). Study and prediction of the energy interactions between buildings and the urban climate Submitted to the Department of Architecture in Partial Fulfillment of the Requirements for the Degree of. MIT.
- Ca, V. T., Asaeda, T., & Abu, E. M. (1998). Reductions in air conditioning energy are caused by a nearby park. *Energy and buildings*, *29*(1), 83-92.
- Chow, W. T., & Brazel, A. J. (2012). Assessing xeriscaping as a sustainable heat island mitigation approach for a desert city. *Building and Environment*, 47, 170-181
- Clarke, J. F. (1972). Some effects of the urban structure on heat mortality. *Environmental Research*, 5(1), 93–104. <u>https://doi.org/10.1016/0013-9351(72)90023-0</u>
- Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J., & Glazer, J. (2001). EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 319–331. https://doi.org/10.1016/S0378-7788(00)00114-6
- Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., & Crawley, D. (2011). U.S. Department of Energy commercial reference building models of the national building stock. *Publications (E), February 2011*, 1–118. <u>https://doi.org/NREL Report No. TP-5500-46861</u>
- Dos Santos Cardoso, R., & De Costa Trindade Amorim, M. C. (2018). Urban heat Island analysis using the 'local climate zone' scheme in presidente prudente, Brazil. *Investigaciones Geograficas*, 69, 107–118. https://doi.org/10.14198/INGEO2018.69.07
- Grimmond, S. (2007). Urbanization and global environmental change: Local effects of urban warming. *Geographical Journal*, *173*(1), 83–88. <u>https://doi.org/10.1111/j.1475-4959.2007.232_3.x</u>
- Hart, M. A., & Sailor, D. J. (2009). Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island. *Theoretical and Applied Climatology*, 95(3–4), 397– 406. https://doi.org/10.1007/s00704-008-0017-5
- Hashemi, F., Marmur, B. L., Passe, U., & Thompson, J. R. (2018). Developing a workflow to integrate tree inventory data into urban energy models.

- Heisler, G. M., & Brazel, A. J. (2010). The urban physical environment: temperature and urban heat islands. Chapter 2. In: Aitkenhead-Peterson, Jacqueline; Volder, Astrid, eds. Urban Ecosystem Ecology. Agronomy Monograph 55. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America: 29-56., 29-56.
- Masson, V. (2000). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-Layer Meteorology*, 94(3), 357–397. <u>https://doi.org/10.1023/A:1002463829265</u>
- McNeel, R. (2009). Rhinoceros 3D. Retrieved from: https://www.rhino3d.com/
- Meerkat (2014), Grasshopper 3D Plug-in Retrieved from: http://www.food4rhino.com/app/meerkat-gis
- Meier, A. (2006). Countermeasures to Urban Heat Islands: A Global View. *Lawrence Berkeley National Laboratory*, 1–5.
- Middel, A., Häb, K., Brazel, A. J., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, 122, 16–28. <u>https://doi.org/10.1016/j.landurbplan.2013.11.004</u>
- Ng, Y. (2015). A Study of Urban Heat Island using "Local Climate Zones" The Case of Singapore. British Journal of Environment and Climate Change, 5(2), 116–133. https://doi.org/10.9734/bjecc/2015/13051

Oke, T. R. (1973). City size and the urban heat island. *Atmospheric Environment (1967)*, 7(8), 769-779.

- Oke, T. R. (1995). The heat island of the urban boundary layer: characteristics, causes and effects. In *Wind climate in cities* (pp. 81-107). Springer, Dordrecht.
- Perera, N. G. R., & Emmanuel, R. (2018). A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka. Urban Climate, 23, 188–203. https://doi.org/10.1016/j.uclim.2016.11.006
- Rosenfeld, A. H., Akbari, H., Romm, J. J., & Pomerantz, M. (1998). Cool communities: strategies for heat island mitigation and smog reduction. *Energy and buildings*, 28(1), 51-62.
- Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93(12), 1879–1900. <u>https://doi.org/10.1175/BAMS-D-11-00019.1</u>
- Tong, H., Walton, A., Sang, J., & Chan, J. C. (2005). Numerical simulation of the urban boundary layer over the complex terrain of Hong Kong. *Atmospheric environment*, *39*(19), 3549-3563.
- Vettorato, D., & Prosperi, D. C. (2011, September). Specifying spatial attributes and relations in Urban Heat Islands: A generalizable model applied to Trento, Italy. In 28th Urban Data Management Symposium UDMS'11 (pp. 181-192).
- United Nations. (2018). 2018 revision of world urbanization prospects.

Small-Scale Testing of Air Barrier Systems Adhered on Sheathing Panels Under In-plane Relative Displacement Simulating Seismic Effect

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Abstract

With the increased emphasis on energy efficient construction, designers are adopting passive house standards for residential and other types of building construction. Passive house standards attempt to limit energy loss due to air leakage through the building envelope, by setting an upper limit for the total air leakage allowed. This has led to increased importance of air barrier tapes and sealants to insure satisfying the stringent air leakage requirements. While commercial air barrier products are effective in achieving the air tightness limits set by the passive house standards right after construction, displacements that occur due to seismic events during the lifespan of the building may jeopardize the air barrier by damaging the airtight seam sealant leading to increased air leakage through the envelope. This paper assesses the performance of commercially available air barrier products under simulated seismic loading. The experimental program consisted of testing small-scale sheathing panels, two side-by-side panels sealed on the long side joint, using an air barrier product in both monotonic and cyclic loading profiles. Multiple combinations of sheathing board material and air barrier tapes were tested. The tested sample groups represented the most common air barrier systems used in the industry, incorporating the following air barrier products; 3M Construction Seaming Tape, Siga Wigluv 60, Prosoco R-Guard Joint and Seam Filler, and Zip System Tape. The failure load and failure displacement were recorded for each test, along with the corresponding failure mode. The experimental program provided insight on key aspects of the air barrier products, determining the displacement and ultimate load capacity for each type of tape and sealant. The results of the monotonic testing, reported on in this paper, showed tape adhesion as the controlling failure mode for all taped specimens and longitudinal tear for the liquid applied seam filler specimens. The liquid applied air barrier Prosoco R-Guard Joint and Seam Filler reached the highest ultimate load capacity while the 3M Construction Seaming Tape resulted in the least ultimate load capacity.

1.0 Introduction

Airtightness is one of the main requirements of construction based on the Passive House (PH) building standard, with strict limitations on air leakage values to prevent excessive loss of energy. Currently, designers and builders are achieving air tightness by sealing the sheathing boards in the perimeter of the building enclosure with an air barrier product. If the PH Standard is to be widely adopted for high-performance buildings, these new, highly insulated walls with minimal infiltration must be designed and proven to resist wind and earthquakes (lateral loads) without compromising their thermal performance. For example, if a small earthquake shakes a wall so that it is not damaged structurally, but there is a tear in the layer providing air tightness, then the thermal performance of the envelope is compromised with no visible exterior signs. This could lead to higher energy use and, more critically, mold in the wall cavity, which can affect the health of the occupants (e.g., allergy or asthma). Failures of this type with concerns for energy loss and health risk would likely lead to resistance from stakeholders in adopting the PH Standard widely, mirroring the rejection of air tightness as an energy saving strategies in the late 1970s and 80s due to moisture and mold issues.

Seismic events vary in amplitude and thus the damage afflicted on a building. Often ranging from a complete building collapse to subtle ground vibrations barely felt by building occupants, both cases yield concise conclusions on the integrity of the building enclosure and in turn the air barrier. However, events that do not cause complete or partial collapse of a building, may incur hidden damage to air barriers. This has been discussed in Memari et al., 2019 where a comprehensive study of the material properties of commercially available air barrier products was conducted. Based on the authors' analysis of the air barriers, they highly recommended conducting experimental testing of the available air barrier products to verify their ability to resist lateral loading.

Theide, et al., 2013 investigated liquid-applied and self-adhered commercially available weather resistive barriers (WRB). The study aimed to assess the load capacity of weather resistive barriers when subjected to wind and seismic induced displacements. The authors gathered and discussed relevant data published in previous literature and concluded the importance of weather resistive barriers to resist wind and seismic loads to preventing tear and degradation of the WRB.

Further research has been conducted to evaluate the performance of sheathing wall systems under various cases of loading, Terntiuk, 2009 studied the effect of monotonic and cyclic loading on structurally insulated panels (SIP) by conducting large-scale racking tests for complete wall assemblies. While Memari et al., 2014 conducted a large-scale experimental program assessing the effect of using different seaming compounds on the shear performance of gypsum wall boards. The program tested five wood frame walls incorporating drywall sheathing under cyclic loading. Memari et al., 2009 conducted a large-scale experimental program on wood and steel stud walls. Specimens were subjected to monotonic and cyclic loading. Failure mode, failure load and ultimate displacement values were measured. This study provided insight on the shear capacity of walls sheathed with gypsum wall board.

This paper aims to provide insight on the behavior of commercial air barrier products when subjected to in-plane monotonic loading. The results provide clear insight on the response of each air barrier product.

2.0 Experimental program

The experimental program, reported on herein, assessed the performance of different air barrier products after experiencing vertical displacement, simulating a seismic event. A small-scale test setup was designed and fabricated from steel unistruts having 1.5-inch channel walls to house two individual sheathing panels. An air barrier product would then be applied vertically at the intersection of the two panels. In total, 41 specimens were tested in monotonic loading. This section presents the details of the test setup and tested specimens.

2.1 Test Setup

Figure 1 shows a schematic of the test setup and sheathing panel dimensions. Each specimen consisted of two sheathing boards measuring two feet in height and one foot in width, one board is fully fixed using wood screws, while the second board is unrestricted to vertical motion; however, a Unistrut rail guided the panel and prevented any lateral movement, without fixation. The movable panel was connected to a 5000lb hydraulic piston. Load and displacement values were recorded directly using the MTS control unit. The Unistruts were clamped to the testing table as shown in Figure 1. Specimen installation began with fixing the right-hand side panel inside the vertical and horizontal unistruts. The second Unistrut was then attached to the hydraulic piston through a horizontal Unistrut clamped to the piston head. The left-hand side vertical Unistrut acted as a guide preventing lateral sway and did not fix the moving panel in place. Panel alignment was then checked and pushed together leaving minimal to no gap between the two panels. The air barrier product was then applied to one side of the seam where the two sheets adjoin. The air barrier was applied evenly along the height of the joint with equal length covering both panels. Manufacturer installation suggestions were followed for each product. Testing began with the elongation of the piston at a rate of 0.2-inch per second. Specimens were tested until reaching the maximum piston stroke of 2-inches.





(c)

Figure 1: (a) Section A-A Showing the Corner Unistrut Connection. (b) Dimensions of the Tested Sheathing Boards. (c) Test Setup Schematic.

2.1 Materials

The sheathing boards and air barrier tapes were the main test components. Each product was purchased independently from commercial retailers. Key material properties are presented in Table 1. Values are reported from the published manufacturers' data sheet.

Table 1: Material Properties.

Product	Tensile Strength	Elongation at
	psi	failure
3M [™] Construction Seaming Tape	38	162%
Siga Wigluv® 60	-	-
PROSOCO R-Guard® Joint & Seam Filler	70	180%
ZIP System [™] Sheathing & Tape	938	400-800%
OSB	1500	-
Plywood	3000	-

2.2 Specimens

Specimens were divided into four sample groups based on the applied air barrier. Each air barrier product was applied to the plywood and OSB boards separately, while the ZIP tape was only applied to the ZIP sheathing panels. The air barrier product was applied to the sheathing panel while it was inside the testing rig to avoid unintentional movement of the sample. Figure 2 shows prepared specimens before testing.



Figure 2: (a) Specimen P-3M-1 Before Testing. (b) Specimen Z-8 Before Testing.

The OSB sample group studied the effect of applying the $3M^{TM}$ Seaming tape and the Siga Wigluv® tape on each side of the panel independently. In both sample groups, three specimens had the air barrier applied on the smooth side, which is characterized by a uniformly laminated surface, while three specimens were applied on the rough side, characterized by an unlaminated surface. Figure 3 shows specimens with rough and smooth surfaces.





Figure 3: (a) Tape Applied on Smooth Side. (b) Tape Applied on Rough Side.

Each sample group consisted of three specimens, however some sample groups had more than three specimens. Table 2 shows the number of tested specimens in each sample group.

Sheathing Panel		C	SB	Diversed	ZID	
		Smooth	Rough	Plywood	ZIP	
	3М ^{тм} -Таре	3	3	8		
Air	Siga Wigluv® -Tape	3	3	6	-	
Barrier	R-Guard® Filler	-	-	5		
	Zip - Tape		_		10	

Table 2: Total Number of Tested Specimens in Each Sample Group.

3.0 Results

This section presents the results of the experimental program. Table 3 shows the average maximum load and average failure displacement values for each sample group, along with the average standard deviation. Values in Table 3 were measured from cured specimens.

Table 3: Average Sample Group Values for Cured Specimens.

		Р	lywood	ZIP		
Sheathing Panel		Load lb	Displacement	Load lb	Displacement	
			inch		inch	
	3M-Tape	94.0(26.8)	0.304(0.083)			
Air	Siga-Tape	135(4.96)	1.09(0.132)		-	
Barrier	R-Guard	204(48.1)	0.897(0.383)			
	Zip - Tape		-	178(26.5)	1.09(0.181)	

Table 4 shows the average maximum load and average failure displacement values for OSB panels. These specimens were tested immediately after applying the air barrier tapes.

Table 4: Average OSB values.

		OSB	Smooth Side	OSB Rough Side		
Bo	oard	Load lb	Displacement	Load lb	Displacement	
			inch		inch	
Air	ЗМтм	97.1(26.3)	0.478(0.168)	10.3(2.60)	0.059(0.018)	
Barrier	Siga	77.4(7.51)	0.923(0.115)	21.6(0.189)	0.289(0.01)	

3.1 Load Displacement Diagrams

The load and machine stroke were recorded for all specimens. Figure 4 shows two sets of load displacement diagrams. The first diagram Figure 4 (a) presents the results of cured specimens while diagram Figure 4 (b) presents instant OSB specimens with the air barrier applied to the smooth side of the panel.



Figure 4: (a) Load Displacement Diagram for Cured Specimens. (b) Load Displacement Diagram for Instantly Tested OSB Specimens.

3.2 Failure Modes

Identifying the possible failure modes of each air barrier was significant to assessing its overall performance. The failure mode of each specimen was documented. The most common failure modes are presented in Figure 5.



(c) (d) Figure 5: (a) One-Sided Delamination of the 3M[™] Tape. (b) Stretching and Partial Delamination of the Siga Tape. (c) Clear-Cut Failure of the R-Guard Specimen. (d) Stretching of the ZIP Tape.
4.0 Discussion and Conclusion

The experimental program provided insight on the behavior of air barriers when subjected to vertical displacement. This section will discuss the results presented in section 3. Conclusions from the experimental program are also provided.

As shown in Table 3, the PROSOCO R-Guard® Joint & Seam Filler reached an average failure load of 204lbs with an average failure displacement of 0.897-inches. The failure mode of this material was consistent throughout testing, characterized by a sudden and complete tear of the material along the panel boundary. The 3MTM Construction Seaming Tape had an average failure load of 94lbs and a corresponding average failure displacement of 0.304-inches. The failure mode of the 3MTM Construction Seaming Tape was a brittle delamination of the tape from one panel, referred to earlier as one-sided delamination.

The ZIP System[™] Sheathing & Tape achieved an average failure load of 178lbs and an average failure displacement of 1.09-inches. The ZIP System[™] Sheathing & Tape presented the highest ductile capacity, as shown in Figure 4 (a); the load displacement graph of this product reached approximately 4-inches while maintaining approximately 150lbs. The failure mode of this product was characterized by stretching of the tape material with minimal tape debonding.

The Siga Wigluv tape reached an average ultimate load of 135lbs and an average failure displacement of 1.09-inches. The corresponding failure mode was characterized by the stretching of the tape material until ultimately debonding from the panel edges. Debonding usually occurred on the edges of the tape, on both panels. This failure mode is referred to earlier as a partial delamination.

The measured values in Table 4 show a drastic decrease in tape performance when applied to the rough side of the OSB panel. Applying the $3M^{TM}$ Tape on the rough side of the panel led to an 89% decrease in both ultimate load capacity and in the average failure displacement. While the Siga Wigluv® tape experienced a 72% drop in load capacity and a 68% drop in failure displacement compared to the values measured from the smooth side of the OSB panel, when applying the tape to the rough side.

Based on these test results, one can simply conclude that not all tapes and substrates will behave the same under relative displacement at vertical joins between substrate sheathing. While reaching more specific and definitive conclusions requires consideration of cyclic loading and more importantly, testing full-scale mock-up wall assemblies, the resulting data clearly indicates there is potential for air leakage in some passive house construction in earthquake prone regions. Further study is needed to determine the threshold racking displacements for such failure in different combinations of tapes and substrates.

5.0 Future Research

Future research opportunities will assess the large-scale performance of the air barriers when applied to complete wall sections. Racking tests conducted on finished wall sections with the applied air barriers would have the ability to test the air leakage through the air barrier after testing and determine the level of drift that would initiate air leakage.

The effect of cyclic loading on the air barrier is the subject of ongoing research at the Pennsylvania State University using the test setup presented in this paper. A cyclic load will study the effect of applying repeated cycles of loading and unloading on the air barrier product, better simulating a seismic event.

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References

- Memari, A. M., Kasal, B., Manbeck, H. B., and Adams, A. R., (2009). "Lateral Load Resistance Evaluation of Wood- and Steel- Stud Partition Shear Walls" [Journal]. - [s.l.] : ASCE, 2009. - 4 : Vol. 15.
- Memari, A. M. and Solnosky, R. L., (2014). "In-Plane Shear Performance of Wood-Framed Drywall Sheathing Wall Systems under Cyclic Racking Loading," *Open Journal of Civil Engineering*, Vol. 4, pp. 54-70.
- Memari, A. M., Iulo, L. D., and Griffin C., (2019). "Study of Vulnerability of Air Barrier Membranes and Sealant Joint Tapes Applied over Wood Sheathing Panel Joints Due to Racking Movement in Passive House Designed Residential Buildings," *Wood Design Focus*, Vol. 29, No. 1,pp. 10-17.
- Terentiuk, S., (2009). *Parametric Study of Structural Insulated Panels Under Monotonic and Cyclics Loading*. - M.S. Thesis, The Pennsylvania State University, University Park, PA, .
- Theide, J. M. and Memari A. M., (2013). "Review and Preliminary Evaluation of the Performance of Weather Resistive Barriers Under Seismic Induced Light Frame Wall Deformations," Proceedings of the Architectural Engineering Institute Conference, ASCE, AEI 2013 pp. 837-846.

A Zero-carbon Bio-based Wall Panel as an Energy Retrofit Solution for Buildings

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ABSTRACT

Existing buildings are one of the most important sources of carbon emissions in the United States, accounting for a larger energy-sector use than transportation or industry. Within total building energy use, the largest impact is from space heating and cooling. More than half of the buildings in the United States have major air leakage and inadequate insulation in their envelopes due to the age of construction. This makes them excellent targets for economically attractive energy use upgrades. Among all the building elements, the walls and their associated fenestration contribute about 60% to the overall heating and cooling energy loss of the enveloped due to transmission and infiltration [1]. Therefore, there is a significant need for cost-effective methods of improving wall thermal performance and reducing infiltration for existing buildings.

The long-term goals of this study are to develop a bio-based retrofit panel system which is optimally sized, efficient for installation, with net-zero embodied carbon and a low-cost installation process, fabricated from a low-density wood-based substrate of three-ply Cross-laminated Timber (CLT) technology supporting the bio-based insulation. The paper analyzes the potential for mold growth of the proposed panel with three different R values of 10, 20 and 30 using hygrothermal modeling tools WUFI[®][2] BIO and WUFI[®] Mould Index VTT for four different climate zones of 4B, 5B, 6B and 7 in United States. The mold growth rate data and mold index results of these modeling are compared with each different alternative to conclude an understanding of the optimized mold-controlled thickness for the retrofit panel in various climate zones. Preliminary results demonstrate that the proposed panels with R values of 10, 20 and 30 applied over uninsulated wall section provides acceptable risk according to ASHRAE standard 160 for mold sensitive materials while providing up to a 73% reduction in wall heat loss.

Keywords: Carbon emission in buildings, Wall insulation, Retrofit panel, Mold growth rate.

1. INTRODUCTION

Existing buildings that were built before 1992, when U.S. Department of Energy's (DOE) Building Energy Codes Program was established, represent approximately 68% of the residential building stock in the U.S. [3];[4], and often have significant air leakage and inadequate insulation. Buildings with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills. Furthermore, 43% of these homes have little to no insulation in the walls [4]. There is a significant need for cost-effective methods of improving wall insulation and reducing infiltration for existing homes. In current building practices, retrofitting the wall mostly includes the air, thermal, liquid moisture, and vapor controls that can be regarded as the best practices for high-performance new home construction. Well-tested and documented retrofit wall systems can help to achieve substantial energy savings and improve home durability, comfort, health, and resilience.

The wall energy retrofit system can significantly improve the energy performance of the building's thermal envelope, helping to manage the indoor environmental pollutants and increasing user comfort. Significant savings in residential building energy consumption through retrofit projects cannot be achieved without creating high-performance enclosures.

Residential wall systems consist of individual components and layers that are assembled to deliver thermal and moisture performance of the wall. The materials that compose the building envelope, the integrity of their assembly, and their resulting collective properties of thermal resistance, airtightness, and moisture control determine the thermal and hygrothermal performance of the wall system [5]. The physical properties of wall materials, combined with the physics of air, water, and vapor movement are complex and require special attention in order to avoid failure of the wall assembly. The cold or warm conditions at both the interior and exterior surfaces of the wall structure can allow moisture to condense, which can result in moisture problems if the wall structure is assembled incorrectly. Thus, thermal and moisture are incorporated into walls using different approaches, depending on climate, to ensure the wall system is hygrothermally sound [6].

In addition to the construction of the wall assembly itself, many interior and exterior environmental factors impact the movement of heat, air, and moisture within a wall assembly. These include ambient temperature and humidity levels, indoor temperature and humidity, solar radiation, exterior condensation, wind-driven rain, construction moisture, ground- and surface water, and air pressure differentials [7]. Therefore, wall assemblies must be constructed in a way that can mitigate the negative effects of environmental conditions.

Mold can cause poor indoor environmental quality conditions impacting human health and wellbeing, such as respiratory symptoms. Moldy environments can be found in buildings with either old or new construction, identifying the issue as a broad problem across the sector that may manifest only a few years after construction completion. Among the factors responsible as primary causes of fungal mold germination and subsequent biological growth of wood decay and material degradation organisms are design and architectural strategies that do not account for moisturerelated issues, inappropriate maintenance, and operational practices such as underventilation of the indoor environments causing higher moisture loads. The suitable conditions for mold growth are determined by environmental parameters, such as temperature and humidity, as well as water and nutrient availability on the surface for the spores to germinate. This germination is strongly affected by the construction materials and their vapor permeability, hygroscopic nature, and the presence of organic compounds [8].

Bio-based insulation materials are a special classification of insulation materials that consist of renewable natural (plant- or animal-based) materials of growing interest because of their ability to sequester atmospheric carbon dioxide through photosynthesis. Their use in construction can reduce the net embodied carbon dioxide of the building resulting in a negative carbon footprint while having a common feature of being vapor active, meaning that they are not only vapor permeable, but they are also capable of buffering moisture, and can act as thermal stores [9].

Several previous studies have provided an overview of the thermal and moisture performance of wall assemblies by explaining the practices for exterior wall retrofits and bio-based material composition for wall systems for buildings, focusing on retrofit applications to the exterior side of a wall assembly.

Brambilla et al [8] evaluated the effect of climate on the hygrothermal behavior and the moisture movement in buildings with timber envelopes including specifically both mass timber and timber-framed typical wall technologies . For this purpose, they compared two mold growth assessment models by the hygrothermal simulation tool, WUFI[®] [2]: the VTT and the IBP bio-hygrothermal. While the VTT model correlates temperature and relative humidity to the risk of mold growth, as a function of the sensitivity of the substrate and time of exposure, the IBP bio-hygrothermal model is based on the comparison between the transient temperature and relative humidity on the surface, with the conditions that sustain growth on typical building materials. Their results, based on the modeling they did in four different climatic contexts in Australia, showed that while use of an additional insulation layer placed on the outside of the timber-framed wall helps to significantly reduce the risk of mold growth, the typical timber frame envelope is most likely prone to fail in all the simulated scenarios.

In a similar study, Holzhueter et al [10] monitored the hygrothermal conditions of six straw bale buildings in Japan and evaluated the risk of mold growth in an interstitial temperature and relative humidity guideline. Straw bale buildings in Japan, and many other countries with high humidity and precipitation, are believed to be susceptible to microbial decay. Their result showed that the potential for mold growth can vary by structure, with buildings utilizing rainscreens found to have a lower risk of mold growth. Also, their final simulations and modeling showed that the tested interstitial temperature and relative humidity profile was found to exaggerate the potential for mold growth.

This paper discusses the hygrothermal performance of a bio-based retrofit wall system, examining the hygrothermal effects associated with their moisture activity by two methods: experimental field panel assembly and testing, and hygrothermal modeling simulations. This paper discusses the reasons why bio-based retrofit panels should be considered for existing buildings based on their actual contribution not only to the energy performance (increased R value) but also to reducing the chance of mold growth in wall components of a building. Figure 1 shows an example of the proposed panel for the wall system of an existing building.



Figure 1. Proposed Retrofit Panel in the Scale of an Existing Building

2. MATERIALS AND METHODOLOGY

This study was done to develop a better understanding, to characterize the behavior, and to optimize the design of the retrofit panel system by critically addressing the complexity of building envelope integrated design with the objective to identify efficient, reliable, and durable building envelope solutions that can improve the quality of indoor environments for wellbeing of the occupants. In the following sections, the materials with the methodologies used to perform the further analysis are explained.

2.1. Panel Fabrication and Field Testing

The concept of this bio-based panel is founded on a cross-laminated timber (CLT) system using eastern white pine, due to its relatively low density and sufficient strength. Three retrofit wall panels 144-inch long, 48-inch wide and 4 ¹/₂-inch thick, were fabricated by assembling a three-ply eastern white pine (Pinus strobus) CLT panel with 2 layers of STEICO Universal Dry wood-fiber insulation, each approximately 1 ¹/₂-inch thick, adhered on top of each panel. The wood fiber insulation used in the project is a market proven product in Europe (e.g., STEICO, Gutex), based on the same material used for the current lowest cost, market accepted insulation – cellulose. The CLT panels were fabricated from flatsawn nominal 1-inch (actual 0.75 inch) eastern white pine boards (1x8 inch x 12 feet long, kiln dried, finish grade) obtained from a local lumber vard near Syracuse, NY, and were surfaced in a planer to 0.5-inch thickness before assembly to assure uniform thickness and adhesive performance. The thickness of the panel has been designed to be optimized to limit both the maximum deflection that would damage other materials in a wall system (e.g., insulation, applied vapor barriers) when handled in a horizontal orientation, and second, for withdrawal and shear loadings when attached to the cladding system in the building. Figure 2 presents an illustration of the wall panel fabrication specifications and dimensions. Figure 3 shows an actual fabricated panel.



Figure 2. Schematic Representation of the Retrofit Wall Panel Dimensions and Specifications



Figure 3. Actual Fabricated Retrofit Wall Panel without (Left) and with (Right) Weather Barrier Finishing

Although field testing is still in progress, expected data and results with these composite retrofit panels will include their moisture permeability, water content level and their thermal conductivity regarding the standards (respectively) ASTM E331 [11], ASTM E96 [12] and ASTM C1363 [13]. The determined moisture levels will help with verifying the potential for mold growth rate in the panels and the thermal resistance values will be acquired from testing samples using guarded hot plate method from ASTM C177 standard [14]. The results of the hygrothermal modeling have been mainly reported in this paper for data/result consideration.

2.2. Hygrothermal Modeling and Simulations

Hygrothermal modeling was used to determine the risk of degradation across the panel hygrothermal profile throughout five years. This modeling phase considered the variable of four different climate zones in United States using ASHRAE 90.1-2019 [15], set to ASHRAE Year 1 for the climate data entry. The simulations were performed on the retrofitted wall construction assembly based on three different thickness; stated as highly insulated, 9-inch (total R value of 30 for the wall), moderately insulated, 6-inch (total R value of 20 for the wall), and lightly insulated, 3-inch (total R value of 10 for the wall) of the wood-fiber insulation used in the wall section. Success of this system will depend on a proper understanding of the performance of this component under the environmental conditions.

The modelling determined dewpoint location and condensation potentials by assigning panel surfaces such as the CLT and the wood-fiber insulation as "mold sensitive" materials and using WUFI[®] [2] BIO and WUFI[®] VTT modeling for panel performance in four climate zones of 4B (New York City, New York), climate zone 5B (Syracuse, New York), climate zone 6B (Burlington, Vermont) and climate zone 7B (Fargo, North Dakota) for the retrofitted wall construction assembly with three different insulation thicknesses, and with vapor and thermal considerations. WUFI[®] [2], developed by the Fraunhofer Institute for Building Physics in Munich (Germany), is a computer program that assesses the risk of mold growth in buildings based on measured or computed climatic conditions. This hygrothermal modeling uses American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE 160 standard [7] to test the materials by mold index.

The envelope performance assessment was run via the software WUFI[®] Pro [2] as the most recent reliable hygrothermal commercial software, based on a validated model that allows for a realistic calculation of the hygrothermal performance in multi-layered building components. This building tool considers the benefit of the envelope analysis with thermal transient features and moisture

transfer assessments. The software models from moisture sources and sinks within the space, the moisture exchange with the envelope through capillarity, diffusion, and sorption-desorption phenomena with standard indoor and outdoor thermal exchanges.

2.2.1. Boundary Conditions and Assumptions

The analysis aims to understand the potential hygrothermal challenges arising with moisture transfer through timber-based envelope systems that are currently being used in the residential building market in United States. The wall typology assessed against mold growth risk was typical of uninsulated light-framed wood construction. Selection and arrangement of the functional layers for the envelope are representative of typical market construction practices in the region. The envelope overlay panel was conceptualized to exceed the thermal and infiltration requirements addressed in building standards. Details of the building used in the modeling are presented in Table 1, as a typical building with the height less than 33 ft and standard construction regarding ASHRAE 160 [5].

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# Bedrooms	RH% Set Point	Construction Type	Air Exchange Rate (1/h)	Rain Exposure Category	Rain Exposure Factor (FE)	Rain Deposition Factor (FD)
2	70	Standard	0.2	Medium	1.0	0.5

Figure 4and Table 2illustrate and report the materials/products properties of the selected wall assembly that were retrieved from the WUFI[®] [2] built-in database, including the specification of major building products, tested, and validated experimentally at the Fraunhofer Institute of Building Physics Laboratories in Munich, according to the relevant building codes and regulations. The wall section is assumed to have a west-east orientation with no source of sinks or water leakage in any of the components.



Figure 4. Schematic representation of the wall assemblies used as two reference scenarios: Mass- timber (CLT) wall, Right: internal surface, Left: external surface

Wall Typology	Layer Composition (Exterior to Interior)	Layer Thickness (in)			Permeability (perm in)	Initial Water Content (Ib/ft^3)	Initial Thermal Conductivity (Btu/hft°F)	Bulk Density (Ib/ft^3)	Porosity (ft^3/ft^3)
Composite Wood Siding		0.5			2.43	4.7	0.05	46.2	0.66
	Weather Barrier		0.03			0	1.3	8.12	0.001
Mass Timber Retrofitted Wall	STEICO Insulation	Highly Insulated 9	Moderately Insulated 6	Lightly Insulated 3	38	1.22	0.02	9.86	0.9
Recionitied wan	CLT Panel	1.5			0.634	3.3	0.06	28.3	0.6
	Air Barrier	0.03			0.0064	0	1.5	8.12	0.001
	Solid Siding		0.5		2.43	4.08	0.01	30	0.4
	Wood Sheathing	1			0.644	3.3	0.052	25	0.73
	Stud Cavity	3.5			859	0	0.34	0.08	0.9
	Gypsum Board	0.5			18.3	0.45	0.09	39	0.7

Table 2. Wall assemblies' description and material properties of the wall layers for WUFI modeling

3. <u>RESULTS AND DISCUSSION</u>

To evaluate the mold growth risk during the panel design stage, the mold prediction IBP biohygrothermal (WUFI[®] BIO [2]) and VTT models (which are the basis for the international building standard ASHRAE 160 [7]), have been used [16]. The WUFI[®] BIO [2] IBP bio-hygrothermal model is based on comparing the transient temperature and relative humidity on the critical surface(s) considering the conditions that sustain growth on typical building materials. In this model, when the moisture content within a mold spore reaches a critical value, which depends on temperature, relative humidity and substrate sensitivity, the mold growth starts to occur. The final results are ranked following the traffic light scheme in three classes: "red" for an unacceptable level of risk, "yellow" when further investigations are needed and "green" when the risk is acceptable. In the VTT simulations, the critical value of relative humidity (RHcrit) refers to the lowest humidity that allows mold to grow on a substrate after a certain exposure time. The conditions in each time step are assessed against RHcrit and, if the conditions are not met, the model allows for either a delay or a decline in the mold index. The initial analysis on individual layers of the retrofit wall showed that the critical layer prone to mold is the STEICO wood-fiber insulation, which should get considered for further analysis. While the mold analysis has been performed on the whole wall section, the data has been recorded and presented here on the woodfiber insulation layer of the wall section. Figure 5 and Figure 6show results obtained for the three levels of wood-fiber insulated wall in four climate zones mentioned earlier based on the retrofit CLT wall hygrothermal assessment, respectively from WUFI® BIO (IBP) [2] and VTT models for the insulation layer of the wall. The results illustrated up to a specific time range indicating the early peaks while there has been no change for the rest of the time period in the models. The green light indicates that the mold growth rate (mold index, MI) is less than 1, for IBP BIO regarding ASHRAE 160 [7] limit, and less than 2 inch (50 mm) per year for VTT corresponding mold index value model, meaning that they both have passed the acceptable mold risk level in both mold models. All the results for 12 models acquired from both simulation methods showed the green light, meeting the standard rate with the initial condition of 68° F temperature and 80% RH (relative humidity). However, the IBP WUFI[®] Bio models demonstrate the fact that increasing the thickness of the insulation make the component more prone to mold growth rate over the first year of construction, while it will be kept in a steady rate for the longer time. The selected locations are in the moist section of the climate zones, however as colder weather air contains less moisture, the results confirm that from zone 4B (New York City, NY) to zone 7B, (Fargo, ND) the mold growth rate has declined from 0.8 inch/year (20 mm/year) to approximately 0.4 inch/year (11 mm/year) for the thickest insulation section (R value of 30) and from 0.3 inch/year (8 mm/year) to 0.2 inch/year (5 mm/year) for a moderately- insulated section (R value of 20) and, from approximately 0.2 inch/year (5 mm/year) to zero for the least thickness of the insulation (R value of 10).



Figure 5. IBP Simulation Mold Growth Rate Results, of Three Insulation Levels in Four Climate Zones



Figure 6. VTT Simulation Mold Growth Rate Results of Three Insulation Levels in Four Climate Zones

Despite the latter mentioned results, Figure 6 which shows the results from VTT models informs that with just a slightly difference in the beginning of the simulations, all wall sections with three

different insulation thickness in four climate zones of 4B, 5B, 6B and 7B would have a mold index rate of zero consistently across the season changes of the succeeding months. As a general observation (Table 3), it can be noted how the IBP model is more conservative than the VTT one, which includes more overall observations made for the assessment of comparison between the alternatives of the retrofitted wall.

Climate Zone	Location	Case Studies	Variables	IBP Modeling Results (Max Values) (in/yr)	VTT Modeling Results (Max Values) (Index)
Zone 4B	New York City, NY.	3- BIO 3- VTT		3-inch = 0.2 6-inch = 0.3 9-inch = 0.042	3-inch = 0.00082 6-inch = 0.02512 9-inch = 0.02894
Zone 5B	Syracuse, NY.	3- BIO 3- VTT	Lightly Insulated: 3-inch, Wall R Value = 10 Moderately Insulated: 6-inch,	3-inch = 0.14 6-inch = 0.28 9-inch = 0.37	3-inch = 0.02041 6-inch = 0.00000 9-inch = 0.05828
Zone 6B	Burlington, VT.	3- BIO 3- VTT	Wall R Value = 20 Highly Insulated: 9-inch, Wall R Value = 30	3-inch = 0.14 6-inch = 0.27 9-inch = 0.38	3-inch = 0.00000 6-inch = 0.00098 9-inch = 0.01497
Zone 7B	Fargo, ND.	3- BIO 3- VTT		3-inch = 0.00 6-inch = 0.19 9-inch = 0.43	3-inch = 0.00000 6-inch = 0.00337 9-inch = 0.03461

4. <u>CONCLUSION</u>

Reducing carbon emissions from the building sector is of critical importance to address the challenge of climate change. Reducing these emissions must be done with approaches that address both the operational carbon and the embodied carbon in this sector. This study provides an analysis of a bio-based over cladding panel for buildings to reduce operational carbon emissions and eliminate embodied carbon impacts. However, with bio-based panels, it is of paramount importance to systematically integrate moisture safety verifications within the design process and assess the hygrothermal performance of envelope components from the early stages of design before actual construction. This study addressed how the hygrothermal performance of a conventional construction type of envelopes can be improved using retrofitted insulation layers and then, how the variation of the thickness of the insulation component can behave in different moist climate zones. The study particularly analyzed 12 different technical design solutions for a bio-based over cladding panel system with a layer of wood-fiber insulation of three different thickness added to the wall, in four different climate zones of 4B, 5B, 6B and 7B using two hygrothermal modeling methods of IBP WUFI® BIO and WUFI® Mould Index VTT. While VTT models showed a more constant zero mold index value performance for all the alternatives, the IBP results show that the higher insulation value panel presents a higher mold growth rate over the first year of construction than the lower insulation value panel.

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5. <u>REFERENCES</u>

[1] G. Brainard, C. Sucuoglu, N. Sharifi, NYSERDA RetrofitNY Market Characterization Study: Building Stock Assessment and Architectural Profiles of Predominant New York State Multifamily Building Types, 2020.

- [2] O. Manfred Kehrer, WUFI (Wärme and Feuchte Instationär), (2014). www.wufi.de.
- [3] & B.R. Livingston O, Elliott D, Cole P, Building Energy Codes Program : National Benefits Assessment, Pacific Northwest Natl. Lab. PNNL-22610 (2014).
- [4] C. Antonopoulos, C. Metzger, J. Zhang, S. Ganguli, M. Baechler, H. Nagda, A. Desjarlais, Wall upgrades for residential deep energy retrofits: A literature review, (2019). https://www.pnnl.gov/main/publications/external/technical reports/PNNL-28690.pdf.
- [5] M.S. Al-Homoud, Performance characteristics and practical applications of common building thermal insulation materials, Build. Environ. 40 (2005) 353–366. https://doi.org/10.1016/j.buildenv.2004.05.013.
- [6] Lstiburek J., Moisture control for buildings, ASHRAE J. 44(2) (2002) 36–41.
- [7] ASHRAE Standards Committee, ANSI/ASHRAE 160-2016, (2016).
- [8] A. Brambilla, E. Gasparri, Mould Growth Models and Risk Assessment for Emerging Timber Envelopes in Australia: A Comparative Study, Buildings. 11 (2021) 261. https://doi.org/10.3390/buildings11060261.
- [9] M. Lawrence, A. Shea, P. Walker, P. de Wilde, Hygrothermal performance of bio-based insulation materials, Proc. Inst. Civ. Eng. Constr. Mater. 166 (2013) 257–263. https://doi.org/10.1680/coma.12.00031.
- [10] K. Holzhueter, K. Itonaga, An evaluation of WUFI-bio to predict mold growth in straw bale walls in Japan, J. Asian Archit. Build. Eng. 16 (2017) 357–362. https://doi.org/10.3130/jaabe.16.357.
- [11] ASTM International, ASTM E331, Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference, West Conshohocken, PA, 2016.
- [12] ASTM International, ASTM E96 / E96M, Standard Test Methods for Water Vapor Transmission of Materials, West Conshohocken, PA, 2016.
- [13] ASTM International, ASTM C1363, Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus, West Conshohocken, PA, 2019.
- [14] American Society for Testing and Materials Committee, ASTM C177-13, Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate, (2018) 1–22. https://doi.org/10.1520/C0177-13.2.
- [15] American National Standards Institutes -American Society of Heating/Refrigerating and Air-Conditioning Engineers ANSI/ASHRAE, ANSI/ASHRAE/IES Standard 90.1-2019 -- Energy Standard for Buildings Except Low-Rise Residential Buildings, Richland, Washington, 2019.
- [16] K. Sedlbauer, M. Krus, K. Breuer, Biohygrothermal method for the prediction of mould growth: Procedure and health aspects., in: Proc. Heal. Build. Proc. ISIAQ Conf., National University of Singapore, 2003: pp. 7–11.

Addressing the Housing Infrastructure Challenges of Rural Alaska in a Changing Climate: Physical Characteristics of Residential Infrastructure

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Abstract

Rural Alaskan communities are presented with housing challenges unique from other areas in the United States. Many communities have limited access to the resources needed to build new housing or retrofit current housing to improve living conditions and performance. As a result, many houses are highly inefficient, leaky, and improperly ventilated, contributing to high electricity and fuel costs. The progression of climate change has significantly impacted housing performance. Melting permafrost creates unstable foundation conditions that causes cracking, thus impacting the building envelope. Similarly, erosion and other climate changeinduced challenges have caused many coastal communities to consider the building of new infrastructure on higher and more stable ground, or the retrofitting of existing structures to better perform under the new and more variable conditions. As communities consider relocation of some or all their infrastructure, building energyefficient homes and retrofitting existing ones is vital to the comfort, health, and sustainability of each community. To provide appropriate new and retrofitted housing, understanding the unique challenges faced by the North is vital. This paper introduces the challenges faced in rural Alaskan communities regarding climate change, inefficient housing and utility infrastructure, cost of electricity and fuel, and remoteness. It then focuses on an assessment of the housing characteristics of rural Alaskan communities in collaboration with Unalakleet, Alaska. Information on building characteristics across the surveyed homes is compared to "typical" housing stock characteristics throughout the U.S. The results of this work will be used as inputs into the development of typical building energy models for the region, which will help to assess potential for energy efficiency improvements to residential buildings under current and future climate scenarios.

Introduction

Rural Alaskan communities face many unique challenges. In addition to ongoing climate changes, the infrastructure is generally inadequate for the harsh climate. Much of the housing built in rural Alaska was constructed in the post-World War II era, mimicking the housing construction more commonly found in the contiguous United States. This construction style was not adequately adjusted to fit Alaska's climate or the needs and lifestyle of the indigenous people who now inhabit a large portion of these homes. Such housing generally contains inadequate insulation and imported building materials that are not easily replaceable with local materials. Many homes also lack adequate ventilation (Hossain et al. 2016). Today, numerous homes in rural Alaska face the same housing challenges as when the homes were first built historically (Hossain et al. 2016). In addition, due to the remoteness of such communities, the ability to repair and retrofit housing is limited. This has resulted in high heating and electricity bills for many homes, where electricity and fuel oil prices are 3 to 5 times and 1.8 times the rates in the continental U.S, respectively (Brutkoski et al. 2016). Given the generally lower household incomes in many rural communities, some estimates suggest the lowest income households use an estimated 47% of their income for home energy, while higher income households spend 6% to 13% of their income (Saylor et al. 2008).

Resolving challenges that stem from the current state of housing infrastructure begins with an understanding of the current characteristics of housing in rural Alaska. This also requires knowledge of the overall Alaskan climate conditions that housing should be built to withstand, and an understanding of the lifestyle of the buildings' occupants. This information can help support appropriate planning for future housing in rural Alaska, including new construction and/or retrofits to existing homes. Future home construction in such communities, and in particular the location of study in Unalakleet, aims to be completed in locations less threatened by coastal erosion while also considering input from community members in their design.

The following section reviews Alaskan climate conditions and rural lifestyle, followed by an overview of rural Alaskan building characteristics, both from public sources. The remainder of this research discusses the methods used to collect more detailed housing data in Unalakleet and a summary of findings of such housing characteristics. This is then compared to U.S. housing characteristics to emphasize the need for a unique definition of rural Alaska home characteristics that can drive analysis of opportunities for efficiency improvements.

Background

Alaskan Climate

Alaska's many ecosystems and extreme climate make it a unique and challenging place to live. The state is home to differing landscapes, from coastal rainforests and flat tundra to glaciers and volcanoes. Permafrost covers 81% of the ground and controls many aspects of soil health while also supporting infrastructure. Over time, however, Alaska's climate has been suffering from the impacts of climate change. Average annual temperatures statewide increased by nearly 2.2°C between 1949 and 2005, most notably during the winter. Precipitation has also increased by 10% annually during this same period (Markon et al. 2012). Both precipitation and temperature projections show continued increases across the next century, particularly if current world emission trends are not substantially reduced. Another concern is the growing number of extreme weather events. Large waves contribute to erosion, threatening many coastal communities' shorelines (Markon et al. 2012).

Historically, Alaskan homes were better built for the climate. Alaska has been populated by Alaska Natives, Russians, and Americans, all of whom brought their own architectural influences to the region (Hoagland 1993). Thousands of years before the Russians discovered Alaska, Alaska Natives built well-insulated homes that were designed for the winters and terrain. These homes varied by location and Native group. For example, in the coastal Arctic (north of the Arctic Circle), homes were semisubterranean. The large room of the home was underground with a membrane-covered window in the roof that served as a smoke hole. Entrances to the home were at the end of a long cold-trapping tunnel that opened to the outside. The inside of the home was warmed sufficiently from the insulation of the ground, body heat, and seal oil (Hoagland 1993). Insulation consisted of sod, soil, moss, and sometimes an extra layer of animal hides on the inside. This kept homes up to 33.3°C warmer than the outside temperature (Hossain et al. 2016). Over time, dwellings began to change with subsistence patterns, and especially with the influence of other cultures. Newer homes were cold and drafty, requiring oil to be imported. Driftwood disappeared from consistent use for heating. Inefficient manufactured homes, generally shipped in by government agencies, also became common in many rural communities such as Unalakleet (Hoagland 1993).

Introduction to Unalakleet, Alaska

Unalakleet is a small community of approximately 700 people on the west coast of Alaska, with origins from around 200 B.C (U.S. Census Bureau 2019; State of Alaska 2021). It is home to diverse cultures due to its history as a trading post for a Russian-American company. Approximately 74% of the community identifies as Alaska Native (State of Alaska 2021). Many homes hold multiple generations or have been in families for generations. The economy is strongly reliant on subsistence activities such as hunting, fishing, and gathering berries. The community is also home to a commercial fishing company, thus many residents leave during the months of May through July to go commercial fishing on the Unalakleet River. There are no roads to Unalakleet, so travel from elsewhere is by boat or airplane only. The median household income in the community is approximately \$70,000, however, 42% percent of households make under \$50,000 per year. The community consists of approximately 224 housing units, with 76% of homes being occupied, equating to an average of 4 people per housing unit (U.S. Census Bureau 2019)

Many buildings, as seen in Figure 1, are similar in structure. These buildings were commonly built by generations of families in the community or barged in fully manufactured. Methods of data collection and the resulting common characteristics of these buildings, especially from 27 homes analyzed through this research, are discussed in further detail below. Such characteristics include size, roof type and color, siding type and color, and percent of window coverage per exterior wall, among others that influence the energy efficiency and consumption of these buildings. This data collection was achieved through a partnership with the Native Village of Unalakleet.



Figure 1: Examples of homes in Unalakleet (Google 2019)

Data Collection Methodology

Remote

Remote data collected included home size, roof and exterior siding type, and percent of window area. In total, data from 227 homes was collected using this method. For *home size*, data was collected using aerial images from Google Earth and its measurement tool. Such methods likely have some error, given that not all images provided a clear close-up. Individual houses were identified by their North and West coordinates. Overhangs, if present, were counted in the measurement and may produce error in actual length of the house. *Roof type* was determined using Google Street View and included the observed roofing material, such as corrugated metal or shingles. *Exterior siding type* was identified and recorded following the same methods as for the roof.

Determining the *percent window area* was a time-intensive process. Of the 227 homes counted in Google Earth, 94 homes were sampled from the north, south, east, and western parts of the community. Each house was viewed from all cardinal directions in Google Street View. These were placed in AutoCAD, where they were measured using the area tool. Windows were measured individually, then the total window area was divided by the wall area to determine this percentage. Error includes snapshots of walls at an extreme angle, making measurement difficult. Partial obstructions of walls also required estimation of its dimensions.

On Site

On-site data collection occurred in July and August, 2021, and was completed for 27 homes with homeowner consent. Participants were compensated for their time. Additional data collection included an interview on current housing concerns and future housing design considerations, as well as infiltration and indoor air quality data collection. However, this research focuses only on housing characteristics resulting from interior and exterior observation of the homes. Relevant comments from interviews pertaining to discussed topics are mentioned, as appropriate, to enhance discussion. Interior air quality and ventilation characteristics are discussed in a separate paper titled "Addressing the Housing Challenges of Rural Alaska: Air Flow and Indoor Air Quality Characteristics of Residential Buildings."

Indoor data collection included a walkthrough of each home. Heating and ventilation systems were inventoried by name plate, efficiency, type, and energy source. Windows and exterior doors were assessed for proper sealing. Participants were asked about insulation in their walls, attic, and crawlspace. Visible mold and damage to the home was recorded for the interior and exterior building shell. The condition, type, and colors

of the exterior walls, roof, and foundation was recorded. Outside, evidence of shifting ground, pooling water, and damage were also recorded. Potential errors or missing data occurred due to coverage of walls and appliances by household items, partially-obscured exterior walls by a close building, blocked entry to the crawlspace, and/or partially unfinished homes.

Results and Discussion

Size of Homes

Measuring all visible homes on Google Earth (n = 227) averaged to 12.7 m in length by 8.6 m in width (109.2 m²), including overhangs. This measurement did not include newly built homes overlooking the community or buildings that appeared to be apartments. For homes where assessments were conducted (n=27), occupants often knew the area of their home, reporting an average area of 97.5 m². The smallest home was 29.7 m² consisting of a kitchen, a bedroom, and a bathroom; The largest was 250.8 m². Thirteen of the 25 single-family homes assessed (2 apartments) were under 92.9 m² (1000 ft²). Figure 2 shows average house size of houses assessed and in Unalakleet total, compared to Alaska and the U.S. overall. As shown, the on-site assessed homes averaged to be similar in size to the overall total single-family homes in Unalakleet. These were both substantially smaller than in Alaska and in the U.S.



Figure 2: Average area of assessed homes, Unalakleet, Alaska and the U.S. (Source: Cold Climate Housing Research Center 2014; U.S Census Bureau 2020)

A common housing concern among those interviewed related to housing size and lack of space. Of the 27 houses assessed, 7 held more than 4 people. The average occupancy of the 27 homes assessed was 3.08 people, not including the one home that currently or previously had no occupants. Figure 3 displays average occupancy of both assessed homes and Unalakleet in total, as compared to Alaska and the U.S. As shown, the overall number of people per home is higher than in Alaska and the U.S., yet Figure 2 shows the houses are substantially smaller. The median size of assessed houses in Unalakleet (97.5 m²) gives an average of 31.7 m² per person. In comparison, an average of 2.6 people per house in the U.S. gives approximately 83.4 m² per person, or a 55% increase in space per person compared to Unalakleet (U.S Census Bureau 2020). Such numbers are important to consider when evaluating indoor air quality concerns and ventilation requirements, as well as differences in internal loads and occupancy for energy modeling applications.



Figure 3: Occupancy of assessed homes and Unalakleet total vs Alaska and US (U.S. Census Bureau 2020; *Quickfacts: Alaska; Quickfacts: United States*)

Roofs

Seventy-eight percent of the homes observed using remote methods had corrugated metal roofs ; however, some had shingles (4%) or large wooden boards (4%). Others were unavailable in Google Street View or hard to view. From onsite data collection, all homes had corrugated metal roofs. The most common color across the community was gray or dark blue/green. Roof pitch was most frequently north to south, including 78.6% in the community as a whole, and 70.4% of on-site assessed homes. A north/south pitch meant the roof sloped to the north and south. One participant mentioned the importance of the roof pitched north to south, where overhangs provide shade from the sun in the summer. Such data on roof characteristics is important as it is a required input for energy modeling purposes, and, as mentioned by one participant, impacts shading and solar gains. For example, a study done by Fernandez-Antolin et al. (2019) in a cold climate in Spain found that roofs pitched north to south and dark-colored corresponded to less energy loss than light roofs.

Crawlspace

Nearly all homes assessed on site (78%) had crawlspaces as their foundation. Six homes (22%) had a slab-on-grade foundation. Many homes were built on level ground; some did have evidence of shifting ground such as cracked foundations, uneven porches (Figure 4), and sloped ground around the foundation, which can affect the building's envelope by causing cracks and air infiltration into the home. Some participants explained that their foundation had to be leveled after the ground shifted. The community and the homes on the hill above it are not built on permafrost; however, the main community is located just off the Bering Sea and built on mainly sandy soil. One participant clarified that shifting of the foundation usually occurred in the spring and winter, and that the house shifts significantly. To avoid pooling, some residents placed rocks as drainage around their crawlspace, however, pooling of water was present around some homes (Figure 4).



Figure 4: An uneven porch crawlspace (left); pooling water around a foundation (right)

Nearly all crawlspaces were covered by a skirt commonly made of wood. When an opening was present to allow for visual inspection, it was typically observed that fiberglass insulation was placed around the skirt of the crawlspace. Some homes also had rotten wood boards due to water damage from the bathroom floor. Two of the 21 crawlspaces were vented. Crawlspace skirts usually matched the color of the exterior siding or were plain wood. Wintertime ventilation through a crawlspace can cause an increase in heat loss for the home and put pipes at risk of freezing, especially if the floor and pipe insulation is not sufficient. For non-vented crawlspaces, it is recommended to condition crawlspaces with insulation around their perimeter and a sealed ground cover as a vapor and air barrier (Lstiburek 2004). However, such systems were lacking in homes with observable crawlspaces.

Exterior Walls

Exterior siding consisted mainly of vinyl (37%) and wood paneling (44%). A few homes had visible water damage to the wood paneling (Figure 5). Chipping was present on the vinyl siding, also shown in Figure 5. Siding was mostly light colors (59%). Of the homes where onsite assessments were conducted, all exterior walls were insulated per participant comment. Foam board was often used on the exterior, with spray foam or fiberglass on the interior. Two homes had cellulose insulation; one new home contained densely packed cellulose. One participant talked about how the fiberglass insulation dropped within the wall cavity, leaving the bottom of the wall much warmer than the top and impacting the effectiveness of the insulation.



Figure 5: Rusting and peeling of wooden panels around a window (left); damage to vinyl siding from a snowbank (right)

Window Placement and Area Coverage

The south side of many homes was commonly the side most covered by windows, allowing for more solar gain in winter. Whether builders and designers intentionally built and/or placed many of the homes in the community for this reason is unknown. However, some participants who built their own home confirmed that they purposefully placed windows on the south side. The average window coverage on the southern side of the 94 homes analyzed remotely was 10.5%. Next largest was the west, at 8.1%. The east side of homes had the least coverage, averaging 6.1%. Some homes had sides of their house with no windows, most often occurring in the east or west orientation. A possible reason for lack of windows on the east side is to prevent the strong eastern wind that blows in winter from infiltrating into the home. As many homes had leaky windows, whether old or new installations, windows lacking on the east wall makes sense to reduce infiltration.

Interior Characteristics, Appliances, and HVAC

As mentioned above in the section on size of homes, many homes lacked space to comfortably accommodate the number of people who live there. Several homes used open space in each room for storage or had beds on the living room floor and/or multiple people staying in one room. Water heaters and laundry appliances were sometimes found in the bathroom or kitchen. Interior doors were lacking in some homes, and when asked why, occupants explained that they were damaged or would not shut all the way due to shifting of the foundation.

Boilers were usually observed to heat most homes and their water. Heating appliances generally included a furnace (e.g., L-73 Toyostove Laser) in a central area and a boiler connected to baseboards that ran through the home. Participants with a central heating system often stated the home would be cold in the winter, unless the home was extremely small or had a wood stove as back-up. Out of the 25 participants of occupied homes, only 2 mentioned using the stove to heat their home if the heating system was insufficient. For water heaters, some homes used the same boiler for heating while others had a separate boiler (e.g. Burnham and Toyotomi Oil Miser Model OM-122DW). Two homes had on-demand water heaters that only heated the kitchen sink or the bathroom water, and 5 homes had electric water heaters. Bathroom and kitchen exhaust fans were common forms of mechanical ventilation, and some homes built after the 2000s had heat recovery ventilators (HRVs). A common trend among smaller homes (less than 92.9 m²) was a lack of sufficient mechanical ventilation, which can negatively impact indoor environmental conditions and cause mold growth (Figure 6). Such mold was most observed around windowsills and in the corners of wall/floor and wall/ceiling joints. Participants noticed that it tended to grow in areas of the home that collected moisture or felt colder.



Figure 6: Black mold growing up a wall near the entrance to a home (left); towel placed to seal exterior door (right)

Frequently, the interior of homes also had damage, such as floors missing tiles, walls with holes, and exterior doors that did not seal well. An example is shown in Figure 6 of a home that used a towel to improve air sealing around the door.

Conclusions

Through combined remote and on-site data collection, typical energy-related characteristics of homes were observed in Unalakleet, Alaska, a rural community. Given the high energy burden for households in rural Alaska, as well as the relatively limited data available on housing characteristics in this region, this study focused on determining a more comprehensive picture of housing characteristics. As observed, homes are generally smaller and more densely inhabited as compared to the continental U.S. These observations are like those found in statewide housing surveys, especially for the Bering Straits region where Unalakleet is located (Cold Climate Housing Research Center 2014). In many cases, homes are in significant need of repair and/or retrofits. Many participants appeared to recognize this and explained that repair in such a remote area was expensive and took a long time, as maintenance and materials had to be shipped from outside the community. Many did repairs themselves. Research on this subject is ongoing, and future funding will provide more opportunity to collect additional data on rural Alaskan housing characteristics. The characteristics observed in this effort can be used to better characterize the housing stock in this area. Further analysis of the physical and interview data collected in Unalakleet will be done to simulate retrofitting opportunities for housing and new construction using energy modeling methods. Such improvements to the housing can help to ensure comfortable, efficient, and affordable homes for residents.

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References

- Brutkoski, A.R. et al. (2016). Sustainable Energy Solutions for Rural Alaska. Regulatory Assistance Project; Lawrence Berkeley National Laboratory.
- Cold Climate Housing Research Center. (2014). 2014 Alaska Housing Assessment. *Alaska Housing Finance Corporation.*
- Hoagland, A.K. (1993). Buildings of Alaska. Oxford University Press. ISBN: 0-19-507363-0. Print.
- Hossain, Y. et al. (2016). Defining energy security in the rural North-Historical and contemporary perspectives from Alaska. *Energy Research & Social Science*, *16*. 89-97.
- Fernandez-Antolin, M.M., et al. (2019). Influence of Solar Reflectance and Renewable Energies on Residential Heating and Cooling Demand in Sustainable Architecture: A Case Study in Different Climate Zones in Spain Considering Their Urban Contexts. *Sustainability*, *11*(23), 1-31. https://doi.org/10.3390/su11236782
- Google. (2019). "Unalakleet, Alaska." *Google Earth*. 63°52'22" N and 160°47'19" W.
- Lstiburek, J. (2004). BA-0401: Conditioned Crawlspace Construction, Performance, and Codes. *Building Science Press*.
- Markon, C. J., et al. (2012). The United States National Climate Assessment Alaska Technical Regional Report: U.S. Geological Survey Circular 1379. U.S. Geological Survey.
- Saylor, B. et al. (2008). Estimated Household Costs for Home Energy Use. Institute of Social and Economic Research, University of Alaska, Anchorage.
- State of Alaska. (2021). *Unalakleet, Alaska*. Retrieved from DCRA Open Data: https://dcced.maps.arcgis.com/apps/MapJournal/index.html?appid=acffb5f1e3 1c4061a8e74ea2a98aa79b#map
- Strand, H. (2018). Breaking Barriers to Renewable Energy Production in the North American Arctic. *Alaska Law Review*, *35*(1). 67-115.
- U.S. Census Bureau. (2019). Unalakleet City, Alaska. https://www.census.gov/searchresults.html?searchType=web&cssp=SERP&q=Unalakleet%20city,%20AK
- U.S. Census Bureau. (2020). *Characteristics of New Housing*. https://www.census.gov/construction/chars/highlights.html
- U.S. Census Bureau. (2020). *Quickfacts: Alaska.* https://www.census.gov/quickfacts/AK#:~:text=People%20%20%20%20Popu lation%20%20%20,%20%2016.1%25%20%2042%20more%20rows%20
- U.S. Census Bureau. (2020). *Quickfacts: United States*. https://www.census.gov/quickfacts/fact/table/US/RHI825219#:~:text=People %20%20%20%20Population%20%20%20,%20%2021.6%25%20%2041%20 more%20rows%20

Design, Construction, and Field Validation of a Blown-in Fiberglass Wall System in a Cold, Wet, and Windy Climate

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ABSTRACT

In the Native Village of Tununak, located on Nelson Island in Southwest Alaska, buildings are exposed to wind-driven rain and snow throughout the year. The Cold Climate Housing Research Center (CCHRC) and Knauf Insulation partnered with the community in 2018 to design a residence for a public safety officer. Construction began in fall 2021 and is scheduled to conclude in summer 2022. The house will use integrated trusses with floor, attic, and wall cavities filled with blown-in fiberglass insulation. Hygrothermal models of the building envelope system demonstrate that the high ambient moisture load will wet the outer edges of the insulation annually regardless of the extent and integrity of exterior weather sealing measures; blown-in fiberglass is expected to be more resilient to this wetting than blown-in cellulose. To verify this, researchers will embed temperature, relative humidity, and moisture sensors in the two windward walls of the house to monitor the ability of the blown-in fiberglass insulation to dry out after wetting events that may have occurred during the transport of the insulation to the building site, storage of the insulation on site, construction process, or after installation in the wall. Sensors will remain in place for two years, documenting the wall's performance over time and verifying the design's potential for use in buildings located in climates where the chance for moisture damage is high. Here, we describe the wall system, design criteria, and the results from the hygrothermal modeling. We share details on the monitoring system's components and the planned management and analysis of data. Finally, we explain how the experiences and data from this project will inform future builds in similar locations.

INTRODUCTION

Tununak is located on Nelson Island off the coast of western Alaska. The community of just over 400 people (ACS, 2019) features scenic views of the ocean meeting the hilly coast. The young, growing population participates in subsistence hunting and fishing, school and city league basketball, and traditional dancing. Unfortunately, a housing shortage has resulted in 37% of current housing stock being overcrowding or severely overcrowded (Wiltse et al., 2014), and has made it difficult to recruit professionals such as teachers, village police safety officers, and health workers. To begin to address this issue, the Native Village of Tununak (NVT) obtained a Teacher, Health Professional, and Public Safety Officer Housing grant from the Alaska Housing Finance Corporation in February 2018 to construct a three-bedroom home that will be used to recruit and house a Village Public Safety Officer (VPSO), a position which NVT has not been able to fill since 2016 (Cotsirilos, 2018). The Cold Climate Housing Research Center (CCHRC) is providing design, construction management, and workforce training for the local crew building the home.

Building in Tununak is challenging from both a design and cost perspective: The remote location requires materials to be barged in during the summer, and non-local trades professionals such as electricians and plumbers to be coordinated and flown in to support construction. The maritime climate produces fog and storm events that can cause delays in travel and shipments. Accordingly, buildings in this local climate (ASHRAE climate zone 8) are exposed to an average of 1.9 meters (75 inches) of precipitation annually, 75% of which is snow (USA.com, 2021), and seasonal storms in the area can produce wind gusts upwards of 42.8 m/s (95 mph) (Vaught, 2007). Under such conditions, the likelihood that moisture and bulk water are driven into the wall cavity is high, regardless of weatherization detailing.



Figure 1: A rendering of the VPSO house under construction in Tununak. In addition to the efficient envelope, the house features a flexible jack foundation that can be releveled if necessary.

CCHRC and NVT chose an integrated truss design for the VPSO home and are hoping to achieve a 6-star rating, the highest possible efficiency rating in Alaska's Building Energy Efficiency Standards energy rating system. As it is critical materials used in the exterior walls can withstand moisture events during transport and storage, as well as cyclical wetting and drying events after construction, the house will feature blown-in fiberglass inside the wall, attic, and floor. CCHRC and NVT are working with Knauf Insulation, Inc. to ship and install the insulation. Blown-in fiberglass is a highly moisture-resistant form of insulation that provides thermal-resistance values comparable to blown-in cellulose. Its density and composition also allow for moisture and air to move freely, which supports its ability to dry completely after a wetting event. Fiberglass is an integral component of a durable and efficient building envelope for the VPSO house.

RESEARCH QUESTION

Blown-in fiberglass is known for its moisture resilience, but there are no studies verifying this in the extreme climate of coastal Alaska. CCHRC, NVT, and Knauf Insulation, Inc partnered to conduct this field validation of the insulation's performance in Tununak. Researchers will monitor the blown-in fiberglass in the two wind-exposed walls of the VPSO house over two winters, with the goal of answering the research question: *What is the moisture performance over two years of a 300 mm (12 inches) thick truss wall with blown-in fiberglass insulation in a cold, wet and windy climate?* Data and results from this monitoring study will inform building envelope design and materials for buildings in cold and wet climates and help transition to the greater durability of future homes and buildings not only in coastal Alaska but around the world.

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Figure 2: Annotated eave wall section of the integrated truss wall for the VPSO house in Tununak.

WALL SYSTEM DESIGN

The integrated truss is a prefabricated wall assembly that connects the roof, wall, and floor into a single structural piece that can easily be tipped into place and sheathed. It was originally developed for emergency housing applications in Alaska, where homes must be constructed quickly during the short building season without compromising durability and efficiency. Since their inception, integrated truss homes have been used for a variety of applications, including emergency housing, affordable housing, and rapid deployment construction.



Figure 3: Annotated gable wall section for the VPSO house in Tununak.

The webbed structure of an integrated truss is designed to reduce thermal bridging through the wood components and provide an economical method of widening the wall and floor cavities for the purposes of super-insulating. The depth of the wall cavity can be scaled depending on the severity of the climate and desired insulation values. Past integrated truss wall designs used by CCHRC have included cavity insulation depths ranging between 175 mm (7 inches) in southwest Alaska to 450 mm (18 inches) in the Arctic. The integrated truss wall depth chosen for the house

structure in Tununak, which is considered a subarctic maritime climate, is 300 mm (12 inches)– twice as thick as a standard 2x6 frame wall. A variety of insulation types can be used in this wall system, from spray foam to blown-in cellulose or fiberglass. The most appropriate insulation for a given application depends on the climate, cost, shipping constraints, moisture resistance, and other factors. The VPSO house in Tununak will use blown-in fiberglass insulation.

HYGROTHERMAL MODELING

A WUFI Pro hygrothermal model was developed for the wall construction early in the design process to help address the main concerns of driving rain, low ambient temperatures, and high indoor humidity. The following different wall configurations were evaluated for moisture performance using Bethel, Alaska weather data (the closest location with typical meteorological year weather data available): blown-in fiberglass insulation with and without an interior vapor/air barrier, fiberglass insulation with and without an exterior rain screen and blown-in cellulose insulation. Table 1 provides material specifics from the WUFI model.

Material	Thickness (mm)	Conductivity (W/mK)	Permeability (perm in)
Dense Fiberglass	350	0.0334	99.1
Polyethene Sheeting	0.991	2.25	0.0026
Plywood	15	0.101	0.3361
Steel Siding	0.76	51.92	0.000099

Table 1: WUFI material properties used in the Tununak VPSO house model.

Weather data outside of major towns in Alaska has not been consistently collected. Bethel is 181 km (113 miles) northwest of Tununak and has similar geography and weather. Bethel 30-year typical metrological year (TMY) data, shown in Figure 4, was used to create the WUFI weather file; however, the rain was inaccurate, and 2005 rain data was used to create an average rain file (that year had the fewest missing data points of the available data). Almost forty of the homes in this region are overcrowded (more than one person per room, all rooms excluding the bathroom) (Wiltse et al., 2014). Interior conditions for overcrowded homes in this region were developed using ASHRAE 160 create an interior relative humidity of 75% most of the year (ASHRAE, 2016).



Figure 4: TMY weather data for Bethel, Alaska.

The area of the wall of the most concern is the exterior layer of plywood sheathing. Interior moisture that can condense on the inner face of the plywood and wetting from exterior rain make it the most moisture susceptible layer in the wall. The initial models demonstrated the need for an interior vapor/air barrier to ensure that interior moisture did not exfiltrate and create mold on the surface of the plywood sheathing. The fiberglass wall without a rain screen saw modeled moisture content in the plywood exceeding 50% within 3 years (20% is the threshold for rot).

The comparison of fiberglass to cellulose was not as clear as the other moisture control questions. Figure 5 shows the subtle difference in the moisture content of the plywood based on the different insulation. The modeled moisture from installation dries over the course of the first year, which is typical of construction materials. The moisture accumulation for both insulation types climbs in the winter and dries each summer. The fiberglass insulation shows slightly less moisture accumulation than the cellulose and it stays below the rot threshold of 20%.



Figure 5: Cellulose vs. fiberglass moisture content results for an integrated truss wall using Bethel, Alaska weather data.

The hygrothermal model of the final wall design (see Figures 2 and 3) with blown-in fiberglass insulation, an exterior rain screen, and an interior vapor barrier showed the best resilience to the cold and wet climate. While both the cellulose and fiberglass insulation demonstrate moisture safe performance in the Bethel climate, the fiberglass performance slightly exceeded (2% lower moisture content at the plywood sheathing) the cellulose performance and the fiberglass did not exceed the 20% threshold after the initial post construction drying.

MONITORING SYSTEM

To monitor the performance of the wall system in Tununak, the research team will employ Campbell Scientific equipment to sample and record data over the course of two winters. The mechanical room of the residence will house two CR1000 data loggers and a power supply to collect data from the two windward walls of the home. The system will use sensors to collect moisture content (MC), temperature (Temp), and relative humidity (RH) from different areas in the walls. Figure 6 shows the planned locations of the sensors and along with the type of sensor.



Figure 6: House diagram with planned sensor location and type.

A total of 30 sensors will be installed, split among six different areas of the house. Locations such as those below windows and below a mechanical opening are known to have high potential for moisture issues due to breaks and transitions in the weatherproof detailing. Figure 7 shows the sensor locations among the six different wall locations.



Figure 7: Sensor locations within the North and East walls of the house.

The data loggers will collect data every two minutes and record average hourly output for each sensor. Each data logger has 4 MB worth of storage, which equates to approximately 90 months of data collection. However, staff will travel to Tununak to check the loggers and download data mid-winter and in the spring each year during the monitoring period to catch any sensors that malfunction during the study or issues with the data logger.

One data logger will collect moisture content and temperature, while the other will record relative humidity. Equation 1 is used to determine the moisture content of the wood from the recorded resistance reading (Straube et al., 2002).

$$Log_{10}(MC_u) = 2.99 - 2.113(Log_{10}(Log_{10}(R_w)))$$
(1)

Where MC_u is the Douglas-fir moisture content measured in % mass and R_w is the electrical resistance measured in Ω . Since the measurement varies depending on the type of wood and temperature of the wood, equation 2 is used to get a more accurate reading of the moisture content.

$$MC_{c} = \frac{\left\{\frac{MC_{u} + 0.567 - 0.0260T + 0.000051T^{2}}{0.881(1.0056^{T})} - b\right\}}{a} - 2$$
(2)

Where MC_C is the corrected moisture content, T is the temperature of the wood in Celsius, and b and a are constants dependent on the wood type. Temperature and relative humidity will be recorded by the sensors.

As data is collected, it will be analyzed to look for potential wetting events that are not followed by drying. From the modeling results, researchers expect moisture intrusion during late winter months, but then to see drying during the summer, allowing the wall to fully dry within a one-year calendar cycle. Researchers will monitor the length of time that temperature, relative humidity, and moisture content sensors present conditions viable for mold growth and evaluate the effect iveness of the fiberglass insulation for this climate.

FUTURE PLANS

The first phase of construction on the house began in summer 2021, which consisted of laying the foundation, righting the integrated trusses, installing the exterior sheathing and weather barriers, and finishing the roof. Phase 2 will begin in spring 2022, and will consist of insulation blowing, interior finish work, and weatherization detailing. The house will be ready for occupancy by the end of summer 2022.

Researchers will install the monitoring system during the second construction phase, placing sensors in the integrated truss wall cavities prior to insulation being blown into place. Research staff will connect the sensors to data loggers in the mechanical room during the final phase of construction and collect data on initial wall conditions. Staff will return to Tununak to download data mid-winter and late spring for two years, so that the monitoring period encompasses two winters, when the wall system is most at risk of moisture intrusion. Analysis will be ongoing after the first winter, with updates posted to the project website (http://cchrc.org/knauf-insulation-

<u>monitoring</u>/) and is expected to immediately inform building designs and installation techniques used by CCHRC across Alaska. As more data is collected and analyzed, results will inform building envelope design and material selection for buildings in cold, moist climates.

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REFERENCES

ACS. 2019. "American Community Survey: 2019: 5-Year Estimates Data Profiles: Tununak CDP, Alaska." Available at: <u>https://data.census.gov/cedsci/</u>. Accessed on August 18, 2021.

Cotsirilos, T. 2018. "Tununak Awarded Thousands of Dollars For New Housing." KYUK: Public Media for Alaska's Yukon-Kuskokwim Delta. Available at: <u>https://www.kyuk.org/post/tununak-awarded-thousands-dollars-new-housing Accessed on August 18</u>, 2021.

ASHRAE. 2016. "Criteria for Moisture-Control Design Analysis in Buildings." ANSI/ASHRAE Standard 160-2016.

Straube, John, Don Onysko, and Chris Schumacher. 2002. "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures." *Journal of Building Physics - J BUILD PHYS* 26 (October): 123–51. https://doi.org/10.1177/0075424202026002098.

USA.com. 2021. "Tununak, AK Weather." Available at: <u>www.usa.com/tununak-ak-weather.htm</u>. Accessed on August 18, 2021.

Vaught, Douglas. 2007. "Mekoryuk, Alaska Wind Resource Report." *V3 Energy LLC*, 1–24. Available at: <u>https://www.v3energy.com/wp-content/uploads/2010/10/Mekoryuk-Wind-Resource-Report-12-04-07.pdf</u>. Accessed on August 18, 2021

Wiltse, N., Madden, D., Valentine, B., Stevens, V. (2014). 2014 Alaska Housing Assessment. Fairbanks, AK: Cold Climate Housing Research Center. Prepared for: Alaska Housing Finance Corporation.

Educating the Youth on Energy and Data Literacy Through VR-ENERGY Learning Platform

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ABSTRACT

Virtual Reality (VR) allows students to "learn by doing" following a constructivist approach (Pantelidis, 2009). VR environments support the active construction of knowledge through repeatable experiments, allowing students to simulate activities in a low-risk setting (Bricken, 1990). VR learning systems immerse students in an interactive 3D computer-generated world which closely emulates operations and equipment found in the real world (Lee et al., 2010). The goal of this research to develop a prototype VR learning platform called VR-ENERGY for computer science skill development, based on smart infrastructure and residential energy monitoring systems. Using the home as a relatable environment, students will learn about sensor installation, data transmission, data storage, data analysis, and data visualization. The VR-ENERGY platform will be a two-part learning system, half in VR and the other half using a data visualization software called Tableau. The VR part of the learning experience will allow students to explore and familiarize themselves with all of the components of the eGauge energy monitoring system. After familiarizing themselves with the components, students will have the option to follow a tutorial or freestyle when installing the eGauge system. After the students have successfully installed the eGauge system, they will be able to download the energy consumption data from the eGauge system in VR to begin data analysis and data visualization in Tableau, which is the second half of the VR-ENERGY learning system. The insights discovered from this study will allows teachers a way incorporate VR into the educational curriculum. Benefits of VR in the classroom include active rather than passive experiences. immediate engagement, help understanding complex theories, immersive experience meaning minimum to no distractions for the students, exploration and hands on approach aids with learning and retention suited to all types of learning styles (Yildirim et al., 2020). This VR-ENERGY platform can serve a template to improve a way to increase the energy literacy rate of today's youth.

INTRODUCTION

The adage "experience is the best teacher" is hard to put into practice because current education systems require students to learn synchronously or asynchronously before gaining work experience. But with virtual reality the adage "experience is the best teacher" can be incorporated to provide realistic learning experiences for students in

the K-12 space. Virtual reality (VR) is a three-dimensional (3D), computer-generated environment that leads the user to perceive the contents in a more realistic way (VR paper). The content in the K-12 space refers to the education curriculum being taught by educators. With VR, the content can be presented in a way that captures the attention of students by combing the four learning styles into one application.

Majority of students fall into one of the three types of learning styles: visual, auditory, and kinesthetic (Hauptman & Cohen, 2011). VR touches learning styles, enabling students to see, hear, interact, and read within a virtual environment (Hauptman & Cohen, 2011). Aside from these features virtual reality contains nonverbal auditory stimulus that tradition teaching methods do not have (Araiza-Alba et al., n.d.). Those auditory cues, include sounds of static electric as the users gets closer to powerlines, or sounds of objects dropping as they hit the ground, providing realism to the learning experience, which allows for more practical learning resulting in higher cognitive functioning. Thus, VR is a dependable application for students in the K-12 space, where different learning styles from the classroom can be combined, to educate students in one immersive environment.

According to a national survey conducted by Dreambox Learning, 90% of educators agree that VR technology is an effective way to provide a different learning experience for students. But teachers who are unfamiliar with VR might reject the idea of incorporating VR technology into their classrooms (Yildirim et al., 2020). With teachers having little experience with VR technology, they think that the learning curve is too high to incorporate their style of teaching (Papanastasiou et al., 2019). Providing teachers with that opportunity to learn, practice, and develop their VR skills will decrease the discomfort teachers have with adopting this new technology into their classrooms (Yildirim et al., 2020). VR is a tool that can create environments in which students can begin to put what they learn into practice to gain experience before heading into the real world.

This technical paper explains the process for developing a VR learning platform called VR-ENERGY. The VR-ENERGY learning platform is a two-phase learning system for students to develop their computer science skills based on smart infrastructure and residential energy monitoring. Using a home as a relatable environment, students will learn about data collection through sensor installation, transmission, storage, analysis, and visualization. The VR-ENERGY learning platform is split into two phases. Phase 1 involves using VR to teach students how to collect energy data from a house, transport the energy data, and learn how energy is consumed throughout a home. Phase 2 involves students learning how to store, analyze, and visualize energy data to reveal energy insights. The VR-ENERGY learning platform objectives for this technical paper are outlined below:

ENERGY VR learning Platform Objectives

• Co-create with educators to:

- Include Computer Science education curriculum in VR-ENERGY learning Platform
- Brainstorm VR capabilities
- Create a virtual environment using Unity 3D and allow users to be immersed using HTC VR headset
- Create a How-to-Station, to teach users how to navigate throughout the virtual environment.
- Create an Energy Monitoring Station, where users are introduced to the components and install an eGauge system.
- Create a Solar Powered Mesh Network station, where users are introduced to the components and build a solar-powered mesh network station.
- Create a solar exploration state, where users are provide information on what a solar panel is and how it works.
- Include energy data facts throughout the virtual home on appliances and electric devices.

BACKGROUND

What is Virtual Reality?

Within seconds, just by putting on a headset, students can become immersed in a virtual environment called virtual reality. "Virtual reality (VR) is an advanced human-computer interface that simulates a realistic environment (Zheng et al., 1998)".VR dates back to the 1800s, but the VR headset was not invented until 1960 by Morton Heilig ("History Of Virtual Reality," 2017). Fast forward to 2021, with technology advancing as we speak. VR headsets are becoming more market-available and fairly priced including the Oculus, HTC Vive, HP Reverb, Sony PlayStation VR, and the Valve Index, just to name a few. Virtual reality is mainly used for entertainment, focusing on video games, 3D cinema, and virtual social worlds ("Benefits of Virtual Reality in the Classroom," 2017). But VRs potential does not and has not stopped there. VR has infiltrated into the education system, providing an alternative method for teaching students various concepts (Kavanagh et al., 2017).

Virtual Reality Learning Environments

The education system is starting to mimic how the video gaming industry incorporated VR into its games (Vogel et al., 2006). VR adds another dimension, creating immersed, intractability, and imaginative capabilities for students to experience, creating a feeling that is not present when teachers are lecturing at the board (Lin & Wang, 2021). VR learning environments provide a special feeling that creates engagement between the students and the subject being taught (Hussein & Natterdal, 2015). This unique feeling allows students to learn about the given subject presented in the VR learning environment. VR will enable students to have a constructivist approach to learning to "learn by doing," practicing the skills learned in the classroom into the virtual world, increasing comprehension.

Computer Science Curriculum

The VR-ENERGY learning platform will allow students to simulate and gain knowledge and accomplish objectives from the computer science curriculum using VR technology. The computer science standards covered in the Energy VR platform are from Virginia's public-school department which are listed below with a brief description of how they are implemented inside the platform.

Computer Systems - CSF.1

Students will explore the hardware and software components to see why the computer systems were chosen to run the VR-ENERGY platform.

Network, the Internet, and Cybersecurity - CSF.04-CSF.06

A solar-powered mesh network system was implemented in the VR-ENERGY platform to provide students with the opportunity to explore the components that exist within a network system.

Data and Analysis - CSF.09-CSF.11

Phase 2 of the VR-ENERGY learning platform will provide students the option to export energy data from the Phase 1. Giving students the ability to explore data analytics and data visualization within Excel, Tableau, Python, or any other data visualization software.

Algorithms and Programming - CSF.12-CSF.21

The VR-ENERGY platform will be created using Unity 3D, which is free for students to download. Students will be given a copy of the learning platform where they can modify the virtual environment. Serving as a learning opportunity for students to implement their own functionality elements.

Impacting of Computing - CSF.22-CSF.24

The VR-ENERGY platform allows students to see how computing can impact their learning experiences through VR. In hope of students seeing the potential ability VR has to recreating real life experience virtually. Along with educating the students on the objectives associated with the computer science education curriculum, students will be able to learn and improve their energy and data literacy skills from interacting with the VR-ENERGY platform.

Energy Literacy

The VR-ENERGY platform has the potential to increase students' energy literacy level by being immersed and interacting with the energy components throughout the environment. Energy literacy is defined as the domain of basic energy-related knowledge, coupled with the ability to understand the impacts of energy productions and consumption on the environment, everyday life, and the adoption of energy
savings behaviors (DeWaters & Powers, 2011). Phase 1 of VR-ENERGY platform has three elements associated with energy literacy; installing the eGauge energy monitoring device, the solar-power mesh network, and the energy facts located inside the virtual home. Phase 2 of the learning platform includes visualizing the energy data collected from phase 1 for students to uncover energy insights hidden within in the energy data. Both phases will allow students the ability to identity their knowledge, behavior, and attitude towards energy. Thus, one's energy literacy consists of three elements: knowledge, behavior, and attitude (Martins et al., 2020). Aside from one's energy literacy, data literacy plays a role in an individual's comprehension of how energy is consumed in a home.

Data Literacy

Insightful data is being produced from residents interacting with appliances and circuits inside of their homes. If residents don't have the data literacy ability to uncover the hidden messages within the energy data, energy insights will forever be lost. Data literacy is defined as the "ability to read, work with, analyze, and argue with data.

- Reading data involves understanding what data is and what aspects of the world it represents.
- Working with data involves creating, acquiring, cleaning, and managing it.
- Analyzing data involves filtering, sorting, aggregating, comparing, and performing other such analytic operations on it.
- Arguing with data involves using data to support a more extensive narrative intended to communicate a message to a particular audience (Bhargava, 2015)."

After students have explored phase 1 of the VR-ENERGY platform, students will have the ability to download the energy data for future exploration. Future exploration will include students storing, analyzing, and visualizing energy data to discover the energy insights.

The Co-Creation Method Used to Design the Energy VR Learning Environment.

To create the VR-ENERGY environment a co-creation method was incorporated between Dr. Frederick Paige, Joseph James, several high school educators from the Radford, Virginia High school district. Co-creation falls under the participatory design umbrella. Co-creation involves active user input throughout the duration of the design process, interacting with users to target specification, realization, and design for tailor ability (Ind & Coates, 2013). Before the creation of the VR-ENERGY learning environment, a proposal was submitted to the 'advance computer science education' grant. The proposal discusses the purpose of creating the VR environment, which is to exposure students to a variety of workplaces and practical training simulations centered around the 5 C's- critical thinking, communication, cooperation, creativity, and citizenship. The Energy VR environment is also tailored to Virginia's education computer science curriculum focusing on: Computer Systems-CSF.1

Network, the Internet, and Cybersecurity - CSF.04-CSF.06

Data and Analysis - CSF.09-CSF.11

Algorithms and Programming - CSF.12-CSF.21

Impacting of Computing - CSF.22-CSF.24

After the proposal was accepted, the co-creation process began with the Radford high school educators. Four Meetings occurred throughout the duration of creating the VR-ENERGY learning platform. During the initial meeting with the Radford high school educators, we reviewed:

- The objectives of the VR experience,
- Integrated curriculum standards into VR experience
- Components to be added to the VR experience
- Component's functionality in the VR experience
- Career Clusters incorporated in the VR experience
- The work schedule for the summer.
- Comments from the educators.

In conclusion of the initial meeting, I received ideas and visions from the educators of what they wanted the VR experience to encompass. Some examples of their ideas and visions include:

- Can you include these avatars of the students in the virtual environment?
- What about if the character could do this fly around the environment instead of walk?
- Would it be possible to include a point system where students can gain badges from completing each station?

As a result of co-creating with Radford high school educators we were able to outline design objectives for Phase 1 of the VR-ENERGY Learning Environment.

- Students will install an eGauge energy monitoring system to collect the energy data produced in the virtual home for the data collection objective. The goal is to teach students what components make up an energy monitoring system and install the eGauge system in the virtual environment. We chose the eGauge device because it is a compact system with minimum components to install. Other benefits of the eGauge device include the ability to monitor 30 circuits in a home, collect energy data on a second-by-second basis, and stream data in real-time.
- Students will install a solar-powered mesh network system to provide internet access to the eGauge device for the data transmission objective, allowing energy data to be transmitted. The goal is to teach students what components make up the solar-powered mesh network and install the network system in

the virtual environment. The solar-powered mesh network provides internet access to the eGauge device, allowing data transmission to occur.

• There will also be energy stations throughout the virtual environment where students learn about renewable energy sources and gather energy facts on appliances and electronic devices within the home.

Aside from the VR-ENERGY objectives, students will have the option to roam around and explore the VR environment. By using Unity 3D I was able to create the VR-ENEGRY Learning Environment and Vive's HTC Cosmos Elite (VR headset). I was able to immerse the students into the virtual environment. Unity 3D is a crossplatform 3D engine used to create virtual environments (Jerald et al., 2014), which is open-source for students. Additionally, the students will have full access to the Unity3D project file and code to alter and expand upon the Energy VR learning environment. After students have completed the VR-ENERGY objectives, students will be able to download the energy data for Phase 2 of the VR learning environment. Future exploration of the energy data includes understanding how to store, analyze, and visualize the data to uncover energy insights. Throughout this project, the other three meetings were update meetings to show the educator's progress of the VR-ENERGY learning environment and receive feedback or suggestions from their perspective.

RESULTS



Figure 1: Displays the storyboard of the ENERGY VR learning experience.



Figure 2: Displays the layout and components of Station #1.

Figure 3: Displays the home breaker panel.

Figure 4: Displays the components of the eGauge energy monitoring system.



Figure 5: Displays the model and components of the mesh network station.

Figure 6: Displays the 4 mesh network stations that students are able to build in VR.



Figure 7: Displays the solar panel station located on the roof of the home.

Figure 8: Displays an energy fact associated with the X-BOX electronic device.

DISCUSSION & LIMITATIONS

Phase 1 of the VR-ENERGY learning platform is composed of four stations to educate students on capturing home energy data. The four stations include: **Station #1 how to play, Station #2 energy data collection, Station #3 data transmission, Station #4 solar panel exploration**. Each station contains an avatar that provides users with overview of the station through an audio message. In addition, students can explore inside the home to discover energy facts regarding appliances and electronic devices.

Station #1 How to Play

Station #1 "how to play" station provides students with instructions on how to navigate the virtual environment. The table at the station includes a CT connector, battery, access point, and a button for students to practice interacting with before moving to other stations. In addition, a whiteboard displays the VR controller functions, highlighting the teleport and the trigger to grip buttons.

Station #2 Energy Data Collection

Station #2, the eGauge data collection station, provides students with the opportunity to learn about each of the components needed to capture residential energy data. Each component of the eGauge system is presented to the students on a table. The components include the eGauge console and the current transformers (CT). The components are interactable; students can use their virtual hands to grab and explore each component. In addition, there are buttons in front of the components. When pressed, a written description of the component appears and an audio reading, providing students with information through two mediums. After students have become familiar with the eGauge system, they will move over to the home's breaker panel, where they will begin to install the eGauge system. The current step-up includes installing the eGauge console and 4 CTs onto the home's breaker panel. Installation occurs by students picking up the components, teleporting to the home's breaker panel, and finding the component's correct position.

There are hover zones throughout the breaker panel to preview the correct component's position before installation. Once a student hovers over the zone, a picture of the proper component is displayed. If the photo matches the component, the student will know that this is the component's correct position, let go of the trigger, and the component will transition into place automatically. Future functionality for hover zones includes incorporating sound, visual effects, and coding updates to only accept the correct component. Currently, hover zones can accept any interactable component in the virtual environment. Updating the hover zones functionality will increase the student's practical knowledge for installing an energy monitoring system. Future functionality for the eGauge device includes making the interface functional, allowing students to see real-time energy data being collected. In addition, the breaker panel will have safety features such as power indicators and hazard warnings to increase the vividness and realistic experience.

Station #3 Data Transmission

The data transmission station provides students with the opportunity to learn about each of the components needed to create a mesh network station. Each component of the mesh network station is present to students on the table. The components include the solar panel, the access point, battery, and an empty enclosure. The empty enclosure challenges students to figure out what other components are needed to have a fully functional solar-powered mesh network station. In addition, there are buttons in front of the components. When pressed, a written description of the component appears and an audio reading, providing students with information through two mediums. Next to the table with the components is a model to show students the correct placement of each component for the solar-powered mesh network station. Hover zones are also present in the mesh network station to help students place the components correctly. A ladder is provided in the virtual environment to install the solar panel, allowing students to reach a higher elevation. Future functionality of this station includes implementing a virtual toolbox that contains wires, screwdrivers, voltmeter, and personal protective equipment to connect the components safely and successfully.

Station #4 Solar Panel Exploration

The solar panel station allows students to travel to the roof of the house by way of a ladder to watch a video explaining the purpose of solar panels. Future functionality of this station includes updating the current code for students to have the ability to create different solar panels layouts on the roof. In addition, students will be able to adjust the brightness of the sun to see what effect the sun has on solar generation of energy.

Energy Facts

Aside from the energy stations around the home, students will also have access to the inside of the home. For example, students can explore and hover over different appliances or electronic devices to learn about energy insights. Future functionality of the home inside includes implementing more appliances with energy feedback, informational videos, avatars, and extracting the energy data for phase 2 of the VR-ENERGY learning platform. In addition, the appliances will generate energy data when students interact with them, which will allow students to see how certain behaviors contribute to specific amounts of energy being consumed. The informational videos and avatars will serve as educational assets to increase students' energy awareness of the home. In addition, extracting the energy data generated from appliances will allow students to visualize and analyze their energy consumption behavior from the virtual environment in phase 2.

CONCLUSIONS

Virtual reality provides students with hands-on experience in an alternate form before stepping out into the real world (Papanastasiou et al., 2019). Virtual reality environments such as VR-ENERGY allow students to connect what they are learning in the classroom to the real world in a manner of seconds. For example, phase 1 of the VR-ENERGY learning platform provides a practical way from students to learn about an energy monitoring system, solar-powered mesh network, and energy facts. In this VR experience, students can learn and make mistakes without the fear of damaging the equipment or themselves, which could result in a mistake that cannot be reversed in the real world.

Exposing students to the VR-ENERGY learning environment has the potential to open students minds to possibilities that VR entails. Likewise, exposing teachers to VR could allow them to see how VR can be an asset to their classroom. Phase 1 of the VR-ENERGY learning platform has also been designed for students and teachers to expand upon the current functionality on their own. Proving teachers and students with the opportunity to alter the VR environment to fit different education curriculums. Thus, tailoring the VR environment to expose students to various educational curriculums providing students with an alternate way of gaining hands-on practical experiences.

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REFERENCES

Araiza-Alba, P., Keane, T., & Kaufman, J. (n.d.). Title: Are we ready for virtual reality in K-12 classrooms? 34.

Benefits of virtual reality in the classroom. (2017, May 5). Virtual Reality Society. https://www.vrs.org.uk/virtual-

reality-education/benefits.html

Bhargava, R. (2015). Beyond Data Literacy 2015. 37.

Bricken, W. (1990). Learning in virtual reality.

- DeWaters, J. E., & Powers, S. E. (2011). Energy literacy of secondary students in New York State (USA): A measure of knowledge, affect, and behavior. *Energy Policy*, 39(3), 1699–1710. https://doi.org/10.1016/j.enpol.2010.12.049
- Hauptman, H., & Cohen, A. (2011). The synergetic effect of learning styles on the interaction between virtual environments and the enhancement of spatial thinking. *Computers & Education*, 57(3), 2106–2117. https://doi.org/10.1016/j.compedu.2011.05.008

History Of Virtual Reality. (2017). Virtual Reality Society. https://www.vrs.org.uk/virtual-reality/history.html

Hussein, M., & Natterdal, C. (2015). The Benefits of Virtual Reality in Education: A Comparison Study. 15.

Ind, N., & Coates, N. (2013). The meanings of co-creation. European Business Review, 25(1), 86–95. https://doi.org/10.1108/09555341311287754

- Jerald, J., Giokaris, P., Woodall, D., Hartbolt, A., Chandak, A., & Kuntz, S. (2014). Developing virtual reality applications with Unity. *2014 IEEE Virtual Reality (VR)*, 1–3. https://doi.org/10.1109/VR.2014.6802117
- Kavanagh, S., Luxton-Reilly, A., Wuensche, B., & Plimmer, B. (2017). A systematic review of Virtual Reality in education. *Themes in Science and Technology Education*, 10(2), 85–119.
- Lee, E. A.-L., Wong, K. W., & Fung, C. C. (2010). Learning with Virtual Reality: Its Effects on Students with Different Learning Styles. In Z. Pan, A. D. Cheok, W. Müller, X. Zhang, & K. Wong (Eds.), *Transactions on Edutainment IV* (pp. 79–90). Springer. https://doi.org/10.1007/978-3-642-14484-4_8
- Lin, Y.-J., & Wang, H. (2021). Using virtual reality to facilitate learners' creative self-efficacy and intrinsic motivation in an EFL classroom. *Education and Information Technologies*, 26(4), 4487–4505. https://doi.org/10.1007/s10639-021-10472-9

- Martins, A., Madaleno, M., & Dias, M. F. (2020). Energy literacy: What is out there to know? *Energy Reports*, 6, 454–459. https://doi.org/10.1016/j.egyr.2019.09.007
- Pantelidis, V. S. (2009). Reasons to Use Virtual Reality in Education and Training Courses and a Model to Determine When to Use Virtual Reality. 12.
- Papanastasiou, G., Drigas, A., Skianis, C., Lytras, M., & Papanastasiou, E. (2019). Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills. *Virtual Reality*, 23(4), 425–436. https://doi.org/10.1007/s10055-018-0363-2
- Vogel, J. J., Greenwood-Ericksen, A., Cannon-Bowers, J., & Bowers, C. A. (2006). Using Virtual Reality with and without Gaming Attributes for Academic Achievement. *Journal of Research on Technology in Education*, 39(1), 105–118. https://doi.org/10.1080/15391523.2006.10782475
- Yildirim, B., Topalcengiz, E. S., Arikan, G., & Timur, S. (2020). Using Virtual Reality in the Classroom: Reflections of STEM Teachers on the Use of Teaching and Learning Tools. *Journal of Education in Science Environment and Health*, 6(3), 231–245. https://doi.org/10.21891/jeseh.711779
- Zheng, J. M., Chan, K. W., & Gibson, I. (1998). Virtual reality. *IEEE Potentials*, 17(2), 20–23. https://doi.org/10.1109/45.666641

Practical Construction of 3D Printed Reinforced Concrete Members

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1. Introduction

Also known as 3D Concrete Printing (3DCP), 3D printing technology has been applied in the industry for building constructions in recent years. Compared to the conventional construction process, 3DCP needs no formwork and is mainly operated by an automatic printing system, and thus, it wastes less material, reduces construction time and labor cost, and increases design freedom for architects. Many research and actual construction projects have been conducted to print various concrete objects ranging from structural members to houses with different printing systems, reinforcement details, and construction steps, as they are discussed below.

Three major printing systems are generally adopted by companies for building construction on-site, gantry system (ICON, Contour Crafting, COBOD, and WinSun), robotic arm system (CyBe and XtreeE), and crane-type robot (Apis Cor. and WASP). The gantry system (**Fig. 1a**) can carry a printing nozzle to move in X, Y, and Z directions after the frame is set on-site. The printed houses are limited to the size of the gantry system. The robotic arm system (**Fig. 1b**) attaches a printing nozzle to a programed multi-axis robotic arm. This printing system is more flexible to move around the construction site, but at the same time, the construction radius is limited by the maximum reachable area of the robotic arm. To solve this disadvantage, multiple mobile robotic arm systems can be applied. The crane-type robot (Fig. 1c, d) attaches the printing nozzle to a crane with a workspace in a circular area around the base (Evjemo et al. 2017). In addition, Crane WASP (Fig. 1c) can be assembled on-site with several independent crane units to form different configurations with the growth of the architectural project.



Fig. 1. a) Gantry system (Slager 2017)), **b)** robotic arm system from CyBe (Dörfler et al. 2019), c) crane-type robot from Apis Cor. (https://apis-cor.com/) and **d)** Crane WASP (https://www.3dwasp.com/en/).

The manufacturing process for 3D printed concrete elements is typically composed of the toolpath design for 2D layers sliced from a 3D geometry, the printing process by extruding concrete material from the printing nozzle attached to a robotic arm that is programmed to move along the designed toolpath layer by layer, and the installation of reinforcement. Many

innovative reinforcement strategies have been proposed in the literature for printed concrete, for example, external steel rebar system (Asprone et al. 2018), in-process studs welding (Classen et al. 2020), and staple reinforcement (Geneidy et al. 2020). However, some methods are not vet practical to apply in large-scale construction (e.g., steel printing, Mechtcherine et al. 2018). For on-site building construction in 3DCP projects, the companies are still relying on the conventional reinforcement methods used in cast concrete, for example, the placement of conventional rebar systems in prefabricated formwork and adding short fibers in the mixture to increase structural strength and reduce shrinkage cracking. Due to the different manufacturing steps, the integration of these conventional reinforcement methods in the printing process becomes crucial. The goal of this paper is to survey existing techniques used by companies for 3D printing building elements (e.g., walls, columns, roofs, and beams) in house construction projects. The paper aims to provide an overall view of different construction options that may serve as a reference in future projects and the building code compliance for 3D printed houses currently under development (e.g., AC509 by International Code Council, the first regulatory document on 3D printed residential houses). Due to the limited number of references found in the literature on 3D printing house projects, the provided overall view is preliminary and will certainly evolve as more projects are developed.

2. The construction process for walls and columns

For a 3DCP project, due to the shipping cost and preinstallation process for an extensive printing system, it is sometimes easier to print concrete members in the factory and ship them to the construction site where they are assembled, like the precast process in conventional construction. However, in this case, the shipping cost of the prefabricated concrete members and the process of assembling the members at the construction site make this method more appropriate for small houses (e.g., single-family homes). WinSun (www.yhbm.com), printed ten single-story houses (200 m²) each) within a day in 2014 using gantry printing system (150 m length X 10 m width X 6.6 m height) with cement material mixed with glass fibers, industrial waste, and a hardening agent (Wu et al. 2016; Hager et al. 2016). In this project, all walls were printed in a factory and shipped to the site for assembling. Two different strategies were presented for the wall fabrication. Some of them were printed vertically with horizontal layers in a hollow structure with internal diagonal pattern left for filling insulation material or reinforcement before casting the concrete (Fig. 2a). After the fabrication process, walls were shipped to the site and assembled with the conventional precast concrete foundation, roof structure, and doors (Kidwell 2017). Another strategy was to print walls vertically in the shape of a square perimeter with an internal diagonal pattern. After filling the printed walls with insulation material or reinforcement, they were transported to the site and placed with 90 degree turns on the ground to make layers run vertically (Fig. 2b). The doors and additional roof structure, if necessary, were installed accordingly. The latter strategy is effective for tiny houses printing. It features an overhanging part above the wall, which was printed as a part of the wall structure, so that the printed house can still be functional even without the post-installed roof structure. However, using this method, the printed houses are restricted to the "duct" shape, and the size is limited. For the process of installing windows and doors in the printed wall section, it is hard to set the windows and doors in place while printing without damaging the surrounded wet concrete. One solution is to leave the area of the opening empty when printing the wall and place a support for printing the above layers.



Fig. 2. a) One-story houses printed by WinSun with layers run horizontally and **b)** vertically (<u>www.yhbm.com</u>). **c)** Wood board support for the printing of window section (<u>https://www.3dwasp.com/en/</u>). **d)** Assembled wall structure (Wu et al. 2016).

In the project of the Gaia constructed by WASP in 2018, a one-story 30 m² house was printed using Crane WASP using as material soil and agricultural waste. The walls in this project were printed onsite with wood boards placed manually between layers to support printing the overhanging part of the window (**Fig. 2c**). To avoid adding supports manually during printing, which may damage the wall section due to human errors, the wall can be printed in segments and assembled to leave the area for windows and doors. WinSun assembled on-site wall segments that had been printed in a factory and shipped to the site in a construction project for a villa (1100m²) in 2015 (**Fig. 2d**). In this project, the overhanging part of the wall before installing windows and doors does not need the support that is necessary if the walls are printed as one piece. After the printing, holes were drilled in the wall for the electrical and plumbing system. However, cracks and damages may occur in the cured concrete part (Wu et al. 2016).

After printing the wall shell, which serves as formwork, reinforcement can be installed. This is the solution found, for instance, in 3DCP projects by Apis Cor (https://www.apis-cor.com/), a global 3D printing company. The company applied a customized robotic arm printing system to print concrete structures, as shown in **Fig. 3**. The unique design of the printing system reminds us of a tower crane, which enables the printing process to operate in and out of the structure (Nadarajah 2018). Instead of printing in a factory and shipping the components to the site to assemble, the walls were printed onsite in some of their construction projects. In one of their projects for a detached house in Russia (2016) (**Fig. 3a**), walls were printed in a hollow structure composed of two parallel filaments for each layer. Horizontal rebars were placed between layers to bridge the filaments during the printing. Depending on the shape of the rebars, they could increase the bond strength between layers if they feature hooks that can be inserted in the printed layers, or they could be used to fix vertical rebars in position through tie connections before casting the concrete. Another example of their on-site printing project is a low-rise building built in Dubai in 2019 (**Fig. 3b**). In this project, vertical rebars and concentrated reinforcement systems were placed in the wall printed with an internal diagonal zig-zagging pattern before casting the concrete.





Reinforcement details were also found in the construction process for two Barracks Huts (B Hut) constructed by US Army Corps of Engineers (https://www.goarmy.com/) using a gantry printing system in Champaign, Illinois (Kreiger et al. 2019). The printed B Hut A and B are composed of conventional cast-in-place concrete foundations, roof, and printed walls. For B Hut A, the walls were printed in a hollow structure serving as formwork that was filled by inserting vertical rebars and pouring the concrete (**Fig. 4a**). During the printing, ladder wires were placed between layers with a slight horizontal shift to confine vertical rebars that were installed after the printing (**Fig. 4b**). Anchors were also installed for connecting walls and the roof structure. After the printed formwork gained enough strength (28 days), concrete was poured to finish the wall section, followed by assembling it to the precast foundation with steel angles anchored in the slab and a steel bolt. For B Hut B, the walls were printed using a zig-zagging pattern with vertical rebars been installed in the open cells and grouted after the printing (**Fig. 4c**). The anchoring details for B Hut A walls with roof and foundation are shown in **Fig. 5**.



Fig. 4. a) Wall construction for B Hut A (Kreiger et al. 2019). b) Reinforcement details of printed walls for B Hut A and c) B Hut B (Kreiger et al. 2019).



Fig. 5. Anchoring systems of walls in roof and foundation for B Hut.

Another way to incorporate reinforcement in wall fabrication is to print or assemble a mesh structure by robot and use shotcrete to fill the interior gap, followed by a surface finish. In the project of DFAB HOUSE at NEST (Richner et al. 2017; Hack et al. 2017; Giftthaler et al. 2017; Dörfler et al. 2019; Hack et al. 2020), the doubly curved wall was fabricated using the Mesh Mould approach, which started with the welding of a steel mesh structure using a robotic arm system that served as stay-in-place formwork and internal reinforcement system (Fig. 6a). To be more specific, discrete and continuous steel rebars were connected through welding to form a double-sided hollow mesh structure using a mobile robotic arm system called in situ fabricator. After the mesh fabrication, cement was manually poured into the mesh structure, and a layer of shotcrete was applied at the surface to cover the steel portion. The resulting wall was claimed to be a fully load-bearing and monolithic building element (Hack et al. 2017). Branch Technology, a Tennessee company, used a similar method, Cellular Fabrication, to construct walls with a robotic arm system (Kidwell 2017). Different from the Mesh Mould approach, this method fills the printed interior mesh structure made of thermoplastic polymer with spray foam insulation and uses one layer of concrete and plaster to cover the wall surface (Fig. 6b). However, this method may be limited to fabricate parapet walls and partition walls rather than structural components due to the lack of steel.





In 3DCP construction projects, the foundation of the wall can be made of conventional cast-in-place or precast concrete as it was in projects by WinSun for ten single-story houses and by US Army Corps of Engineers for the B Hut. Alternatively, the foundation can be printed using the same strategy for the wall section to keep consistency. For example, in one of the projects from Apis Cor, the foundation wall was printed for the inner and outer shell, leaving the core to be filled by placing a conventional reinforcement system and pouring concrete (**Fig. 6c**). During the printing of the foundation, plastic tubes were placed between layers to bridge the inner and outer shells. The tubes could be used for plumbing purposes or lift the later placed reinforcement system, making the steel rebars wholly buried in the concrete. After casting the concrete, the anchoring rebars as part of the reinforcement in the foundation stick out of the surface to connect the above wall structure by using steel couplers to join vertical rebars in the wall.

To reduce the shrinkage cracking resulting from temperature changes, a house in Arizona constructed by PERI (https://www.peri.com/en), a German construction company, features small gaps in the wall section, shown as white lines in the wall in **Fig. 7a**. The gaps were filled with silicon material after printing to form an expansion joint to control cracks.





b)

Fig. 7. 3D printed house by PERI featured with a) expansion joint in the wall to control shrinkage cracking and b) printed beam section on-site with support (https://www.peri.com/en). c) Printed columns with reinforcement on site by WinSun (http://www.winsun3d.com/).

Columns are more commonly seen in projects for larger size printed habitats where slabs and beams are also coupled. According to Faluyi (https://www.winsun3dbuilders.com/news/), the printing process Winsun used for large columns was separated into several prints to allow for the installation of reinforcement (Fig. 7c). Since the high concentrated reinforcement system is hard to insert appropriately after the printing and the printing system is unlikely to print concrete around an existing high reinforcement system without touching it, shorter reinforcement segments were installed before the printing of column formwork with the same height around the reinforcement. Reinforcement segments were connected using rebar couplers to create a continuous reinforcement system inside of the formwork (Fig. 8). Concrete was then poured to fill the hollow structure.



Fig. 8. Printed columns with reinforcement on site (http://www.winsun3d.com/).

In summary, to print one-story houses, walls instead of columns are used as main structural members to resist vertical loads. In this case, the construction process consists of three components, wall foundation, walls, and roof structure. The foundation fabrication can either follow the conventional precast or cast-in-place construction procedures or use 3DCP technology to print formwork filled with conventional reinforcement system and cast concrete. Anchors should be buried in the foundation for the connection of the above wall structure. The most common approach for wall printing is to print a hollow shell to serve as formwork, then place the reinforcement, and then pour concrete inside. Different reinforcement types can be used for various purposes in this process, including vertical reinforcement (e.g., vertical rebars and concentrated reinforcement) for resisting vertical loads and horizontal reinforcement (e.g., ladder wires and horizontal rebars) for fixing the vertical reinforcement. Regarding the creation of windows or doors, supports are needed for continuous printing of the part above these

elements. After wall printing, predesigned gaps in the wall can be filled with silicon material to effectively control shrinkage cracking. Regarding the roof structure, it is usually precast and shipped to the site for assembling. Columns are printed primarily on multi-story building construction coupled with beams and slabs. The fabrication process of tall columns can be separated into several prints to avoid collision with reinforcement elements during printing.

3. The construction process for beams and roofs

Although the roof structure is mainly precast and assembled on-site to construct a 3D printed house (e.g., the construction process mentioned in Kidwell (2017) and Kreiger et al. (2019), it can also be printed using an innovative formwork system. For example, a thin-shell concrete roof was printed in ETH Zurich in 2015 (Echenagucia et al. 2019). The construction process (**Fig. 9**) for the roof structure starts with fabricating a cable-net falsework that is tensioned between timber boundary beams joining fabric shuttering on the top. The falsework was designed digitally to ensure proper load distribution in steel cables. Then, textile reinforcement was attached to the connections of cables as the surface to hold the wet concrete sprayed later. This method is effective in building curved roof shells with complex shapes using concrete material. However, the process of making the cable-net falsework seems too elaborate and time-consuming. The concept is not suitable for the construction of houses but for projects where aesthetics have an increased role.





The process of manufacturing a printed beam or girder with reinforcement on a laboratory scale is easy to find in the literature (e.g., Feng et al. 2015; Asprone et al. 2018; Vantyghem et al. 2020). However, the process of building a printed beam on-site in a house printing project is rarely reported. One construction video from Gross (2021) for the printed house constructed by PERI was found in this regard. In this project, the beams were printed on the steel shell sitting on top of two printed columns (**Fig. 7b**). The beam should be covered by a surface finish after the printing to bury the steel part. In fact, beam elements can also be precast and assembled on site to eliminate the need for support, but extra shipping fees and the separated construction process may be of concern.

Similar to a beam, a bridge was printed and reinforced using tensioned steel cables in a construction project. The bicycle bridge constructed by BAM Infrastructure group, a Dutch 3D construction company, and the Eindhoven University of Technology was completed in the Netherlands in 2017 (Salet et al. 2018). The whole construction process consists of three significant steps, printing, assembling, and reinforcing. For the printing process, several bridge segments were printed in the lab using a gantry system with the pattern shown in **Fig. 10a**. After printing, the printed segments were transported to the site, lifted using a gantry crane, and placed in 90 degree turns on top of a temporary wooden scaffold for assembling (**Fig. 10b**). The hollow portions of the printed elements were aligned to form a continuous duct. Synthetic epoxy-based material was applied on the interface to smooth it and join adjacent segments together. Steel cables were then stressed in the ducts to reinforce the printed bridge providing bending resistance (**Fig. 10c**), followed by hoisting the bridge and placing it in position. This method is

effective for bridges with short-span and low load-bearing requirements and can provide a reference for onsite beam construction.





In summary, instead of using conventional construction processes to fabricate roof structures in house printing projects, the roof can also be printed based on a cable-net falsework with attached textile reinforcement. However, this method seems more suitable for projects where aesthetics has a major role and require printing a thin shell structure on the ground, rather than for house printing projects. For beam fabrication, printing beams on a preset support is one option for continuous printing on-site. In addition, beams can also be precast and assembled on site. Considering as a reference the construction process of bridges, large beams may be printed in segments and reinforced using tensioned cables after the assembling process.

4. Summary and Conclusions

A summary of potential construction options for different structural members in house printing projects is provided in **Table 1**. For houses with a single room, assembling precast foundation and roof with walls printed in the factory and shipped to the site seems the most practical way from an economic viewpoint. For one-story houses, the construction process includes the cast-in-place of wall foundations, walls that are printed as formwork and filled with reinforcement and cast concrete on site, and a precast roof structure. For multi-story houses, printed shell cast core columns with reinforcement, beams printed on top of supports, and precast slabs and roof are usually involved.

Table 1. Construction options categorized by different structural members (commonly used cases are highlighted).

	Construction options on site	Reference source	
Wall	Printed formwork filled with reinforcement or insulation	Wu et al. 2016; Hager et al. 2016;	
	material and sealed by casting concrete	Kidwell 2017; Nadarajah 2018;	
	Printed in horizontal direction and placed 90 degree turns	Kreiger et al. 2019; www.yhbm.com; http://apis-cor.com/	
	Precast and assembled at the construction site	Wu et al. 2016	
	Applying Mesh Mould or Cellular Fabrication method to	Richner et al. 2017; Hack et al. 2017;	
	build interior reinforcement stucture and fiiling the gap with	Giftthaler et al. 2017; Kidwell 2017;	
	concrete or insulation material	Dörfler et al. 2019; Hack et al. 2020	
Wall foundation	Precast or cast-in-place	Kidwell 2017; Kreiger et al. 2019	
	Printed formwork with interior reinforcement sealed by	http://apis-cor.com/	
	casting concrete		
Column	Printed in several prints with reinforcement been installed	http://www.winsun3d.com/	
	before every printing		
Roof	Precast and assembled at the construction site	Kidwell 2017; Kreiger et al. 2019	
	Fabricated based on a cable-net falsework and textile	Echenagucia et al. 2019	
	reinforcement		
Beam	Printed on the support sitting on columns	https://www.peri.com/en	
	Precast and assembled at the construction site	Wu et al. 2016	
	Printed in segments and reinforced using tensioned cables	Salet et al. 2018	

Due to the limited number of house printing projects found in the literature, it is not possible to have a comprehensive view of potential construction options at the current stage. However, by referencing dispersed construction details in different projects, an overall picture was drawn to tentatively identify suitable construction options for specific members depending on the size of the construction project. The outlined options provide a reference and guidelines for operators interested in printing houses on-site in future projects.

References

Apis Cor. (n.d.). Retrieved September 27, 2021, from http://apis-cor.com/.

- Asprone, D., Auricchio, F., Menna, C., & Mercuri, V. (2018). 3D printing of reinforced concrete elements: Technology and design approach. *Construction and Building Materials*, 165, 218–231. https://doi.org/10.1016/j.conbuildmat.2018.01.018
- Classen, M., Ungermann, J., & Sharma, R. (2020). Additive manufacturing of reinforced concrete—development of a 3D printing technology for cementitious composites with metallic reinforcement. *Applied Sciences*, 10(11), 3791. https://doi.org/10.3390/app10113791
- Dörfler, K., Hack, N., Sandy, T., Giftthaler, M., Lussi, M., Walzer, A. N., Buchli, J., Gramazio, F., & Kohler, M. (2019). Mobile robotic fabrication beyond factory conditions: Case study mesh mould wall of the DFAB House. *Construction Robotics*, 3(1-4), 53–67. https://doi.org/10.1007/s41693-019-00020-w
- Evjemo, L. D., Moe, S., Gravdahl, J. T., Roulet-Dubonnet, O., & Gellein, L. T. (2017, September). Additive manufacturing by robot manipulator: An overview of the state-of-the-art and proof-of-concept results. In 2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) (pp. 1-8). IEEE.
- Feng, P., Meng, X., & Zhang, H. (2015). Mechanical behavior of FRP sheets reinforced 3D elements printed with cementitious materials. *Composite Structures*, 134, 331–342. https:// doi.org/10.1016/j.compstruct.2015.08.079
- Geneidy, O., Kumarji, S., Dubor, A., & Sollazzo, A. (2020). Simultaneous reinforcement of concrete while 3D printing. *RILEM Bookseries*, 895–905. https:// doi.org/10.1007/978-3-030-49916-7_87
- Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F., & Buchli, J. (2017). Mobile robotic fabrication at 1:1 scale: The in situ fabricator. *Construction Robotics*, 1(1-4), 3–14. https://doi.org/10.1007/s41693-017-0003-5
- Hack, N., Dörfler, K., Walzer, A. N., Wangler, T., Mata-Falcón, J., Kumar, N., Buchli, J., Kaufmann, W., Flatt, R. J., Gramazio, F., & Kohler, M. (2020). Structural stay-in-place formwork for robotic in situ fabrication of non-standard concrete structures: A real scale architectural demonstrator. *Automation in Construction*, *115*, 103197. https://doi.org/10.1016/j.autcon.2020.103197
- Hack, N., Wangler, T., Mata-Falcón, J., Dörfler, K., Kumar, N., Walzer, A., Graser, K., Reiter, L., Richner, H., Buchli, J., Kaufmann, W., Flatt, R., Gramazio, F., & Kohler, M. (2017). *Mesh Mould: An on site, robotically fabricated, functional formwork: Semantic scholar.* undefined. Retrieved September 27, 2021, from https://www.semanticscholar.org/paper/Mesh-Mould%3A-An-On-Site%2C-Robotically-Fabricated% 2C-Hack-Wangler/e33d6ec963485e83544b50dcd56439ba32d1e6a7.
- Hager, I., Golonka, A., & Putanowicz, R. (2016). 3D printing of buildings and building components as the future of sustainable construction? *Procedia Engineering*, 151, 292–299. https:// doi.org/10.1016/j.proeng.2016.07.357
- Kidwell, J. (2017). *Best practices and applications of 3D printing in the construction industry*. DigitalCommons@CalPoly. Retrieved September 27, 2021, from https://digitalcommons.calpoly.edu/cmsp/79/.
- Kreiger, E. L., Kreiger, M. A., & Case, M. P. (2019). Development of the construction processes for reinforced additively constructed concrete. *Additive Manufacturing*, 28, 39–49. https:// doi.org/10.1016/j.addma.2019.02.015

- Li, Z., Hojati, M., Wu, Z., Piasente, J., Ashrafi, N., Duarte, J. P., ... & Radlińska, A. (2020). Fresh and hardened properties of extrusion-based 3D-printed cementitious materials: a review. Sustainability, 12(14), 5628.
- López, M. V., Carmen Sanz Contreras, M., & Ramon Osanz Díaz, J. (2017). 3D printing in Presentation Architecture Projects. *Putting Tradition into Practice: Heritage, Place and Design*, 636–644. https://doi.org/10.1007/978-3-319-57937-5 66
- Mechtcherine, V., Grafe, J., Nerella, V. N., Spaniol, E., Hertel, M., & Füssel, U. (2018). 3Dprinted steel reinforcement for digital concrete construction – manufacture, mechanical properties and bond behaviour. *Construction and Building Materials*, 179, 125–137. https://doi.org/10.1016/ j.conbuildmat.2018.05.202
- Mueller, S., Mohr, T., Guenther, K., Frohnhofen, J., & Baudisch, P. (2014). faBrickation: Fast 3D Printing of Functional Objects by Integrating Construction Kit Building Blocks. CHI '14 Extended Abstracts on Human Factors in Computing Systems. https://doi.org/10.1145/2559206.2582209
- Méndez Echenagucia, T., Pigram, D., Liew, A., Van Mele, T., & Block, P. (2019). A cable-net and fabric formwork system for the construction of concrete shells: Design, fabrication and construction of a full scale prototype. *Structures*, 18, 72–82. https://doi.org/10.1016/j.istruc.2018.10.004
- Nadarajah, N. (2017). Development of concrete 3D printing (thesis).
- Pan, Y., Zhang, Y., Zhang, D., & Song, Y. (2021). 3D printing in construction: State of the art and applications. *The International Journal of Advanced Manufacturing Technology*. https:// doi.org/10.1007/s00170-021-07213-0
- Peri. (2021, September 16). *Peri Group*. PERI Group Formwork, Scaffolding, Engineering. Retrieved September 27, 2021, from https://www.peri.com/en.
- Poullain, P., Paquet, E., Garnier, S., & Furet, B. (2018). On site deployment of 3D printing for the building construction – the case of YHNOVATM. *MATEC Web of Conferences*, 163, 01001. https://doi.org/10.1051/matecconf/201816301001
- Rajan, A., Akre, V., Nassiri, N., AlAli, A. H., & Sabt, Z. B. (2018). 3D printing of buildings in UAE: Success and failure factors. 2018 Fifth HCT Information Technology Trends (ITT). https:// doi.org/10.1109/ctit.2018.8649541
- Richner, P., Heer, P., Largo, R., Marchesi, E., & Zimmermann, M. (2018). Nest a platform for the acceleration of innovation in buildings. *Informes De La Construcción*, 69(548), 222. https://doi.org/10.3989/id.55380
- Salet, T. A., Ahmed, Z. Y., Bos, F. P., & Laagland, H. L. (2018). Design of a 3D printed concrete bridge by testing. *Virtual and Physical Prototyping*, 13(3), 222–236. https:// doi.org/10.1080/17452759.2018.1476064
- Slager, G. J. (2017). *Influence of the interface between layers on the tensile properties of 3D printed concrete* (thesis).
- Ur Rehman, A., & Sglavo, V. M. (2020). 3D printing of geopolymer-based concrete for building applications. *Rapid Prototyping Journal*, 26(10), 1783–1788. https://doi.org/10.1108/ rpj-09-2019-0244
- Veenendaal, D., Bakkera, J., & Block, P. (2015, January 1). *structural design of the cable-net and fabric formed , ferrocement sandwich shell roof of Nest Hilo*. [PDF] Structural design of the cable-net and fabric formed , ferrocement sandwich shell roof of NEST HiLo | Semantic Scholar. Retrieved September 27, 2021, from

https://www.semanticscholar.org/paper/Structural-design-of-the-cable-net-and-fabric-%2C-of-Veenendaal-BAKKERa/b0d3d4ad8474261dce5434f8f77baa404a67f780.

WASP. (2020, April 30). Retrieved September 27, 2021, from https://www.3dwasp.com/en/.

- WinSun. (n.d.). Retrieved September 27, 2021, from http://www.winsun3d.com/.
- Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, 68, 21–31. https:// doi.org/10.1016/j.autcon.2016.04.005
- Wu, Z., Memari, A. M., & Duarte, J. P. (2022). State of the Art Review of Reinforcement Strategies and Technologies for 3D Printing of Concrete. Energies, 15(1), 360.

Review of Mechanical and Structural Testing for 3D Printed Concrete

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1. Introduction

Additive Manufacturing has been applied in building construction field in recent years, but for such application, it is generally known as 3D Concrete Printing (3DCP). The 3DCP involves an extensive robotic system with a printing nozzle programmed to move along a designed toolpath while extruding concrete material by layers to form 3D structures. According to the latest report from Grand View Research, Inc. (grandviewresearch.com), the global 3D printing construction market is predicted to have an annual growth rate of 91.5% from 2021 to 2028. The main reason for this rapid growth is that the 3DCP is seen as a way to achieve "green" construction by reducing the amount of used concrete material, thereby lowering the cost and environmental damage. In the structural design process, the design strength should be larger than or equal to the required strength for each structural member with selected load combinations. For conventional cast concrete components, nominal strength can be calculated based on the reinforced concrete standard design requirements. as embodied in ACI 318 (ACI Committee 318 1999). For printed concrete, however, some of the standard tests and reinforced concrete design provisions may not be suitable to apply due to the different manufacturing processes used in printed and cast concrete. The acceptance criteria for 3D printed houses are currently under development (e.g., AC509, the first regulatory document on 3D printed residential houses). The equations for calculating the nominal strengths of printed concrete components should be calibrated using full-scale test results. Therefore, determining whether the conventional experimental procedures for cast concrete can still be used in testing the properties of printed concrete is crucial for the development of the 3DCP. This paper reviews some of the available literature related to various tests on printed concrete and summarizes some of the potential changes in the testing procedures that will be required for 3D printing concrete. One main category of tests considered includes safety-related tests for material properties of printed concrete and mechanical properties of printed components. Another category of tests includes tests for thermal resistance and shrinkage properties. Moreover, the results of the tests on printed concrete components are also discussed toward a better understanding of their behaviors and capacities under selected loading conditions.

2. Tests for hardened properties of printed concrete

The material properties of printed concrete, including density, elastic modulus, compressive strength, tensile strength, and interlayer bond strength, have been significantly studied in the literature as it is fundamental for a safe structural design. The standard testing procedures for concrete density are specified in ASTM C138 (Standard Test Method for Density, Yield, and Air Content of Concrete), which weighs a specific volume of a cylindrical vessel filled with compacted cast concrete and calculates the density by dividing the weight by volume. This testing method can be used to measure the density of printed concrete by filling the same type

of container with printed concrete without compaction and weighing it, but depending on the rheological properties of concrete, voids may exist at the bottom of the container resulting in errors. Another method to determine the density of printed concrete was reported in Le et al. (2012), which measures the void content of concrete by using software to analyze the scanned image of the cross-section of cut concrete specimens. The authors showed that the voids measured for a high-quality printed concrete specimen with sand aggregate (1%) are much less than that for a tested cast concrete specimen (3.8%). Although the typical air content of the non-air entrained cast concrete (1-2%) may be smaller than the tested results (3.8%), the study still reveals that high-quality printed concrete can achieve or even exceed the density of cast concrete, which according to the authors may be caused by the gentle vibration of concrete container and the small pump pressure from the hose.

The standard testing procedures for the elastic modulus of concrete can be found in ASTM C469 (Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression), which applies a compression load on a cast concrete cylinder and measures the strain through attached Linear Variable Differential Transformers (LVDTs) while loading. The stress vs. strain curve resulting from the test is used to calculate the elastic modulus. The same process has been applied to printed concrete in cubic specimens by Zahabizadeh et al. (2021). The elastic modulus value was calculated by dividing the stress acting on the cubic specimen by the vertical strain averaged from the four LVDTs (**Fig. 1a**). A reduction of 1-8% for the elastic modulus compared to cast concrete was reported for printed concrete specimens.





The compressive strength test for cast concrete consists of loading the cylindrical specimen in the testing machine and recording the maximum load for calculation of the compressive strength according to ASTM C39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). The same testing process for cast concrete has been applied in cubic printed concrete specimens with different load directions by Le et al. (2012). In the schematic diagram shown in Fig. 1b, the filaments in the printed beam segments run in the Y direction. The load is applied on the sides in directions 1 and 2, and on the cross-section surface of the beam in direction 3. It should be noted that due to different interface bond strengths between horizontal filaments (without gravity load) and vertical filaments (with gravity load), load direction 1 and 2 are characterized separately. The authors reported that the compressive strength is similar for 100 mm printed cubic specimens loaded in three directions (Fig. 1b) (with 11% variation). The compressive strength of printed concrete is 15% less than that of cast concrete specimens in the scenario of load direction 2, which is the maximum reduction among all load direction cases. However, this difference in compressive strength was much higher in the research conducted by different authors, Joh et al. (2020), who reported 68% strength reduction by performing the compressive strength tests on the cast and printed cubic specimens (the maximum reduction reported being in load direction 1). Unlike the results reported by Le et al.

(2012) (that there was no significant difference in compressive strength for loading in directions 1, 2, and 3), the variation of the compressive strength for printed concrete in different loading directions (load direction 1 and 3) reported by Joh et al. (2020) is 24%. Although the maximum compressive strength was obtained from testing in load direction 3 in both studies, which is parallel to the filament direction, these highly scattered results may be attributed to the difference in mixture designs, printing qualities, and printing parameters such as the interlayer time interval, which are not specified in the standard testing procedures for cast concrete.

Three methods are commonly applied to determine the tensile strength of concrete, flexural strength test, splitting tensile test, and direct tension test (Fig. 2a). The standard procedures for flexural strength testing and splitting tensile testing are specified in ASTM C78 (Standard Test Method for Flexural Strength of Concrete) and C496 (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens), respectively. However, no ASTM standard is available for direct tension testing on a concrete block due to difficulties in applying uniaxial stress evenly (Kim and Reda Taha 2014). In the case of printed concrete, the tensile strength is highly dependent on the direction, as the bond at the interface between filaments is prone to tensile stresses. The standard flexural strength test and splitting tensile test have been applied in printed concrete for achieving tensile strength, whereas the direct tension test was commonly used to determine the interface bond strength when the tension load is applied at the interface between layers. Le et al. (2012) showed that the flexural strength of beam specimens from high to low was in direction 1, 2, and 3 (Fig. 2b) when they were subjected to a 4-point bending load. The critical stress occurs at the bottom center of the beam specimens, where is the interface between filaments for the case of load direction 3, resulting in the lowest flexural capacity. For load direction 1 and 2, the flexural strengths (13-16 MPa) are notably higher than those for cast concrete (11 MPa). Joh et al. (2020) applied the splitting tensile test in the printed cubic specimens. The maximum tensile strength was reported in load direction 1, which creates tension in the filament direction. The above findings from both studies are also aligned with the results from Paul et al. (2018), who reported that the tensile strength is higher in the direction that is parallel to the filament direction rather than perpendicular.





As a critical characteristic of the printing process, the interface bond strength between filaments may result in localized stress concentration and develop into a weak point in printed concrete elements. Numerous studies have explored the characteristics of interface bond strength and its

influencing factors. Le et al. (2012) tested the bond strength of printed cylinder specimens by using the direct tension test, which applies tension load perpendicular to the printing plane on the top and bottom faces of the cylinders (Fig. 3a). Results indicated that the bond failure was not detected for a 15 min interlayer time interval, which is defined by the time taken by the nozzle to come back to the exact location of the sublayer, but it happened at 30 min. Wolfs et al. (2019) reported that the filament direction does not play an essential role in the strengths of printed specimens in the flexural strength test, splitting tensile test, and compression test with 15 s of time interval (the maximum difference is 14% for the flexural tension test). This indicates that the bond strength at the interface between vertical filaments and between horizontal filaments are similar if the interval time is short enough (e.g., 15 s), resulting in isotropic behavior of printed concrete members. The difference becomes more noticeable if the time interval increases. The authors also studied the effects of nozzle height (8, 9.5, and 11 mm) and surface dehydration (covered and uncovered) on bond strength. The results found that covering the extruded layers during the interval time effectively increases the bond strength between layers, while nozzle height is not relevant to the bond strength if the interval time is sufficiently short (e.g., 15 s). Panda (Panda et al. 2018; Tay et al. 2018) tested the interface bond strength between two filaments with varied time intervals using the direct tensile test for concrete surfaces (ASTM C1583) by applying tension load on the top and bottom surfaces of the top and the base filaments (Fig. 3b) after 28 days of setting. Results showed a significant decrease in bond strength (more than 50%) from 1 to 10 min of time interval. In an on-site construction of a 3D printed house, the interlayer time interval depends on the size of the printed structure. Kreiger et al. (2019) reported that the print linear speed ranging from 400 to 600 in/min was used in an on-site 3DCP project for a typical CMU Army Barracks Hut with a footprint of 16 ft x 32 ft. The one filament thick wall formwork was printed with a 96 ft travel distance for the printing head per layer, resulting in around 2.3 min for the interlayer time interval. Therefore, for a single-family home-scale printing process, a 15 min interlayer time interval appears to be achievable. However, for the printing of larger home sizes, it is suggested to print the entire structure separately or cover the printed filament during the interlayer time interval to increase the interface bond strength.



Fig. 3. Interface bond strength tests using direct tension load on a) cylindrical specimen (Le et al. 2012) and b) two printed filaments (Panda et al. 2018). c) Interface bond strength test using a compression testing machine (Alchaar and Al-Tamimi 2021).

A novel test set-up for interlayer bond strength of printed concrete has been reported by Alchaar and Al-Tamimi (2021), in which the compression testing machine was used. The test set-up (**Fig. 3c**) consists of two custom steel objects in T-shape and U-shape, which sandwich the printed specimen in the center. The specimen is printed horizontally with three filaments in the vertical direction and loaded at 90-degree turns to make the layer interface vertical. In the test, the specimen is compressed by the convex part of the top T-shaped steel at the inner layer and supported by the bottom U-shaped steel at the two outer layers, such that the compression load transfers to the shear load acting on the interface between filaments. Before the failure, the maximum load was recorded to calculate the bond strength by dividing it by the interface area.

3. Mechanical tests on printed concrete components

Because of the nature of the additive manufacturing process for printed concrete, conventional reinforcement strategies cannot be applied directly without considering the effect of the printing process. Various reinforcement strategies have been proposed in the literature for printed concrete. Because of the uniqueness of these reinforcement concepts, different testing methods have been developed that would be appropriate for evaluating the effectiveness of each reinforcing approach. Among those, continuous reinforcement (steel cable) and discontinuous reinforcement (short fibers) methods are relatively practical and have been explored and tested by several authors, as described subsequently.

The discontinuous reinforcement method adds short steel fibers during the concrete mixing and extrudes the fibers with concrete from the printing nozzle so that the fibers are embedded in the printed filaments. To evaluate the ductile capacity of printed concrete reinforced using steel fibers, Bos et al. (2019) performed Crack Mouth Opening Displacement (CMOD) tests, which is a standard testing method for fiber reinforced concrete (International Federation for Structural Concrete 2013), on printed and cast concrete beams with and without fibers. In these test, simply supported and notched beam specimens were basically subjected to a three-point bending test. The crack mouth opening was recorded using a clip gage, and the CMOD vs. load curves were plotted to achieve the flexural strength of the beam (Fig. 4a). The results from the study showed that the added steel fibers (2.1 VOL%) significantly increase the flexural strength of printed concrete (from 1.14 to 5.96 N/mm² with 423% increase) and cast concrete (from 1.79 to 5.6 N/mm² with 213% increase), and result in similar flexural strength for the reinforced printed and cast concrete beams. The standard four-point bending test according to ASTM C78 (Standard Test Method for Flexural Strength of Concrete) has been applied by Ding et al. (2020) to explore the effect of the ratio of added fibers on the performance of printed beams (Fig. 4b). The maximum load was recorded for calculation of the flexural strength. The results showed that increasing the ratio of fibers, leads to an increase in the flexural strength, while the number of cracks and their spacing also increases. The study also showed that after adding fibers, the crack development was significantly reduced, and a strong strain-softening behavior after peak strength was observed indicating the material transfers from brittle to ductile.



Fig. 4. Bending tests for printed beam specimens with fiber reinforcement: a) CMOD test (Bos et al. 2018) and b) four-point bending test (Ding et al. 2020).

The method of feeding continuous steel cable in the nozzle at the same speed with concrete extrusion to allow the cable to be buried into the printed concrete filament has been applied to reinforce printed concrete in a few cases (Ma et al. 2019; Bos et al. 2020, Li et al. 2020). To test the bond strength between buried steel cable and concrete, the pull-out test as the most common method for evaluating the bond strength of rebars (ASTM C234-91a) has been applied

by Bos et al. (2017). In this test, a displacement-controlled tensile force was applied vertically at the exposed end of the buried cable, trying to pull the cable out of the printed concrete (**Fig. 5**). The concrete specimen was printed horizontally and loaded in 90-degree turns in the Instron universal test rig. The two LVDTs located at the other end of the steel cable recorded the cable slip. The load vs. displacement curve was measured as the outcome of this test. The results showed that the bond strength of a steel cable in printed concrete is similar to that of a smooth rebar and is considerably less than the strength in cast concrete.



Fig. 5. Pull-out test for the bond strength between steel cable and concrete (Bos et al. 2017): a) specimen preparation and b) test set-up.

Beam and wall elements are commonly seen in printed houses. To identify if the printed beam and wall can withstand the required flexural stress and compressive stress, flexural bending and compression tests must be conducted, respectively. Different from the standard testing procedures for cast concrete, the material preparation process and testing steps for printed concrete and the test results are discussed as follows.

A printed beam element with reinforcement was tested under bending load by Gebhard et al. (2021). The beam specimens were printed vertically and laid 90 degrees down with a cavity left throughout the beam. Two longitudinal reinforcement strategies (unfilled post-tensioning reinforcement or grouted passive reinforcement) (**Fig. 6a**) were coupled with two shear reinforcement strategies (continuous steel cable or short fibers manually placed between adjacent layers during printing) (**Fig. 6b**) to reinforce printed beam specimens. The four-point bending test was carried out on the beam, and the displacement was monitored using LVDTs located below the load application points. The results indicated that the grouted passive longitudinal reinforcement coupled with interlayer shear reinforcement is the best combination in all cases, and the continuous steel cable is more efficient at failure than the short fibers.



Fig. 6. a) Two longitudinal reinforcement strategies, b) three shear reinforcement strategies (Gebhard et al. 2021), and c) Uniaxial test for wall specimen (Daungwilailuk et al. 2021).

The printed wall elements have been tested under compression load by Daungwilailuk et al. (2021). The wall specimen featured a flat surface on one side and a 3D diamond pattern on the other side was printed with an interior zig-zag pattern. Two cast beam specimens were attached to the top and bottom of the wall to provide support and load the wall uniformly (**Fig. 6c**). A uniaxial loading machine was used to load the wall with a constant loading rate, and the strain was recorded via the strain gauges and LVDTs attached on both sides of the wall to calculate the compressive strength. The results showed that the compressive strength is higher on the diamond-shaped side, while the spalling on this side during the loading process might be an issue for the building residents. The interior zig-zag pattern was reported to serve as bracing under compressive load, providing buckling resistance.

4. Serviceability tests on printed concrete

The shrinkage cracking is more critical in printed concrete elements as most surfaces are exposed rather than covered by formwork during the curing process (Le et al. 2012). The conventional methods for measuring shrinkage of cast concrete (ASTM C157) cannot be applied to printed concrete because they start the measurement after 24 h when most shrinkage is already taking place in printed concrete. A novel method for testing the shrinkage of printed concrete has been proposed by Federowicz et al. (2020) with the advantage of contactless measurement for the first 24 h. After printing, the small steel reference point was attached to the end of the filament (**Fig. 7**). The laser measurement sensors traced the reflected light from the steel point to plot the movement vs. time curve as the filament shrinks. The results showed that the printed concrete shrinks around ³/₄ of the total shrinkage in the first 24 h, emphasizing the need to measure the shrinkage on the first day after printing.



Fig. 7. Test set-up for measuring shrinkage of printed concrete immediately after printing (Federowicz et al. 2020).





Understanding the mechanical behavior of printed concrete at high temperatures is crucial as it is relevant to the fire resistance of printed concrete houses. The standard method for testing fire resistance of cast concrete follows procedures from ASTM E119 (Standard Test Methods for Fire Tests of Building Construction and Materials), in which the cast concrete floor is directly

exposed to fire. For a smaller testing scale, Cicione et al. (2021) exposed a printed square specimen with one-layer thickness and multi-layer height to direct radiation from the radiant panels until the thermocouples, which were buried in the middle of the specimen during the printing, reached 300°C (**Fig. 8**). The temperature vs. time curve was recorded as the outcome of this test. The study showed a similar behavior of printed concrete and cast concrete under high temperatures with no spalling happening during the test.

5. Summary and conclusions

As mentioned earlier, the standardizing of 3DCP requires tremendous experimental data support to calibrate the analytical formulations. This paper serves as an initial step to summarize the adaptability of various standard tests for cast concrete in printed concrete and presents possibilities for using new testing methods on printed concrete proposed in the literature. The mentioned tests include hardened material properties tests, mechanical properties tests, and serviceability tests. The literature review clearly showed that the material properties of printed concrete are highly dependent on the printing parameters, such as the interlayer time interval and layer orientations. Such parameters should be unified in future testing standards to achieve replicable results. The unique feature of printed concrete, interlayer bond strength, can be tested using the direct tension test or a novel test using a compression testing machine. For the mechanical tests on printed components, standard testing procedures generally match well with printed concrete. The load direction should be given thoughtful attention to reflect the loading condition in real cases because of the anisotropic property of printed concrete. For serviceability tests, the evaluation of the shrinkage of printed concrete. The standard fire resistance test is also suitable for printed concrete.

The test results for the properties and behaviors of printed concrete relative to conventional cast concrete are summarized below in bullet points to provide a clearer understanding of the structural performance of 3D printed concrete structures:

- The density of the printed concrete is highly dependent on printing quality. Well-printed concrete can achieve or even exceed the density of cast concrete.
- The compressive and tensile strengths of printed concrete is directionally dependent due to the anisotropic property, in contrast to cast concrete that is an isotropic material, while the maximum strength is expected to be observed when loaded in the filament direction.
- As a unique feature of printed concrete compared to cast concrete, the interlayer time interval was found to have a strong relation to the interface bond strength. For laboratory-scale printing, a time interval of 15 s is desired to achieve an isotropic property. For on-site industrial printing, a time interval of 15 min is desired to prevent the bond failure from happening and is achievable in a single-family home-scale printing.
- Steel cable or fiber reinforcement is not enough to reinforce printed members on their own. A combination of different reinforcement strategies, which will function as longitudinal and shear reinforcement in cast concrete, seems more effective for printed concrete.
- An interior zig-zag pattern is effective in resisting bulking under compression load.
- The shrinkage is more severe in printed concrete due to the large, exposed surface area after printing. But this should not be an issue if printed concrete is properly cured.
- Similar fire resistance is expected to be observed in printed concrete and in cast concrete.

References

- ACI Committee 318. (1999). Building code requirements for structural concrete: (ACI 318-99) ; and commentary (ACI 318R-99). Farmington Hills, Mich: American Concrete Institute.
- ASTM C138 / C138M-17a. (2017). Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C469 / C469M-14. (2014). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C39 / C39M-21. (2021). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C78 / C78M-21. (2021). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C496-96. (1996). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C1583 / C1583M-20. (2020). Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method), ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C234-91a. (1991). Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel (Withdrawn 2000), ASTM International, West Conshohocken, PA, www.astm.org
- ASTM C157 / C157M-17. (2017). Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, ASTM International, West Conshohocken, PA, www.astm.org
- ASTM E119-20. (2020). Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, www.astm.org
- Alchaar, A. S., & Al-Tamimi, A. K. (2021). Mechanical properties of 3D printed concrete in hot temperatures. Construction and Building Materials, 266, 120991.
- Baz, B., Aouad, G., Kleib, J., Bulteel, D., & Remond, S. (2021). Durability assessment and microstructural analysis of 3D printed concrete exposed to sulfuric acid environments. Construction and Building Materials, 290, 123220.
- Bos, F. P., Ahmed, Z. Y., Jutinov, E. R., & Salet, T. A. (2017). Experimental exploration of metal cable as reinforcement in 3D printed concrete. Materials, 10(11), 1314.
- Bos, F. P., Bosco, E., & Salet, T. A. M. (2019). Ductility of 3D printed concrete reinforced with short straight steel fibers. Virtual and Physical Prototyping, 14(2), 160-174.
- Bos, F., Dezaire, S., Ahmed, Z., Hoekstra, A., & Salet, T. (2020, July). Bond of reinforcement cable in 3D printed concrete. In RILEM International Conference on Concrete and Digital Fabrication (pp. 584-600). Springer, Cham.
- Cicione, A., Kruger, J., Walls, R. S., & Van Zijl, G. (2021). An experimental study of the behavior of 3D printed concrete at elevated temperatures. Fire Safety Journal, 120, 103075.
- Daungwilailuk, T., Pheinsusom, P., & Pansuk, W. (2021). Uniaxial load testing of large-scale 3D-printed concrete wall and finite-element model analysis. Construction and Building Materials, 275, 122039.
- Ding, T., Xiao, J., Zou, S., & Wang, Y. (2020). Hardened properties of layered 3D printed concrete with recycled sand. Cement and Concrete Composites, 113, 103724.
- Ding, T., Xiao, J., Zou, S., & Zhou, X. (2020). Anisotropic behavior in bending of 3D printed concrete reinforced with fibers. Composite Structures, 254, 112808.
- Esposito, L., Menna, C., Asprone, D., Rossino, C., & Marchi, M. (2020, July). An Experimental Testing Procedure to Assess the Buildability Performance of 3D Printed Concrete Elements. In RILEM International Conference on Concrete and Digital Fabrication (pp. 235-245). Springer, Cham.
- Federowicz, K., Kaszyńska, M., Zieliński, A., & Hoffmann, M. (2020). Effect of curing methods on shrinkage development in 3D-printed concrete. Materials, 13(11), 2590.
- Gebhard, L., Mata-Falcón, J., Anton, A., Dillenburger, B., & Kaufmann, W. (2021). Structural behaviour of 3D printed concrete beams with various reinforcement strategies. Engineering Structures, 240, 112380.
- Grand View Research. (2021). Virtual reality market share & trends report, 2021-2028. Virtual Reality Market Share & Trends Report, 2021-2028. Retrieved October 24, 2021, from https://www.grandviewresearch.com/industry-analysis/virtual-reality-vr-market.

- Hou, S., Duan, Z., Xiao, J., & Ye, J. (2020). A review of 3D printed concrete: Performance requirements, testing measurements and mix design. Construction and Building Materials, 121745.
- International Federation for Structural Concrete (FIB) model code for Concrete Structures 2010. Issuu. (2013, October 30). Retrieved October 27, 2021, from
 - https://issuu.com/ernstundsohn/docs/probeseiten_978-3-433-03061-5_inter.
- Joh, C., Lee, J., Park, J., & Yang, I. H. (2020). Buildability and Mechanical Properties of 3D Printed Concrete. Materials, 13(21), 4919.
- Kim, J. J., & Reda Taha, M. (2014). Experimental and numerical evaluation of direct tension test for cylindrical concrete specimens. Advances in Civil Engineering, 2014, 1–8. https://doi.org/10.1155/2014/156926
- Kreiger, E. L., Kreiger, M. A., & Case, M. P. (2019). Development of the construction processes for reinforced additively constructed concrete. Additive Manufacturing, 28, 39-49.
- Kruger, J., Cicione, A., Bester, F., van den Heever, M., Cho, S., Walls, R., & van Zijl, G. (2020, July). Facilitating ductile failure of 3D printed concrete elements in fire. In RILEM International Conference on Concrete and Digital Fabrication (pp. 449-458). Springer, Cham.
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Law, R., Gibb, A. G., & Thorpe, T. (2012). Hardened properties of high-performance printing concrete. Cement and Concrete Research, 42(3), 558-566.
- Li, Z., Wang, L., Ma, G., Sanjayan, J., & Feng, D. (2020). Strength and ductility enhancement of 3D printing structure reinforced by embedding continuous micro-cables. Construction and Building Materials, 264, 120196.
- Li, Z., Hojati, M., Wu, Z., Piasente, J., Ashrafi, N., Duarte, J. P., ... & Radlińska, A. (2020). Fresh and hardened properties of extrusion-based 3D-printed cementitious materials: a review. Sustainability, 12(14), 5628.
- Liu, C., Yue, S., Zhou, C., Sun, H., Deng, S., Gao, F., & Tan, Y. (2021). Anisotropic mechanical properties of extrusion-based 3D printed layered concrete. Journal of Materials Science, 56(30), 16851-16864.
- Ma, G., Li, Z., Wang, L., & Bai, G. (2019). Micro-cable reinforced geopolymer composite for extrusionbased 3D printing. Materials Letters, 235, 144-147.
- Moelich, G. M., Kruger, J., & Combrinck, R. (2020). Plastic shrinkage cracking in 3D printed concrete. Composites Part B: Engineering, 200, 108313.
- Panda, B., Paul, S. C., Mohamed, N. A. N., Tay, Y. W. D., & Tan, M. J. (2018). Measurement of tensile bond strength of 3D printed geopolymer mortar. Measurement, 113, 108-116.
- Panda, B., Noor Mohamed, N. A., Paul, S. C., Bhagath Singh, G. V. P., Tan, M. J., & Šavija, B. (2019). The effect of material fresh properties and process parameters on buildability and interlayer adhesion of 3D printed concrete. Materials, 12(13), 2149.
- Paul, S.C., et al.,2018. Fresh and hardened properties of 3Dprintable cementitious materials for building and construction. Archives of Civil and Mechanical Engineering, 18 (1),311–319. (13) (PDF) Time gap effect on bond strength of 3D-printed concrete. Available from: https://www.researchgate.net/publication/326508588_Time_gap_effect_on_bond_strength_of_3Dprinted concrete [accessed Oct 15 2021].
- Sanjayan, J. G., Nematollahi, B., Xia, M., & Marchment, T. (2018). Effect of surface moisture on interlayer strength of 3D printed concrete. Construction and Building Materials, 172, 468-475.
- Sun, J., Xiao, J., Li, Z., & Feng, X. (2021). Experimental study on the thermal performance of a 3D printed concrete prototype building. Energy and Buildings, 241, 110965.
- Tay, Y. W. D., Ting, G. H. A., Qian, Y., Panda, B., He, L., & Tan, M. J. (2019). Time gap effect on bond strength of 3D-printed concrete. Virtual and Physical Prototyping, 14(1), 104-113.
- Wolfs, R. J. M., Bos, F. P., & Salet, T. A. M. (2019). Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. Cement and Concrete Research, 119, 132-140.
- Wu, Z., Memari, A. M., & Duarte, J. P. (2022). State of the Art Review of Reinforcement Strategies and Technologies for 3D Printing of Concrete. Energies, 15(1), 360.
- Zahabizadeh, B., Pereira, J., Gonçalves, C., Pereira, E. N., & Cunha, V. M. (2021). Influence of the printing direction and age on the mechanical properties of 3D printed concrete. Materials and Structures, 54(2), 1-22.
- Zareiyan, B., & Khoshnevis, B. (2017). Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete. Automation in Construction, 83, 212-221.

On the Use of Plastic Waste in Building Construction Industry

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ABSTRACT

The accumulation of waste plastics in landfills and the natural environment has been an issue of ongoing concerns. However, robust and widely available global information regarding the amount of plastic waste sent to landfills and recycling facilities is still vague in describing a complete and accurate picture. Environmental and testing data indicate and establish that plastics do not decompose, and therefore they pose an environmental hazard, even if they are buried in landfills. Examples are also plentiful where in some societies trash is disposed of in rivers, and as a result, plastics end up in oceans harming marine life. It is therefore important to find ways to recycle plastics. Waste plastics can be used in the construction industry in ways that are environmentally friendly, such as a focus on recycling and processing waste plastics into raw materials used in the production of building materials. This paper reviews methods that can be beneficial when using plastic waste in making concrete for home and other building construction. The effect of using such recycled material in concrete leads to a reduction of embodied energy as it relates to aggregates. Concrete properties can also be improved from using such plastics in the mixture; examples include more flexibility within the elastic range, reduction of shrinkage cracks, increase in tensile strength if plastic fibers are used, better thermal resistance, and moisture penetration resistance. Plastic waste recycling can provide opportunities to address barriers and issues with plastic waste accumulation and to achieve resource and energy sustainability in concrete materials.

INTRODUCTION

Waste materials pose some of the most pressing environmental problems that need to be addressed by recycling and reusing if they cannot be safely disposed of. One opportunity for recycling and reusing waste materials is in the construction industry. The sources of such materials can be curbside waste and construction and demolition (C&D) and construction waste, where in general materials such as glass, plastic, steel, metals, and paper can be collected. A study by Funch et al. (2021) proposed a novel method for detecting consumer waste sorting quality during waste collection. The study aims to provide decision support for waste management systems and explains the difference between such sources. Governments worldwide have generally struggled for many years to reduce plastic waste. For example, the U.S. waste industry manages several different waste types, including municipal solid waste, industrial waste, and hazardous waste. However, statistics show that the U.S. is the world's largest generator of plastic waste (Castaldi et al, 2018) with average American generating roughly 130 kilograms of plastic waste per year. The use of waste plastic especially in the production of concrete and cement-sand mortar as a partial replacement of natural (fine or coarse) aggregate is beneficial, not only for minimizing the waste plastic footprint, but also for preserving the natural resources. Wastes from different sources such as C&D and/or household curbside waste may have different types of plastics. Therefore, it is important to identify the types that may be more useful for concrete application, whereas other types may be more appropriate for other products such as synthetic wood. C&D waste is one the largest sources in waste stream portfolios. Among others, it includes bricks, concrete, plasterboard, asphalt, metals, timber, glass, plastics, and cardboards (Wu et al., 2020). Several studies have been conducted to evaluate the properties of cement composites containing various types of plastic waste as aggregate or filler (Eskander et al, 2021). Most types of plastic products are produced from chemicals derived from oil, natural gas, and coal, which are considered non-renewable resources (Mishra and Mohanty, 2020). Accumulation of plastic waste in the natural environment can create inevitable setback on developments aimed at mitigating the impact on the environment. For example, the use of plastic waste has been considered not only in concrete manufacturing but also in road construction.

Combrinck et al. (2021) report that the use of plastic waste in concrete improves the mechanical and durability properties of concrete. More specifically, the study aims at investigating the effect of adding plastic waste as aggregate on compression and tensile strengths of concrete. Accordingly, two replacement contents were investigated: 15% and 30%, replacing fine aggregate by volume. The significance of the study is to show that these waste materials can be used as a partial replacement for natural aggregates in concrete without negatively affecting the fresh and hardened properties of concrete. Construction materials account for 50%–80% of the total value of construction and in the building sector, these materials are the source of a large number of natural resources and energy consumption.

Making concrete more sustainable is a major goal for the construction industry. However, to realize the barriers of replacing aggregates with plastics in concrete, it is helpful to understand the influence of waste plastic materials on the properties of concrete. Although using larger percentages of plastics can decrease the strength of concrete and increase the water absorption rate (Hu and Xu, 2020), such use also has the advantages of yielding a more lightweight, elastic, moisture-resistant, and shock absorbing concrete, which makes this material applicable to non-load-bearing structural engineering projects (Siddique et al., 2008). Furthermore, use of plastics can lower the density and the brittleness of concrete. It also helps performance in thermal insulation, waterproof, and noise reduction features (Thomas and Gupta, 2016).

The main objective of this paper is to present an overview of recycling waste plastics for use in building construction, which may require developing new building material mixture designs or reconfiguring the compositions of existing materials to include recycled plastics. The paper presents a literature review of the methods for using plastic waste as partial replacement of natural aggregates in making concrete structures, of their effectiveness to reduce embodied and operational energy, and of properties and mechanical performance in comparison with the conventional concrete structures, in the context of finding sustainable use and practices using recycled plastics.

STATE OF THE ART

The role of concrete in generation of CO₂ in building construction is undeniable. Its production is energy-intensive and emits CO₂ during the manufacturing process. Numerous studies have been conducted to eliminate CO₂ that is generated from the concrete manufacturing process (Peng, Yin, and Song, 2018; Yi et al, 2019). The process of modification of concrete manufacturing and enhancing energy efficiency are important for carbon reduction. By identifying these sources and suggesting workable interventions, it is possible to help decarbonize the concrete industry. Concrete mixtures vary based on ingredients (e.g., cement, sand, aggregates, water, admixtures) and result in different strengths and appearances, and need to satisfy application specific conditions as well as local code requirements. To reduce the environmental impact of concrete, incorporation of plastic waste aggregate can significantly contribute to this objective by providing lightweight concrete without substantially reducing its compressive strength. Because of the need to address sustainable solutions for the production of concrete, it is necessary to consider its manufacturing using ingredients that have lower energy demand for their production and result in lower operational costs.

PROCESSING OF PLASTIC WASTE

The use of plastic waste has been studied for various applications such as energy generation and biochemical production; however, its application in concrete is still at its infancy stage and poses some questions. Identification of environmental aspects related to the use of plastic waste in concrete is an important step toward improving outcomes. Several studies have reported the use of waste plastics in concrete and the production of many consumable products, but there is still significant inconsistency in terms of appropriate methodology to recycle waste plastics and selection of the correct type of waste plastics to be used. The utilization of waste plastics in concrete involves various processes and techniques.

Plastics are used in concrete mainly in two forms, plastic aggregates and plastic fibers. Table 1 shows common types of plastics that are mostly reprocessed including Polyethylene Terephthalate (PET), Low-density polyethylene (LDPE), High-density Polyethylene (HDPE), and Polypropylene (PP). PET is also known as a wrinkle-free fiber. It is mostly used for food and drink packaging purposes due to its strong ability to prevent oxygen from getting in and spoiling the product inside. It also helps to keep the carbon dioxide in carbonated drinks from getting out. Although PET is most likely to be picked up by recycling programs, this type of plastic contains antimony trioxide, which is a chemical added to some flame retardants to make them more effective in plastics. Polyethylenes are the most used family of plastics in the world. The LDPE polymers have significant chain branching including long side chains making it less dense. It is mostly used for bags, plastic wraps, and coatings for paper milk cartons. Although LDPE is considered as a safer plastic option for food and drink use, it is quite difficult to be recycled.

HDPE is commonly used as the grocery bags, opaque milk jugs, and medicine bottles, and it has long virtually unbranched polymer chains which align and pack easily making it dense with highly crystalline form (structurally ordered). It is considered as a safer option for food and drinks use. PP is widely used for hot food containers. Its

strength quality is somewhere between LDPE and HDPE. PP is included in the disposable diaper and sanitary pad liners.

Plastic source	Characteristics	Common use of virgin plastic	Common use for recycled plastic	References
Polyethylene Terephthalate (PET)	Clear hard plastic	Soft drink and mineral water bottles	wrapping, rug fibers, rain coats, and can also be used as aggregate in concrete	Choi et al., 2005
Low density polyethylene (LDPE)	Soft, flexible plastic, milky white,	containers, garbage bags, and rubbish bins	Wrapping industry, plant Packaging, and can also be used as aggregate in concrete	Mohan et al., 2021
High density Polyethylene (HDPE)	Commonly used plastic in white or colored	Puckered shopping bags, milk storage bags (freeze)	detergent bottles, crates, and can also be used as aggregate in concrete	Naik et al., 1996
Polypropylene (PP)	Hard, but flexible plastic	potato crisp bags	Compost bins, curb side recycling crates	López- Buendía et al.,2013

Table 1. Types of plastics, characteristics, original use, and potential application of recycled forms as reported in literature.

The diversity of plastics has important implications for their end of life management. Furthermore, there are the issues of hindering in material collection, sorting, and recovery that can differ substantially across plastics. Sustainable material management can contribute to solve these problems. It is based on a systematic understanding of the context that is necessary to use, reuse and recycle materials more productively over their entire life cycles. In the field of plastic waste, recycling and incineration are being designed as appropriate approaches that can either help relieve the landfill capacity or regain some energy from post-consumer plastics waste. However, the plastic recycling process has great benefits and is lower due to its simple mass production. Figure 1 shows the main steps such as collection, separation, manufacturing, and using the process in plastic recycling.



Figure 1. The steps involved in plastic recycling.

The processing of plastic waste can be divided into two major categories such as mechanical and chemical recycling (pyrolysis, gasification, depolymerisation). However, the most common method for the recycling of plastic waste is mechanical recycling. An alternative to mechanical processes is the chemical recycling of plastic that has a high potential for heterogeneous and contaminated plastic waste material if separation is neither economical nor completely technically feasible. Although chemical processing may not be fully relevant to processing recycled plastics for use in concrete, it can be used at different steps of plastic recycling process. It is a method for reducing unwanted wastes and land-filling activity. Sometimes mechanical recycling cannot efficiently remove additives and other impurities from plastics.

Solvent-based purification, depolymerization, feedstock recycling are three reprocessing technologies that are likely to be a way towards a circular economy for plastics, as they can address contamination, mixing, and gradual degradation. Solvent-based purification processes provide a non-chemical, lower-energy pathway to recycle waste plastics. Depolymerization allows the plastic material to be chemically recycled again and broken down into oligomers or monomers through a chemical reaction. Feedstock recycling is one of the alternatives available for recycling plastics that allow them to be turned into valuable chemical building blocks that can then be used in various applications. The economic efficiency of chemical recycling depends on various factors. Chemical recycling could be seen as a supplement to mechanical recycling, but cannot replace it at present.

LITERATURE REVIEW ON USE OF PLASTIC WASTE IN CONCRETE

Concrete has low tensile strength since it is brittle and any tendency for volume expansion leads to cracking, unless reinforcement is used. Incorporation of plastic waste in concrete can be designed to increase the tensile strength and ductility of concrete and improve its mechanical performance for many applications, such as concrete pavement slabs. It can also help to reduce corrosion in reinforced concrete. A study by Saikia and de Brito (2013) highlighted that the incorporation of PET-aggregate in concrete increases the toughness behavior. The results indicate that the splitting tensile and flexural strength of concrete containing any type of PET-aggregate are proportional to the loss in compressive strength of concrete.

A study by Foti (2016) investigated the use of plastic reinforcement (i.e., the use of shredded plastic as fiber reinforced plastic) by using PET waste and carbon fiber reinforced polymer (CFRP), which is composed of linked-chain carbon atoms in a matrix structure of polymer resin. The results from the study showed that they both

limit cracks and reduce corrosion in reinforced concrete structures. This is because they did not use steel. PET can be used to manufacture coarse aggregates and substitute natural aggregates. PET plastic waste as artificial coarse aggregates can also be used to produce lightweight concrete with high heat resistance. Nursyamsi and Zebua (2017) recommended the use of coarse aggregate of PET plastic waste in concreate as an alternative to reduce self-weight on the buildings and highlighted the importance of using PET plastic waste in creating lightweight structural concrete.

Although the performance of concrete with PET particles has demonstrated lower modulus of elasticity and splitting tensile strength (Rahmani et al., 2013), it has been found that the addition of PET particles to concrete would act as crack arresters and would significantly improve certain properties of concrete, like reduced density. Rahmani et al. (2013) investigated the effects of 5%, 10% and 15% substitution of sand with PET processed particles. The results showed that concrete with PET particles has lower modulus of elasticity and splitting tensile strength with respect to conventional concrete. It is important to mention that adding recycled plastic will not increase tensile resistance (i.e., modulus of rupture), but it helps keep controlling the crack width. A study by Silva et al. (2013) stated that the shape of the PET plastic aggregate affects the workability of the concrete. Bottles made of PET can be used as substitutes for sand and fine aggregates in concrete composites. Various volume fractions of sand varying from 2% to 100% can be substituted by the same volume of granulated plastic, and various sizes of PET aggregates can be used (Marzouk et al., 2007).

It can be seen from the above mentioned literature review that the inclusion of waste plastic in concrete as aggregates affects the mechanical properties. However, the rate of strength reduction is not directly related to the percentage replacement of plastic in concrete. Other parameters such as the type of plastic, size, and shape may be the factors contributing the most to the reduced concrete strength.

PERFORMANCE OF CONCRETE WITH WASTE PLASTIC

The use of plastic waste as coarse aggregate has a significant effect on the mechanical properties of structural concrete. Typically, adding plastic to the concrete can enhance structural integrity. Babafemi et al. (2018) reported the effects of recycled waste plastics when used as fine and coarse aggregates, and fibers on fresh properties of concrete, as well as mechanical and durability properties. They showed that the intrinsic non-reactive behavior of plastic aggregates reduces the performance of concrete under both mechanical and durability tests. Increased air content and weak bonding between plastic aggregates and natural aggregates have been explained as the main causes of the reduced performance of recycled waste plastic concrete.

In a study by Abu-Saleem et al (2021) the performance of three types of recycled plastic wastes including PET, HDPE, and PP was compared in the concrete mixture for curb application. The results showed that the use of plastic waste as a partial replacement for natural coarse aggregate up to 20% meets the curb design requirement and the strength loss is not detrimental. The fresh density of concrete is an important parameter for concrete strength. The study furthermore compared the percentage of decrease of fresh density of different concrete mixes to the control mix. It indicated that the fresh density of the recycled plastic concrete mixes showed a decrease in weight as the plastic


aggregate substitution rate increased (Figure 2).

Figure 2. Fresh density reduction of concrete mixes with different types of plastic (adopted from Abu-Saleem et al., 2021).

In order to show how plastics are used in concrete, how it affects the properties of concrete material, how it changes the performance of members made with that kind of concrete, it is useful to review test results, mixture designs, and any variations. For example, ultrasonic pulse velocity (UPV) is a non-destructive test to check the quality and uniformity of concrete. Concrete strength and durability are assessed by measuring the velocity of an ultrasonic pulse through the concrete specimen. The test procedure has been standardized as "Standard Test Method for Pulse Velocity through Concrete" (ASTM C 597, 2016). For example, the UPV performance of concrete specimens at different curing ages with different percentages of PET content can vary greatly (Figure 3). The horizontal axis shows the percentage of recycled plastic (unit weight).

"Green concrete" is defined as a concrete produced by using recycled waste materials such as plastic wastes as at least one of its components (Suhendro 2014). The use of waste plastic materials in the concrete mixture is an innovative concept to produce sustainable green concrete by saving natural resources. Green concrete uses plastic waste replacing sand in concrete and minimizes difficulties of dumping and reduce environmental issues by plastic wastes. In a study by Gravina et al. (2021), the performance of concrete containing post-consumer plastic aggregates was investigated using life cycle assessment (LCA) in order to determine whether green concrete has appropriate engineering properties. Based on the LCA results, it is observed that the developed concrete containing PET and HDPE aggregates can be successfully applied in engineering practice for pavement applications.Green concrete can reduce environmental impact for energy saving, Co2 emissions, and waste water. Further positive effect of green concrete is explaied to be due to using waste products generated by industries in various forms like rice husk ash, micro silica, etc. to make resourcesaving concrete structures. It is cheap to produce because waste materials are used as a



Figure 3. UPV in concrete with different percentages of PET in the mix (Rahmani et al., 2013).

partial substitute for cement and energy consumption in production is lower. With green concrete, it is possible to save natural materials (limestones, shale, clay, natural sand and rocks) for future use. In other words, with waste materials such as plastics as an alternative, it is possible to reduce the environmental problems and protect the naturally available less energy and becomes economical in use.

CONCLUSIONS

The main objective of this study was to show how recycled plastic can be used in construction in general and concrete in particular. Furthermore, this study presented a literature review to determine if the use of waste plastics in concrete construction can help produce environment-friendly green concrete. The current study aimed to review research studies on sustainable concrete, which uses plastic waste as the replacement of fine aggregate. The results highlighted that the use of different types of plastics has a practical outcome in the mortar and concrete mixture properties. The literature also explains how recycled plastics can be used as an alternative to coarse aggregates, which has been an assumption in the literature. The effect of using recycled plastic bags as aggregates in concrete on mechanical has been reviewed. It has been concluded that the bulk density reduces , and the compressive strength will be lower.

The presented study also discussed some of the physical and mechanical properties of concrete containing recycled plastic as a part of its fine aggregates.

Based on these preliminary findings, this study provides an approach to identify research gaps that relate to plastic waste as an aggregate replacement or fiber reinforcement in concrete. Overall, the limited available literature highlights a lack of sufficient research in the longer-term effects of particles of plastic waste on behvior of concrete structures and also lack of literature related to evaluation of fire resistance and acoustics performance of green concretes. All these areas are required to be comprehensively researched in future studies.

References

- Abu-Saleem M., Zhuge Y., Hassanli R., Ellis M., Rahman M., Levett P. (2021).
 "Evaluation of concrete performance with different types of recycled plastic waste for kerb application," *Construction and Building Materials*, Vol. 293.
- ASTM C 597. Standard Test Method for Pulse Velocity through Concrete; American Society for Testing and Materials: West Conshohocken, PA, USA, 2016.
- Babafemi A. J., Šavija B., Paul S. C., and Anggraini V.(2018). "Engineering Properties of Concrete with Waste Recycled Plastic: A Review" *Sustainability*, Vol. 11.
- Castaldi M. J., Tsiamis D. A., Torres M. (2018). "Role of plastics in decoupling municipal solid waste and economic growth in the U.S.," *Waste Management*, Vol. 77, pp. 147-155.
- Combrinck, R., Babafemi, A.J., Fataar, H. and Steyn, Z.C. (2021). "Concrete containing waste recycled glass, plastic and rubber as sand replacement," *Construction and Building Materials*, Vol. 269, pp. 121242.
- Choi Y. W., Moon D.J., Chung J.S., Cho S.K. (2005). "Effects of waste PET bottles aggregate on the properties of concrete," *Cement and Concrete Research*, Vol. 35, pp.ages 776-781.
- Eskander, S. B., Saleh, H. M., Tawfik, M. E. and Bayoumi T. A. (2021). "Towards potential applications of cement-polymer composites based on recycled polystyrene foam wastes on construction fields: Impact of exposure to water ecologies," *Case Studies in Construction Materials*. Vol. 15.
- Foti D. (2016). "Innovative techniques for concrete reinforcement with polymers," *Construction and Building Materials*, Vol. 112, pp. 202-209.
- Funch O.I., Marhaug R., Kohtala S., Steinert M. (2021). "Detecting glass and metal in consumer trash bags during waste collection using convolutional neural networks," *Waste Management*, Vol. 119, pp. 30-38.
- Gravina, Rebecca J., Tianyu Xie, Bree Bennett, and Phillip Visintin. (2021). "HDPE and PET as Aggregate Replacement in Concrete: Life-Cycle Assessment, Material Development and a Case Study." *Journal of Building Engineering* 44 (December): 103329. https://doi.org/10.1016/j.jobe.2021.103329.
- Hu, S. and Xu, Y. (2020). "Preparation, performance test, and microstructure of composite modified reinforced concrete," *Advances in Civil Engineering*, Vol. 2020, pp.1-14.
- López-Buendía A. M., Romero-Sánchez M. D., Climent V., Guillem C. (2013). "Surface treated polypropylene (PP) fibres for reinforced concrete," *Cement* and Concrete Research,
 - Vol. 54, pp. 29-35.
- Marzouk O. Y., Dheilly R.M., Queneudec M. (2007). "Valorization of postconsumer waste plastic in cementitious concrete composites," *Waste Management*, Vol. 27, pp. 310-318.
- Mohan H. T., Whitaker F., Gaskell D., Mohan R., Mini K.M. (2021). "Performance assessment of recycled LDPE with sand fillers," *Materials Today: Proceedings*, Vol. 42, , pp. 1526-1530.

- Mishra R. K., Mohanty K. (2020)." Co-pyrolysis of waste biomass and waste plastics (polystyrene and waste nitrile gloves) into renewable fuel and value-added chemicals," *Carbon Resources Conversion*, Vol.3, pp. 145-155.
- Naik T.R., Singh S.S., Huber C.O., Brodersen B.S. (1996). "Use of post-consumer waste plastics in cement-based composites," *Cement and Concrete Research*, Vol. 26, pp. 1489-1492.
- Nursyamsi, Zebua W. S. B.(2017). "The Influence of Pet Plastic Waste Gradations as Coarse Aggregate Towards Compressive Strength of Light Concrete," *Procedia Engineering*, Vol.171, pp. 614-619,
- Peng, H., Yin J. and Song W. (2018). "Mechanical and Hydraulic Behaviors of Eco-Friendly Pervious Concrete Incorporating Fly Ash and Blast Furnace Slag," *Applied Sciences*, Vol. 8.
- Rahmani E., Dehestani M., Beygi M.H.A., Allahyari H., Nikbin I.M. (2013). "On the mechanical properties of concrete containing waste PET particles, " *Construction and Building Materials*, Vol. 47, pp. 1302-1308.
- Saikia N. and de Brito J. (2013). "Waste Polyethylene Terephthalate as an Aggregate in Concrete," *Materials Research*, Vol. 16, pp. 341-350.
- Siddique, R., Khatib, J. and Kaur, I. (2008). "Use of recycled plastic in concrete: a review," *Waste management*, Vol. 28, pp. 1835–1852.
- Silva R.V., Brito J. de, Saikia N. (2013). "Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates," *Cement and Concrete Composites*, Vol. 35, pp. 23-31.
- Suhendro, Bambang. (2014). "Toward Green Concrete for Better SustainableEnvironment." ProcediaEngineering 95:https://doi.org/10.1016/j.proeng.2014.12.190.305–20.
- Thomas, B. S. and Gupta R. C., (2016). "A comprehensive review on the applications of waste tire rubber in cement concrete," *Renewable and Sustainable Energy Reviews*, Vol. 54, pp. 1323-1333.
- Yi, J., Song W., Wu H., He X., Song Q., Yin J. (2019). "Effect of carbon fiber on mechanical properties and dimensional stability of concrete incorporated with granulated-blast furnace slag," *Journal of Cleaner Production*, Vol. 238, p. 117819.
- Wu H., Zuo J., Yuan H., Zillante G., Wang J. (2020). "Cross-regional mobility of construction and demolition waste in Australia: An exploratory study," *Resources, Conservation and Recycling*, Vol. 156, p.104710.

Multiple benefits through residential building energy retrofit and thermal resilient design

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ABSTRACT

The simulation of thermal resilience of buildings to extreme weather events has been usually separated from that of building energy efficiency technologies. Their interconnections are rarely quantified for residential energy retrofit studies. This study develops a method to assess multiple benefits through residential building energy retrofit and thermal resilient design. In this regard, EnergyPlus and Radiance validated simulation engines are adopted through Ladybug tools in Grasshopper's interface to calculate the heat stress index of wet bulb globe temperature (WBGT) and energy use intensity (EUI) as the performance metrics. A week-long heat wave of July 14-20, 2013 caused killing of four elderly citizens across New York City. We conducted a case study of four residential buildings, including single-family houses, brick mid-rise, high-rise, and all glass high-rise apartments where the blackout (power loss) occurred for the same period. Various retrofitting solutions, including but not limited to improving infiltration, adding insulation to exterior walls and roofs, improving windows (applying low-emissivity (low-e)), and implementing natural ventilation, were considered to improve energy efficiency and reduce heat stress of occupants. A comparison was provided between simulation results for the existing condition of buildings and their improved states after retrofitting. Results show that strategies that may not improve energy efficiency may significantly improve thermal resilience. Findings of this paper indicate the importance of implementing scalable solutions in the sense those that are not contributing to energy saving may be considered because of their impact on resilience to extreme heat events.

KEYWORDS

Building retrofit, Resilience, Extreme heat, WBGT, Energy efficiency

INTRODUCTION

Extreme heat events, or heat waves, are among the top reasons for weather-related deaths in the United States (U.S. Environmental Protection Agency, 2016). Heat waves are expected to become more intense and frequent in the future (Masson-Delmotte et

al., 2018). An increase in the average number of heat waves in the U.S. from two in 1960 to six in 2010 is an example of this trend (U.S. Global Change Research Program, 2020). A 1980 heat wave caused at least 1700 deaths in the U.S. (Jones et al., 1982), while another case of 1995 in Chicago claimed more than 700 lives over five days (Dematte et al., 1998). Although more than 600 Americans die because of extreme heat every year, an analysis of the effects of climate change on extreme temperature in metropolitan areas in the U.S. revealed that number of deaths increases significantly if greenhouse gas (GHG) levels continue to rise over the 21st century (Mills et al., 2015). An indoor space can be thermally resilient if it maintains indoor thermal comfort in the disturbance event. Various types of disruptions (indoor and outdoor) can cause a building's failure to resilience. In addition to heat waves, power outages, air pollution, fire, earthquakes, windstorms, flooding, water shortages, and pandemic are other disruptions that can affect the built environment (Attia et al., 2021). Building thermal zone also represents a hidden danger for occupants because of these events. For instance, heat stress occurs when the human body is unstable to balance excess heat, and body core temperature increases, accordingly. Field data from the Harlem Heat Project shows up to 7-degree higher indoor temperature than those of outdoor in Manhattan, New York City, representing 80% of the New Yorkers' mortality happened indoors (Mills et al., 2015). Therefore, buildings should be able to react to these changes and maintain their performance over time. The built environment sector needs to go beyond the minimum performance requirements of standards to incorporate sustainability and achieve resilience (Roostaie et al., 2019).

Several studies have assessed the resilience performance of building under abnormal conditions. Samuelson et al. (2015) assessed the resilience of apartment design against power failure. They showed that high thermal mass envelope and modestly sized high performance windows could represent the most appropriate design. O'Brien and Bennet (2016) applied passive survivability and thermal autonomy to evaluate the resilience of high-rise residential buildings against power failure during summer and winter in Canada. Sun et al. (2020) conducted a real case study of a nursing home in Florida to investigate how various active and passive energy efficiency measures can boost thermal resilience to decrease heat stress risk for patients. They found that miscellaneous load reduction and natural ventilation are the most effective measures. Although recent studies have addressed the simulation of thermal resilience of buildings to power outages and extreme weather events, resilience quantification has been usually separated from that of building energy efficiency technologies. Most of available studies considered the performance improvement only for the design of buildings (rather than buildings that are in operation phase). Therefore, the interconnections of resilience and energy efficiency improvement are rarely quantified for residential energy retrofit projects.

The objective of this paper is to develop a method to assess multiple benefits through residential building energy retrofit and thermal resilient design. Increasing electricity demand during heat stresses can lead to grid failures and blackouts (Attia et al., 2021), which can directly cause the perception of occupants to be out of thermal comfort range and affect health of vulnerable populations, including elderly citizens (Bono et al., 2004). For this reason, we considered heat waves and power loss as disruption events that can influence indoor thermal comfort. Accordingly, we identified performance

metrics for heat stress quantification (related to indoor thermal comfort) and building energy efficiency assessment. These metrics are applied to various building envelope retrofitting configurations using a simulation-based case study for different residential buildings in New York City. The impact of various solutions is explored. Trade-offs and synergies between building energy retrofitting and thermal resilient design are discussed. Finally, concluding remarks and future research needs are presented at length.

METHODOLOGY

The purpose of this study was to explore how building energy retrofitting scenarios can enhance the thermal resilience of buildings under both extreme heat and power loss conditions. To this aim, we used reference building models introduced by the U.S. Department of Energy (Office of Energy Efficiency and Renewable Energy, 2021) to develop a baseline building model. Then, various retrofit scenarios were considered and simulated to assess their impact on energy efficiency and thermal resilience. Figure 1 shows the workflow of this study. The workflow is scalable, so that a baseline model can be created from building energy audit, and be used for applying retrofitting solutions.



Figure 1. Workflow of the study, with possible future work component.

Data collection, which is important in energy auditing, compromises creating geometry input using scanning techniques (e.g., drone thermography (Mirzabeigi and Razkenari, 2022)). It includes collecting thermal and visual data during building inspection, in addition to using them for reconstructing building geometry for energy simulation. Other important inputs for the model are weather data, internal loads, occupancy information (e.g., physics based or data driven approaches (Mirzabeigi and Razkenari, 2021)) and retrofit history. In the baseline model development, EnergyPlus was used to create and calibrate an energy model with available data or with assumptions. The energy auditing block is set to feed the next two blocks, energy retrofitting and thermal resilience. Energy use intensity (EUI), which is an indicator of energy efficiency and is expressed as kilowatt-hour used per square meter per year (kWh/(m².year)), is estimated in this step. Finally, the impact of disruption event was quantified using the heat stress index of wet bulb globe temperature (WBGT (°C)). WBGT is a screening method for the presence or absence of heat stress, taking into account weighted air temperature, natural wet bulb temperature and black globe temperature, with presence

of direct solar radiation that is comprehensively addressed in (Mirzabeigi et al., 2021). These two blocks had some interactions in the forms of trade-offs and synergies that are assessed and addressed in the results and discussion.

The simulation framework is set up to calculate two performance metrics of WBGT and EUI (considering annual heating, cooling, lighting and electric equipment energy). To account for the effect of direct solar radiation on thermal comfort, the introduced framework by Mirzabeigi et al. (2021) has been implemented with some modifications (in order to integrate with the proposed workflow). In this regard, the EnergyPlus and Radiance validated engines are used through Ladybug tools (Sadeghipour Roudsari and Pak, 2013) in Grasshopper's parametric interface (McNeel, 2010). While different disruptive events can be considered in the simulation framework, this paper considered a fixed duration of power loss and heat wave as disruptive events. In the post-processing phase, the modifications include calculating the heat stress index for the period of interest and EUI for each simulation iteration.

To assess the interactions between retrofitting and thermal resilience, we conducted a case of New York City during a four-day heat wave and blackout of July 17-20, 2013. Actual Meteorological Year (AMY) data, in the form of historical weather data of New York City, for the mentioned period, has been extracted from (Weather Underground, 2021). On the other hand, Typical Meteorological Year (TMY) data is the file created in a way that for each month in the year the data have been chosen from the year that was accounted most typical for that month. LaGuardia TMY3 weather file has been extracted from EnergyPlus Weather Repository. Figure 2 shows a comparison of these two for a 4-day period, where actual data showed higher dry bulb temperature values. These actual data are becoming increasingly important as moving toward energy efficiency goals. The AMY data has been used as weather input for the simulations.

The geometry of building models replicates the residential single-family house, midrise, and high-rise apartments (to have referrable generalized models). We changed the building envelope characteristics to create a wide range of iterations and create a parallel comparison between the reference building envelope to those of retrofitting scenarios adopted from (Leigh et al., 2014), both with the same level of details, for New York City. These scenarios represent four residential buildings, including singlefamily houses, brick mid-rise, high-rise, and all glass high-rise apartments (Figure 2right). In total, we considered 84 scenarios by changing building geometry, envelope materials, infiltration, applying natural ventilation, and altering the location of the manikin inside the room.



Figure 2. Comparison of weather data for a 4-day period (left) and model geometry of test case scenarios (right).

Following a zone sensitivity analysis for the single-family house, a single zone for the first floor can represent an accurate representation rather than two identical North and South zones (Baniassadi and Sailor, 2018). Therefore, one single floor zone (highlighted in bold green in Figure 2) represents the target zone model for the scenario of the single-family house. For the other three scenarios, including brick mid-rise, highrise, and all glass high-rise apartments, two North and South apartments (highlighted in bold colors in Figure 2) for each selected as the target zones for the purpose of model development. Whole opaque wall resistance (m².K/W) for single-family house, midrise, high-rise, and all glass high-rise apartment is 1.40, 0.46, 0.50, and 1.40, respectively. Infiltration (ACH) values with the same order is 2.8, 0.4, 0.6, and 0.6, respectively. For all scenarios, for the transparent elements of the building envelope, the same thermal transmittance value (U-value) of 3.4 W/m².K, Solar Heat Gain Coefficient (SHGC) of 0.7, and visible transmittance (VT) of 0.8 have been considered. In addition, various internal load densities, including equipment (3.9 W/m^2) , lighting (11.9 W/m^2) , and people $(0.03 \text{ people/m}^2)$, were set according to the residential use. The occupancy, equipment, and lighting schedules were obtained accordingly from the default residential schedules of Honeybee plug-in. The range of 20-26 °C was set as the indoor thermal comfort boundary in these simulations.

Various retrofitting solutions have been considered to explore the interactions of building energy retrofitting with thermal resilience in the test case scenarios. These solutions were selected because of their potential impact on reducing the heat stress of occupants and energy efficiency. Table 1 summarizes various retrofit measures in this study. It should be noted that operable window natural ventilation is applied to get free cooling when the outdoor air temperature is below the indoor air temperature. In addition, the minimum outdoor air temperature to naturally ventilate is 20 °C.

Retrofitting scenario	Α		В
	(Improving insulation)		(Improving infiltration)
Test case scenario	Whole opaque wall resistance (m ² K/W)		Infiltration (ACH)
Single-family house	5.28		0.29
Brick mid-rise apartment	3.5		0.05
Brick high-rise apartment	3.5		0.08
All glass high-rise apartment	3.5		0.08
Retrofitting scenario	С	D	Ε
	(Applying	(Implementing	(Whole
	triple glazed	natural	package)
	and low-e)	ventilation)	
All test case scenarios	U = 1.13	$T_{outdoor} < T_{indoor}$	applying all
	W/m ² .K,		retrofitting
	SHGC = 0.5,		scenarios
	VT = 0.5		

Table 1. Summary of building envelope related retrofitting scenarios.

RESULTS AND DISCUSSION

The results from the simulations for a four-day period of heat wave and blackout, which is low probable but high impact event, are presented, as the outcomes of the methodology. Figure 3 shows the impact of various building scenarios on the indoor temperature of existing building condition, considering the duration of disturbance. It shows that by the start of the disturbance event, temperatures started to rise and were placed out of thermal comfort range (highlighted in orange), because of the power failure effect. Although the power failure ended by the last hours of July 21, the building system needed more time to provide the comfort level for the occupant. End of this dynamic state has been shown by a vertical dotted line in the same figure (seven hours after end of disturbance, in this case). This situation was characterized as the dynamic state after the disturbance based on heat wave and blackout effect. Various building scenarios showed different effects on their indoor temperatures. All glass high-rise S reached the extremes in terms of peak temperature series compared to all other scenarios for each day of the blackout. However, single-family house experienced the lowest unhabitable indoor temperatures among all scenarios during the same period.



Figure 3. Comparison of indoor temperatures of buildings' existing condition.

Figure 4 demonstrates the comparison of post-processed WBGT series of existing condition of test case scenarios.



Figure 4. Comparison of WBGT series of buildings' existing condition.

It was segmented into three low, medium, and high risks areas according to the classification provided in (Khalilinasr and Mirzabeigi, 2020). According to this classification, two thresholds due to metabolic rates of 115 W (very low metabolic rate) and 415 W (high metabolic rate) were considered to identify three pre-mentioned areas of risks. Following the BS EN ISO 7243: 2017, these two reference WBGT (as a function of metabolic rate) were calculated as the basis of thresholds. It should be noted that results were represented for a perpendicularly seated manikin in the distance of one meter to the center of the window (to account for an extreme direct solar radiation). WBGT series for various test case scenarios placed over the threshold of medium risks (reference WBGT of 22.99 °C) for the duration of disturbance (high stress).

Figure 5 illustrates the calculated result percentages of activity risks based on WBGT for the near window and center of the room placed manikin for all test case scenarios. A simple comparison among the near window and center option for each test scenario shows that higher (medium and high) risks calculated in the near window is due to the aggregated direct solar radiation (correspondingly the delta mean radiant temperature) on the manikin resulting in a riskier condition. For instance, the near window option of the single-family house showed 15.5% high risks, while this percentage is zero for the center placed manikin of the same scenario. Comparison among the near window option of all test scenarios represented all glass high rise S apartment (51.6% of medium risks and 47.4% of high risks) as the worst scenario among all simulations building types, while the single-family house ranked showed 6.2%, 78.3%, and 15.5% for each of low, medium, high risks correspondingly.



Figure 5. Comparison of percentage of risks based on WBGT for near window and center of the room placed manikin for the buildings' existing condition.

Annual EUI for single-family house, mid-rise S, N, high-rise S, N, all glass high-rise S and N is 94.52, 77.32, 38.21, 88.04, 53.58, 66.71, and 76.38 kWh/(m².year). These values were served as the baseline for energy improvement percentage for applying retrofitting solutions. Although all glass high rise S has been recognized as the least resilient building type, the energy consumption results showed that this option is not characterized as highest energy consumption scenario (66.71 kWh/(m².year)). In this

case, single-family house showed highest energy consumption (94.52 kWh/(m^2 .year)) among all scenarios. Therefore, possible ranking of building scenarios might be very different for resilience and energy efficiency quantification. Figure 6 shows percentage of EUI and high risks + improvement for various retrofitting scenarios. Each percentage has been calculated and compared with the existing building condition. It should be noted that for resilience quantification, only the heat stress area of high risks + has been accounted as the extreme criteria of calculations.



Figure 6. Percentage of EUI and high risks + improvement for retrofit scenarios.

Applying scenario E showed the largest energy saving potential and resilience improvement among all building types. Improving wall insulation, though had a negative effect on high-rise and all glass high-rise scenarios' resilience, improved the resilience for single-family house and mid-rise S minimally. This solution improved the energy performance of various scenarios (from 1.1% to 12.6% for all glass highrise N to high-rise S, respectively). Reducing infiltration presented a negative impact on resilience in the simulated cases, and had positive energy saving potential, among all cases. Applying natural ventilation did not show a significant effect on improving energy efficiency, though had a positive effect on thermal resilience of all building scenarios. Additionally, scenarios C and E were the only solution having positive influence on both building energy improvement and thermal resilience of all scenarios. Therefore, the impact of solutions on resilience varies by building type. Some of scenarios, such as natural ventilation, that significantly boosts thermal resilience may not be yielding very high energy improvement. Others, such as reducing infiltration, improves the energy efficiency but does independently not help a heat resilient design. These should be an important consideration in the energy retrofit process.

CONCLUSION AND FURTHER DEVELOPMENT

In this study, we examined the impact of applying retrofitting solutions on energy efficiency and thermal resilience during a blackout and heat wave period. We focused on four residential building types in New York City. We conducted these case studies using the EnergyPlus and Radiance simulation engines that are adopted through Ladybug tools in Grasshopper's parametric interface. We found that applying a

retrofitting package (improving construction by adding insulation, infiltration, applying triple glazed and low-e, and implementing natural ventilation) was the most effective solution to improve energy efficiency and reduce heat stress of WBGT. Results showed that strategies that may not improve energy efficiency (e.g., natural ventilation) may greatly improve thermal resilience. Another finding was about infiltration improvement that even reduce the annual energy consumption, made it more difficult for occupant in the sense that higher indoor temperature than the outdoor temperature caused higher heat stresses than the baseline condition of the building. These findings encourage energy savings combined with thermal resilience quantification, which is lacking in the current building standards, in designing scalable retrofitting solutions for existing buildings toward reaching energy efficient, resilient and healthy buildings. Further analysis is needed to characterize various retrofitting packages in different climate zones (to assess heat and cold stress conditions) through a decision-making platform with a more holistic resilience quantification framework that takes into consideration the phase, the hazard level, and the exposure time of the disturbance event to assess trade-offs and synergies of thermal resilience and energy performance. The goal of platform could be automatically creating an integrated retrofitting package based on existing information. Other aspects, about the cost of applying retrofitting packages, the construction effort and time needed for each of them, compatibility and effectiveness of scenarios for being combined, are also needed to be considered in an additional study. Furthermore, life cycle analysis may help to represent a more realistic value of retrofitting solutions or packages.

REFERENCES

- Attia, S., Levinson, R., Ndongo, E., Holzer, P., Berk, O., Homaei, S., ... Heiselberg, P. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. Energy & Buildings, 239, 110869.
- Baniassadi, A., & Sailor, D. J. (2018). Synergies and trade-offs between energy effi ciency and resiliency to extreme heat - A case study. Building and Environment, 132(January), 263–272.
- Bono, A. De, Giuliani, G., Kluser, S., & Peduzzi, P. (2004). Impacts of summer 2003 heat wave in Europe.
- Dematte, J. E., O'Mara, K., Buescher, J., Whitney, C. G., Forsythe, S., McNamee, T., ... Ndukwu, I. M. (1998). Near-Fatal Heat Stroke during the 1995 Heat Wave in Chicago. Annals of Internal Medicine, 129(3), 173–181.
- Jones, T. S., Liang, A. P., Kilbourne, E. M., Griffin, M. R., Patriarca, P. A., Wassilak, S. G. F., ... Thacker, S. B. (1982). Morbidity and Mortality Associated With the July 1980 Heat Wave in St Louis and Kansas City, Mo. JAMA, 247(24), 3327–3331.
- Khalilinasr, B., & Mirzabeigi, S. (2020). Solar radiation and human comfort: assessment of the effect of solar radiation on thermal comfort using wet bulb globe temperature as a heat stress index. Politecnico di Milano.
- Leigh, R., Kleinberg, J., Scheib, C., Unger, R., Kienzl, N., Esposito, M., ... Tillou, M. (2014). Leaks and Lives: How Better Building Envelopes Make Blackouts Less Dangerous. 2014 ACEEE Summer Study on Energy Efficiency in Buildings, 156–167.

- McNeel, R. (2010). Grasshopper generative modeling for Rhino. Retrieved from http://www.grasshopper3d.com
- Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., ... Waterfield, T. (2018). Summary for Policymakers. In Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.
- Mills, D., Schwartz, J., Lee, M., Sarofim, M., Jones, R., Lawson, M., ... Deck, L. (2015). Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. Climate Change, 131, 83–95.
- Mirzabeigi, S., Khalili Nasr, B., Mainini, A. G., Blanco Cadena, J. D., & Lobaccaro, G. (2021). Tailored WBGT as a heat stress index to assess the direct solar radiation effect on indoor thermal comfort. Energy & Buildings, 242, 110974.
- Mirzabeigi, S., & Razkenari, M. (2021). Data-driven Building Occupancy Prediction: An educational building case study. ASCE International Conference on Computing in Civil Engineering (I3CE2021). Orlando, Florida, USA.
- Mirzabeigi, S., & Razkenari, M. (2022). Automated Vision-Based Building Inspection using Drone Thermography. CI and CRC Joint Conference 2022. Arlington, Virginia, USA.
- O'Brien, W., & Bennet, I. (2016). Simulation-Based Evaluation of High-Rise Residential Building Thermal Resilience. ASHRAE Transactions, 455–468.
- Office of Energy Efficiency & Renewable Energy. (2021). Residential Prototype Building Models. Retrieved from United States Department of Energy website: https://www.energycodes.gov/prototype-building-models
- Roostaie, S., Nawari, N., & Kibert, C. J. (2019). Sustainability and resilience: A review of definitions, relationships, and their integration into a combined building assessment framework. Building and Environment, 154(March), 132–144.
- Sadeghipour Roudsari, M., & Pak, M. (2013). Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of the 13th International IBPSA. Lyon, France.
- Samuelson, H., Goyal, A., Claussnitzer, S., Romo-castillo, A., Chen, Y., & Bakshi, A. (2015). Toward Pre-Simulated Guidelines for Low-Energy High- Rise Residential Design in Megacities Graduate School of Design 48 Quincy St. SpringSim-SimAUD, 119–127. Alexandria, VA, USA.
- Sun, K., Specian, M., & Hong, T. (2020). Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. Building and Environment, 177(November 2019), 106842.
- US Environmental Protection Agency. (2016). Heat-Related Deaths. Retrieved from https://www.epa.gov/sites/production/files/2016-08/documents/print_heatdeaths-2016.pdf
- US Global Change Research Program. (2020). Our changing planet: The U.S. global change research program for fiscal year 2020.
- Weather Underground. (2021). New York City, NY Weather History. Retrieved from https://www.wunderground.com/history/daily/us/ny/new-yorkcity/KLGA/date/2012-6-6

Towards a New Type of Construction Documents for Affordable Housing in the United Arab Emirates

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ABSTRACT

The United Arab Emirates has housing programs to provide many of its citizens with affordable housing. These are villas that are financed through the government, but that are built through an owner-selected consultant and contractor. In many cases, government agents provide owners with several design models and their construction documents to select from. Because of the small size of the project and the constraints on funds, owners commonly hire small, low-cost contractors who use low-skilled construction workers. Unfortunately, technical supervision by qualified personnel is rare and so the owner typically ends up as the work supervisor. With these conditions, correctly following the provided construction documents becomes a major issue. The documents are too technical for the owner to understand. They are also difficult for many low-skilled construction workers to grasp. The result is a lot of miscommunications, errors, time delays, cost overruns, and disputes. This paper presents on-going research to investigate the possibility of using BIM technology to develop a new type of construction documents for these small-sized villa projects. The purpose is to communicate the construction information in a manner that allows both technical and non-technical personnel to understand what needs to be constructed. The research approach is to challenge the current standards for construction documents and to promote the use of colored, three-dimensional, multimedia-embedded, hyperlinked, and multi-language documents. These documents are not solely divided by the design discipline as is usually the case. Rather, they also have coordinated multi-disciplinary room-by-room views of the constructed villa. These two- and three-dimensional views help owners and low-skilled workers understand any construction task in relation to other tasks. The paper presents the primary stage of the research as it shows the characteristics of the new documents, their proposed structure, and samples of the documents.

INTRODUCTION

In 2020, the United Arab Emirates (UAE) was ranked eleventh in the world in terms of the gross domestic product at purchasing power parity per capita (Knoema Enterprise Data Solutions, 2021). With such economic prosperity, the UAE government is capable and indeed provides its citizens with a variety of support programs including affordable housing (The United Arab Emirates' Government portal, 2021).¹ As per UAE standards, an affordable house is typically a villa with an area in

¹ UAE citizens represent roughly 11.5% of the total country's population (Global Media Insight, 2021).

the range of 200 to 400 m² and with a construction cost in the range of US300,000 to US600,000.² Figure 1 shows a sample design of such housing. The government's support in the construction of these villas depends on various criteria. However, that support is typically provided through subsidized loans, grants, land grants, or a combination of these support mechanisms.

In many parts of the world, buildings of such size and typology are commonly developed in clusters, with a large number of villas constructed simultaneously. The development is typically the work of a private developer who then delivers the completed villas to their owners. When clustered in large numbers, the development of these small buildings becomes attractive to large consulting firms and to large contractors. They will have the necessary resources to design and construct good quality buildings. More experienced designers in the various disciplines are involved and more time is spent in design and coordination as the same design is repeated for a large number of villas. Qualified, experienced, and well-paid construction laborers can be hired by large contractors as the job size is attractive for these types of laborers. Construction work is also supervised by qualified foremen and engineers to ensure the quality of the outcome.

In the UAE, however, the majority of the affordable housing projects are not developed in this manner. Rather, they are put in the hands of the owners. The owner is typically a person with no experience in building design or construction. S/he has at hand limited funds to construct a very small-sized project (See Figure 2). The project is typically located on a new and far-away piece of land with some scattered new projects around. Under these circumstances, good designers or contractors find such a project unattractive to get involved with. Consequently, in many cases, the non-experienced owner ends up hiring a small-size, low-quality design firm to develop the design and the necessary construction documents. The quality of these documents is difficult to appraise by the owner who usually cannot fully understand the technical drawings provided by the designer. As construction starts and the owner sees the formed spaces. s/he may require changes after realizing that the design is not according to his/her expectations. In addition, many design coordination mistakes are discovered during construction resulting in some compromises to overcome them. The design firm typically provides sporadic supervision for the construction work and only for items that are reviewed by the municipality such as the main structural elements. The owner (or a close family member who has more time) becomes the actual manager of the project and the one who has the real interest in having the best possible quality outcome. Hence, s/he ends up supervising the daily construction work with hardly any preparation to be able do so.

As expected from the circumstances within which these projects are developed, most of them end up with errors, delays, cost overruns, and disputes. The owner - who is making one of the biggest investments in his/her life and expects to build a dream home - quickly starts to have a nightmare of problems that are difficult to grasp.

² Based on Abu Dhabi and Dubai Construction Cost Benchmarking (Colliers International, 2019).

Like other construction projects, problems in these small projects are caused by a variety of reasons (Al-Hammad, 2000). These can be financial, such as delays in payments by the owner, contractual, such as change orders, environmental, such as weather conditions, or others, such as poorly skilled laborers. No recent research work is found that tries to identify the major causes of construction problems in these very small size projects in the UAE or the wider Gulf region. There are, however, several surveys that aim to find such causes in the UAE for the construction industry in general, rather than specifically for these affordable housing projects. An example is a survey conducted by Al Mousli and El-Sayegh (2016) which revealed that "most significant interface problems in the UAE include lack of coordination inside the design firm, lack of specialist construction manager, poorly written contract, lack of project management as individual professional service and time limitation in the design phase" (p. 353).



Figure 1. Sample affordable housing project (Sheikh Zayed Housing Program, 2021).



Figure 2. Example of a housing project under construction (photo taken by the author).

Recognizing the variety of problems, some government agents in the UAE tried to address some of these reasons by providing owners with some high-level support. These include providing a recommended list of consultants and contractors, management of payment installation as the project progresses, and assistance in the project commissioning. Another important source of support is providing standard design models that owners can select from. These models are designed by quality designers and come with a full package of detailed construction documents that follow industry standards (Sheikh Zayed Housing Program, 2021). This has greatly solved the issue of design quality, including coordination among the various disciplines.

However, the accurate performance of the construction tasks remains one of the major problems considering the nature of contractors and the laborers who agree to work on these projects, as discussed above. The owner can have a very good set of construction documents. Yet, neither s/he nor the low-qualified laborers can fully understand its requirements as it follows the industry standards and is oriented for technical users. Therefore, conducting and supervising the day-to-day construction functions can be problematic as the design may not be followed accurately. While the logical approach is to hire only qualified laborers and qualified supervisors, this does not seem to be working because of the circumstances under which these projects are developed. The

author easily noticed this problem firsthand through dealing with numerous cases of owners who seek his advice on construction problems they face when building their villas.

This paper documents the results of the first step in a research project that tries to address the problem by making it easier for owners and barely qualified laborers to be able to understand what needs to be built. The paper explains the research approach and methodology. It then shows the structure, contents, and explaining samples of a new type of construction documents that aim to help address the problem. Finally, it discusses the next steps in the research.

APPROACH AND METHODOLOGY

The author's approach to addressing this problem is to help both owners and lowskilled laborers to better understand the job that needs to be performed. The help comes in the form of a new type of construction documents that supplement the standard technical documents. These documents should be much easier to understand. Figure 3 and Figure 4 illustrate this approach in a simple example. Figure 3 shows a sample technical drawing for plumbing to a kitchen sink. This drawing is clear to a person trained to read technical drawings. Yet, it is difficult to comprehend by an owner who sees this way of presenting information for the first time. Figure 4 presents very much the same information but in a way that is easier to comprehend by a non-trained person. To ensure such ease of comprehension, the simplified version is expected to be structured in a very different way in comparison to the standard construction documents. This new type of construction documents should be supplementary to the standard technical drawings. In addition, they must be compatible with the technical documents as both types of documents are describing the same building.



Figure 3. Typical technical drawing.



Figure 4. An easier-to-understand version of the same technical drawing.

In comparison with the standard technical documents, the new documents may differ as shown in table 1.

Table 1 A comparison between the typical technical construction documents and
the proposed type of construction documents.

Technical Construction Documents	New Construction Documents	
Limited to two dimensional views and text	Have many more three-dimensional views and possible virtual reality views	
Show the information in terms of full building plans, sections, and elevations with few details	Show further information at a room-by-room level	
Organize the information by discipline	Organize the information in a way that follows the typical stages of construction	
Have a very small number of drawings for such small projects	Have a significantly larger number of drawings and hence may need to be hyperlinked for easier navigation	
Use mono-color	Use a variety of colors for clarity	
Typically in English only	Use multi-lingual information to accommodate the nature of the labor who may only be able to read in their native language ³	
Does not include any construction techniques.	Have links to multi-media components showing techniques of construction	

The challenge is how to generate this new type of construction documents without making it a difficult, complicated, and expensive process for design firms. This is particularly challenging considering that it is common to make some design modifications before or during construction.

Building Information Modeling (BIM) technology can provide a practical way to address this challenge. With BIM technology, the designer is basically filling a database that holds the design decisions. Once a group of related decisions is recorded in the database, a variety of views can be generated to represent these decisions. These views can be highly technical and in compliance with the industry standards and can be very simplified to allow a non-technical person to understand the construction requirements. Any change in the decisions that are recorded in the database is directly reflected in all the views. Hence, compatibility among the views remains because the origin of all the views is the same.

The BIM technology became an industry standard. Hence, there should be no difficulty in using it to generate the new type of construction documents. Yet, the difficulty is in what is to be generated. The technology itself allows a variety of ways to represent the design decisions. The author aims to address this difficulty by providing some standards to generate the new construction documents.

The author's methodology is to go through the following tasks:

³ Laborers in the UAE come from many countries but mainly from the Indian sub-continent, the Philippines, and some Arab countries. Many speak their native language only.

- 1. Investigate the capability of the technology to communicate the information to the stakeholders (owners, contractors, consultants, and officials).
- 2. Organize the information in a way that is easy to comprehend by owners and low skilled workers. This is done through developing initial documentation for a sample villa. This is the focus of this paper.
- 3. Show the documentation to a sample of the different stakeholders and get their feedback about their ability to understand the documents. The feedback will be used to further improve the documents' ability to more easily communicate the information. This task will be repeated until the documents achieve their purpose.
- 4. Develop a program that enables the automatic generation of the new construction documents from the typical technical documents with very little or no special effort from the consultants.
- 5. Propagate this system into common design and construction practices in the affordable housing market.

PROPOSED DOCUMENT STRUCTURE

The objective here is to structure the proposed new type of construction documents so they are easy to read by an owner or a low-skilled laborer. Hence, one should put himself in the shoes of a non-technical person. The approach to the documents' structure should be similar to making a manual for a do-it-yourself furniture assembly, yet on a larger scale. To achieve this, the proposed documents are divided into two main categories: "Building Systems" and "Sequence of Construction".

Building Systems. This category aims to dissect the building into its main systems (spaces, structure, masonry, plumbing, electric, HVAC, and finishing). Each system is presented as a standalone one. This is similar to the standard technical documents which are divided by design discipline. Yet, the nature of presenting the information here is very different as explained below. The purpose of this category of documents is to do the following:

- Enable the owner to comprehend a relatively complex task by making an anatomy of the project,
- Enable the owner and the laborers to link between the proposed new construction documents and the standard technical construction documents. Hence, this simplifies the conversation between the owner and the sub-contractors as s/he supervises the job, and
- Help low-skilled labor to identify their specific tasks.

Due to the different nature of the various building systems, they are presented at different configurations. The configurations are:

• *Total system:* this is used for the structure system (see sample in Figure 5 a). Different colors present different structural elements to help the owner identify these elements. This configuration helps the user to recognize how a final system will look like. Several perspectives show the structure from different points of view so every structural element can be seen clearly.

- *Level-by-level:* this is used for the spaces, the structure, and the masonry systems. Figure 5 (b) shows the structural system of the ground level while Figure 5 (c) and (d) shows the masonry system at the same level. Note that different sizes of concrete masonry units are shown in different colors. The objective here is to enable the user to review the different systems as they are being constructed. Several plans and perspective plans show each system from different points of views at each level so each element in the system can be seen clearly.
- *Room-by-room:* this is used for plumbing, electric, HVAC, and finishing systems. Figure 6 shows an example for the plumbing, electric, and finishing systems for the same room. For each room, each system is shown separately so the owner and the laborers can understand the requirement for a particular discipline. In addition, the systems are shown together for coordination purposes as shown in figure 6 (c). A variety of perspectives, plans, and elevations are shown for each system in each room so each element in the system can be seen clearly.
- *Details:* this is used to show the same technical details that appear in the standard documents but in views that are easier to understand by a non-technical person. Figure 7 shows an example for the details of a foundation type along with its rebar. The detail includes various perspectives and uses different colors for the different elements of the foundation. It also uses different colors for the different rebar sizes.

Sequence of Construction. This category aims to show the process of constructing the project step-by-step. The purpose is to do the following:

- Help an owner follow the major steps in the construction process. Figure 8 shows a sample for presenting the sequence of constructing the building skeleton. A variety of perspectives, plans, and elevations are shown for each construction step so the owner can supervise the process.
- Clarify the interdisciplinary nature of the process. For example, figure 9 shows the electric conduits (electric system) location within the concrete slab (structure system). Another example is in figure 10, which shows the opening in masonry to accommodate a door, the masonry recess to host an electric panel, and the location of the electric conduits in the masonry. A variety of focused perspectives show these relationships in their appropriate sequence in construction.

Presenting the information follows a reference construction activity schedule. Based on the nature of the activity, the information will be presented at the *Level-by-level*, *Room-by-room*, and *Details* configurations as explained above. Clearly, there is significant overlap between the information presented in the Building Systems and Sequence of Construction categories. In addition, having multiple views for the same item results in a very large set of documents. Therefore, it is not reasonable to have this new type of construction documents in a paper format. Rather, it is presented in the form of a ".pdf" file that is designed with hyperlinks to ease the navigation through the large number of drawings. This file is expected to be seen on a mobile phone or a tablet on site. With the ability to zoom in to any drawings, all the necessary details can be seen on a small size screen.



Figure 5. Samples for the contents of the structure "Total system" (a) and the "Level-by-level" configurations for structure (b) and for masonry (c) and (d).



Figure 6. A sample for the contents of the "Room-by-room" configuration showing from left the views for (a) plumbing, (b) electric conduit with light fixture, (c) coordination, and (d) finishing.



Figure 7. A sample detailing for a foundation and its rebar showing different rebar diameter at different colors.



Figure 8. A sample for the "Sequence of Construction" contents showing the stages for constructing the villa structure.



Figure 9. A sample of the electric conduit locations within the reinforced slab.



Figure 10. A sample of a detailed perspective during the masonry construction stage.

SUMMARY

This paper presents the results of the preliminary stage of a research project that aims to develop a new type of construction documents. The documents are intended to make it easier for an owner to supervise the construction if his/her villa and for low skilled labor to understand the required tasks. The paper presents the nature of the documents and how they differ from the typical technical construction documents. It also presents the proposed structure of the document so it can achieve its objective. The next step in the research is to get feedback from owners and low-skilled labor about the clarity and ease of using the proposed documents' structure. The feedback will be used to further improve the structure, the contents, and the presentation technique for the documents.

REFERENCES

Al-Hammad, A. (2000). "Common interface problems among various construction parties," *Journal of Performance in Constructed Facilities*. Vol. 14, No. 2. pp. 71-74. doi: 10.1061/(ASCE)0887-3828(2000)14:2(71)

AL Mousli, H., El-Sayegh, S. (2016). "Assessment of the design–construction interface problems in the UAE," *Journal of Architectural Engineering and Design Management*. Vol. 12, No. 5. pp. 353-366. doi:10.1080/17452007.2016.1187111

Colliers International (2019). *Abu Dhabi and Dubai* | *Construction Costs - Update May 2019*, Visited site on 21 July 2021, <<u>https://www2.colliers.com/en-AE/Research/Dubai/Abu-Dhabi-and-Dubai-Construction-Costs-Update-May-2019></u>.

Global Media Insight (2021), *United Arab Emirates population statistics (2021)*, Visited site on 21 July 2021, <<u>https://www.globalmediainsight.com/blog/uae-population-statistics/</u>>.

Knoema Enterprise Data Solutions (2021). *Gross domestic product per capita based on purchasing-power-parity in current prices,* Visited site on 21 July 2021, <<u>https://knoema.com/atlas/ranks/GDP-per-capita-based-on-PPP>.</u>

Sheikh Zayed Housing Program (2021). *Darak*, Visited site on 21 July 2021, <<u>https://www.szhp.gov.ae/BuildingTemplates</u>>.

The United Arab Emirates' Government portal (2021). *Housing authorities and programmes*, Visited site on 21 July 2021, <<u>https://government.ae/en/information-and-services/housing/housing-authorities-and-programmes></u>

A Data-Driven Indoor Overheating Warning System For Residential Buildings

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ABSTRACT

Overheating in residential buildings during extreme heat events can cause wide-scale health risks to occupants, particularly older people, who spend most of their time indoors, are more vulnerable to heat exposure. With rising outdoor temperatures and heat waves frequency and intensity caused by climate change and the growth of the senior population in Canada, such health risks can be expected to become more common in the future. Currently, heat warning systems (HWS) are being progressively adopted around the world in order to alert and warn the population of overheating risks in built environments. However, current HWSs are primarily based on short-term weather forecasts and are unable to identify the precise time, location and severity of overheating events in built environments. In contrast, the growth in the use of connected thermostats has allowed for such warning systems to be tailored to the occupants and buildings. In this study, data from more than 180 connected thermostats was used to develop an indoor temperature forecast model. The effectiveness of the models was assessed by evaluating the accuracy of predictions over the heat wave of July 2019 at different lead times (12, 24 and 48 hours ahead). The results showed that the current approach can be used in an overheating warning system with high reliability up to 12 hours ahead for more than 90% of sample houses.

INTRODUCTION

Excessive indoor heat and prolonged periods of outdoor hot weather affect the health and wellbeing of building occupants and increase the risk of mortality and morbidity. It is shown that the elderly are less sensitive to thirst and heat, and therefore are at a higher risk of dehydration and hyperthermia during long exposures to high indoor temperatures (Lomas & Porritt, 2017). In addition, future indoor temperatures and heat wave frequency and intensity are predicted to increase due to future climate change. These factors have contributed to a growing concern about an increased occurrence of overheating during the warm summer weather in Canadian homes. In Canada, the need to implement mitigation strategies has been driving the demand for more energy efficient residential buildings. Driven by energy efficiency standards and reduction of greenhouse emission, highly-insulated and airtight houses are currently being built, and existing dwellings are being retrofitted to reduce winter space heating energy use. However, there is evidence that new and highly insulated dwellings are more disposed to overheating than older leaky and less insulating homes (Laouadi et al., 2020; Laouadi et al., 2019). Furthermore, as Canada is shifting towards a super-aged country (Government of Canada, 2014) and older people are being increasingly encouraged to 'age in place' and remain in the family home, the risk of indoor heat exposure to the

seniors is increasing. In addition, indoor temperatures and heat wave frequency are predicted to increase due to climate change (Environment and Climate Change, 2019). These factors have contributed to a growing concern about an increased occurrence of overheating events during the warm summer weather in Canadian homes.

The indoor thermal conditions depend on both the outdoor weather conditions and the building characteristics and occupant behaviour. Thus, associating indoor overheating solely with outdoor conditions at a regional level is inadequate. There have been several studies in which indoor condition measurements have been conducted to evaluate overheating events in different types of residential buildings. Loughnan et al., 2015 performed indoor measurements and occupant surveys in 20 houses with elderly occupants in a regional town in Australia during the summer of 2012. They found that the indoor maximum temperature was not significantly correlated with the outdoor temperature in houses with air-conditioning (AC) units. Surveys showed residents were comfortable at indoor temperatures up to 26.6°C. Significant differences in the indoor temperature were observed and related to the house characteristics and operation. Beizaee et al., 2013 conducted an indoor conditions study during the cool summer of 2007 in 207 homes across England. Among the dwellings, 193 were not air conditioned. They found that bedrooms of homes built after 1990 were significantly warmer and those built before 1919 were significantly cooler. Touchie et al., 2016 conducted field measurements in seven mid and high-rise retrofitted multi-unit residential buildings located in the City of Toronto, Canada. The outdoor and indoor conditions were collected over three years: prior (2015), during (2016), and after retrofit (2017). The results showed that indoor temperatures increased with the outdoor conditions in un-conditioned suites not facing north. In those suites, the indoor temperatures were higher than the adaptive thermal comfort and outdoor temperatures during the heatwave periods. Furthermore, the occupants were exposed to medium to high levels of heat stress, particularly during nighttime. Based on the previous literature overview, most efforts to understand residential indoor conditions from real household measurements have historically relied on small samples, during relatively short periods of time and in a localized geographic area due to practical constraints. The growth in the use of connected thermostats has allowed for such studies to be conducted without the limitations of traditional data collection methods. In this work, the indoor temperature measurements from more than 180 connected thermostats, during the summer of 2019 and from homes located in Ontario, Canada, are used to investigate the feasibility of developing a predictive warning framework. The connected thermostat data, in particular, was leveraged to develop an indoor overheating forecast framework tailored to the dwelling's thermal conditions and occupant behaviour. Regardless of the indoor overheating mitigation strategy, it has been shown that heat-related health risks can be decreased by using a predictive indoor overheating warning system (Gustin et al., 2017, 2020). The geographical distribution of the selected houses is shown in figure 10. Most homes are located in the highly populated areas in southern Ontario with around 25% of houses in the Greater Toronto Area.



Figure 1. Geographical distribution of the selected houses

DATA DESCRIPTION

In this study, we used the data from houses located in Ontario, Canada based on the Donate Your Data (DYD) program. Therefore, the dataset in the context of this study refers to the thermostats in dwellings that were located in Ontario where central air conditioning (AC) units were not used. For each building, the DYD dataset contained indoor and outdoor temperature and relative humidity data from the first connection (or from January 2015 if actual online status occurred before that date) until the release of the data on August 30, 2019. The DYD dataset provides information on the number of installed cooling stages which we used to select homes without central air conditioning. In the selected homes, the runtime of the heating equipment controlled by the thermostat was checked and the days that had heat runtime greater than zero were flagged as unusable for the overheating analysis. If the temperature readings were missing for less than three consecutive hours, a linear interpolation was used to fill the missing values. Otherwise, that period of time was flagged as unusable for the overheating analysis.

INDOOR TEMPERATURE MODELS

Prediction of indoor temperature has been attempted using white, grey, and black box models. White box models are purely theoretical, physics-based models that typically use empirical equations. A Gray box model combines a simple theoretical model structure with parameter estimation from observed data. Black box models do not assume any model formulations and knowledge of building properties and characteristics. The performance of these models for indoor temperature and relative humidity has been investigated in various studies (Cui et al., 2019; Delcroix et al., 2020). In this study, two gray box models were developed based on the hourly indoor and outdoor temperatures. The gray box models were implemented in a recursive forecasting strategy using sliding training and forecast time periods to provide the forecasted hourly indoor temperatures. Note that gray box models developed in this work are linear which, due to their lower computational cost, make them more suitable for large-scale studies. Furthermore, it has been shown that more complex non-linear prediction models and the use of additional predictors, do not necessarily increase the forecasting accuracy obtained by linear models (Gustin et al., 2019). The gray box models are based on an equivalent electrical circuit (RC model). In this

approach, the temperature difference is the driving potential, and the flow through the circuit is the heat flow. Various RC network models have been proposed in the literature. As shown in (Baasch et al., 2019), the low-order 1R1C model usually results in a large number of outliers. High-order RC models are generally more accurate but they are more computationally intensive to use, which makes them less suitable for large-scale time-series analysis. Therefore, in this study, we developed a 2R2C and a 3R2C model to examine if these relatively simple models can offer a reasonable trade-off between performance and computational cost. In this work, the solar and internal heat gains were neglected since this data is not collected by the connected thermostats and is therefore not included in the data set. The governing equations from the thermal network models can be derived from the Kirchhoff's node potential law. For the 2R2C model:

$$\frac{\partial T_{in}}{\partial t} = -\frac{1}{R_w C_i} T_{in} - \frac{1}{R_b C_b} T_w + \frac{1}{R_w C_i} T_{out} \quad (1)$$
$$\frac{\partial T_w}{\partial t} = -\frac{1}{R_b C_w} T_{in} \quad (8)$$

For the 3R2C model:

$$\frac{\partial T_{in}}{\partial t} = -\left(\frac{1}{R_b C_b} + \frac{1}{R_g C_b}\right) T_{in} + \left(\frac{1}{R_b C_b}\right) T_w + \left(\frac{1}{R_g C_b}\right) T_{out} \quad (2)$$

$$\frac{\partial T_w}{\partial t} = \left(\frac{1}{R_b C_w}\right) T_{in} - \left(\frac{1}{R_w C_w}\right) T_w + \left(\frac{1}{R_w C_w}\right) T_{out} \quad (3)$$

In these equations, T_{in} , T_w and T_{out} represent indoor, walls and outdoor temperatures, R_w is the thermal resistance of walls and C_i and C_b are the internal space and building envelop thermal capacitance, respectively. R_b is the thermal resistance between the building interior space and the walls. R_g is the thermal resistance of parts of the building envelope that are not included in R_w , such as windows and the doors. C_w is the capacitance associated with the walls.

PARAMETER ESTIMATION FOR GRAY BOX MODELS

To estimate the model parameters, the differential equations (1)-(3) were converted into a linear state-space representation, as follow:

$$\frac{\partial x}{\partial t} = Ax + Bu \quad (4)$$
$$y = Cx + Du \quad (5)$$

In equations (4) and (5), the temperatures form the state vector (x), the indoor temperature is the output represented by y, and the outside temperature forms the input vector denoted by u.

The state matrices are as follows:

For 2R2C model:

$$A_2 = \begin{bmatrix} -\frac{1}{R_w C_i} & \frac{1}{R_b C_b} \\ -\frac{1}{R_b C_w} & 0 \end{bmatrix}, B_2 = \begin{bmatrix} \frac{1}{R_w C_i} \\ 0 \end{bmatrix}, u = [T_{out}], x_2 = \begin{bmatrix} T_{in} \\ T_b \end{bmatrix}$$

For 3R2C model:

$$A_{3} = \begin{bmatrix} -\left(\frac{1}{R_{b}C_{b}} + \frac{1}{R_{g}C_{b}}\right) & \frac{1}{R_{b}C_{b}} \\ \frac{1}{R_{b}C_{w}} & -\frac{1}{R_{w}C_{w}} \end{bmatrix}, B_{2} = \begin{bmatrix} \frac{1}{R_{w}C_{i}} \\ 0 \end{bmatrix}, u = [T_{out}], x_{2} = \begin{bmatrix} T_{in} \\ T_{w} \end{bmatrix}$$
$$C = \begin{bmatrix} 0 & 1 \end{bmatrix}, D = \begin{bmatrix} 0 & 0 \end{bmatrix}$$

The response to the system described in (4)-(5) can be written as (Seem et al., 1989):

$$x_{(t)} = (F.I - \Phi)^{-1} (q.\Gamma_2 + \Gamma_1 - \Gamma_2) u_{(t)}$$
(6)

where q denotes the forward shift operator:

$$\Phi = e^{A\delta}, \Gamma_1 = A^{-1}(\Phi - I)B, \Gamma_2 = A^{-1}\left(\frac{\Gamma_1}{\delta} - B\right)$$

By substituting equation (13) in (12):

$$y_{(t)} = C(q.I - \Phi)^{-1} (q.\Gamma_2 + \Gamma_1 - \Gamma_2) u_{(t)}$$
(7)

Assuming that inverse of $(q.I - \Phi)$ is non-singular:

$$y_{(t)} = \sum_{j=0}^{2} (S_j u_{t-j\delta}) - \sum_{j=1}^{2} (e_j y_{t-j\delta}) \quad (8)$$

where:

$$S_{0} = C\Gamma_{2}$$

$$S_{1} = C[R_{0}(\Gamma_{1} - \Gamma_{2}) + R_{1}\Gamma_{2}] + e_{1}D$$

$$S_{2} = CR_{1}(\Gamma_{1} - \Gamma_{2}) + e_{2}D$$

where R matrices can be found based on Leverrier's algorithm as follow:

$$R_0 = I, \ R_i = \Phi R_{i-1} + e_i I$$
 where $e_i = \frac{Trace(\Phi R_{i-1})}{n}$ for $i = 1, 2$

Using this approach, as shown in equation (8), the indoor temperature $(y_{(t)})$ can be expressed as a linear function of indoor temperature at the previous time step and the outside temperature at the two previous time steps. The connected thermostat data (i.e. indoor and outdoor temperature time series data), along with equation (8), was utilized to estimate the state matrices by using a non-linear least squares method.

RESULTS

In this study, the forecasting accuracy was evaluated using two scale-dependent error metrics: mean absolute percentage error (MAPE) and mean absolute error (MAE). As mentioned in the previous sections, a recursive forecasting strategy using sliding training and forecast windows was utilized to forecast indoor temperatures. Five training windows namely 48, 72, 96, 120 and 144 hours were used to train gray box models. The trained models were implemented in a recursive forecasting strategy to

predict the hourly indoor temperature during the next 12, 24 and 48 hours. Figures 2a and 2b show the MAE of indoor temperature predictions of 2R2C and 3R2C models, respectively. As can be seen, the 2R2C models perform noticeably better than the 3R2C model for all training windows. The 2R2C model is able to predict indoor temperature with a median MAE less than 0.2°C. However, both models result in a number of outliers. Although figure2 can provide useful information about the gray box models performance, the accuracy of the forecasting models can only be evaluated based on the recursive strategy. In a recursive strategy, the prediction from a one-step-ahead is used as an input for future prediction horizons. An important advantage of the recursive approaches is that only one model is required, which considerably reduces the computational time, particularly in large-scale studies when a model needs to be trained for each house. Conversely, recursive forecasting typically produces biased predictions. This is because any error generated in the first step of prediction accumulates with each subsequent prediction, making accurate predictions at longer forecasting horizons more challenging (Chandra et al., 2017).



Figure 2. MAE distribution of a) 2R2C; and b) 3R2C grey box models for various training windows

The MAPE values of the models were used to evaluate the performance of the forecast tools for the three forecast horizons, namely 12, 24 and 48 hours (figure 2). The results show that in all cases the 2R2C-based model outperforms the 3R2C-based model. Furthermore, it is evident that the forecast accuracy decrease with the forecast horizon. As mentioned above, this is an inherent feature of the recursive forecast strategies. In 2R2C-based models, the 96-h training horizon produced the lowest MAPE and therefore, this model was selected as the best performing model.





Figure 3. MAPE distribution of 2R2C (left) and 3R2C (right) based forecast models for various training windows

In this study, an MAPE of 5% is used as the threshold for the forecast accuracy. Table 1 represents the percentage houses for which the selected forecast model (2R2C-based model with 96-h training window) can achieve an MAPE lower than 5% for various forecast horizons. Table 1 shows that the selected model is able to forecast the 12-h ahead indoor temperatures with less than 5% error for the majority of houses. As the forecast horizon increases, the model's prediction ability decreases, which can mainly contribute to the error accumulation in the recursive forecast strategy.

Forecast horizon (hours)	Percentage of houses with MAPE
	lower than 5%
12	92
24	87
48	61

Table 1. Performance of 2R2C-based model with 96-h training window

To provide a more detailed overview of the selected model performance, three houses were selected to represent the best (minimum MAPE), typical (median MAPE) and the worst (maximum acceptable) forecast accuracy.

The indoor and outdoor temperatures variation for all three houses is shown in figure 4. For House A, the forecasts are very accurate with the maximum error of 0.4° C, while the model tends to forecast a smooth temperature profile. For House B, the model overestimates the minimum indoor temperature by about 0.9° C, while at higher outdoor temperatures the model is relatively accurate and the error does not exceed 0.3° C. For house C, the model struggles to adapt to the rapid outdoor temperature increase

between 5am and 12am and underestimates the indoor temperature with a maximum error of 1.2° C. As the outdoor temperature becomes more stable during the rest of the day, the model accuracy significantly increases (the mean absolute error between 13pm and 23:59pm is 0.3° C).



Figure 4. Measured and predicted daily profiles of the indoor and outdoor temperatures for the three selected houses

DISCUSSION

The aim of this work was to investigate the feasibility of using data collected from connected thermostats for developing indoor conditions forecast models. Such a model can provide an early warning of likely elevated temperatures and indoor overheating events. First, two gray box models were developed to capture the house-specific response to the outdoor conditions. Then, the effects of training window and forecast horizon on the models performance were studied to identify the best performing forecast strategy. The global strategy is an important feature of the forecast models since it removes the need for manual model identification for each house. However, it was shown that no model was able to forecast the indoor conditions of all houses. For a 12-h forecast horizon, the selected model was able to forecast indoor temperature in 92% of houses with less than 5% MAPE, while that number dropped to 61% for a 48h forecast horizon. Three main reasons may contribute to these observations. First, in this work, a recursive strategy was used and because of the error accumulation in each subsequent prediction, the model performance decreases at larger forecast horizons. Second, the DYD dataset offers no detailed information about the building characteristics (e.g. house orientation, shading, and thermostat location). Therefore the effects of solar radiation on indoor temperature cannot be modeled. Furthermore, the

dataset only contained data about the central cooling system. Therefore, some houses may use window AC units that were not noted in the dataset. Third, in residential buildings, the occupants' behaviour can have strong effects on the indoor conditions, especially during warmer days. Behavioral mitigating actions during a heat wave could include opening windows and even doors for space ventilation, and closing shading devices during the day to reduce solar heat gains. There were no data on these actions and therefore, the models cannot learn the effects of these mitigation actions. In this study, the effects of behavioral mitigation actions were decreased by training the gray box models over relatively short periods of time, as well as, using a sliding approach. However, the forecast models can be viewed as a forecast of what will happen if no one takes any mitigation action (beyond the established patterns of operation). From a health perspective, this can be useful information since it allows the occupants (or their caregivers) to proactively take action to lower the indoor temperature in order to maintain it within safe levels. Because at shorter forecasting horizons (12-h) the predictions are more accurate and consistent, a warning framework with a 12-h horizon could be set to alert the occupants or caregivers ahead of dangerous indoor conditions. This is especially beneficial for elderly homeowners and long-term care homes in which occupants are more vulnerable to indoor heat events.

CONCLUSIONS

Early prediction of impending high temperatures in buildings could play a vital role in reducing heat-related morbidity and mortality. In this work, the potential for leveraging data from connected thermostats to predict indoor conditions was investigated using hourly data from 189 houses in Ontario during the summer of 2019. A combination of gray box and black box models along with a recursive multistep-ahead approach with sliding training windows and forecast horizons was used to forecast indoor temperature. These provided predictions for forecasting horizons of 12, 24 and 72 hours. The accuracy of the predictions over the real measurements was evaluated using MAPE and MAE over different forecasting horizons. Comparison between the various forecast horizons showed that the proposed approach can forecast 12-hour ahead indoor temperature in 92% of houses with less than 5% MAPE. Also, the mechanisms behind lower accuracy in longer forecast horizons were discussed. Overall, the early findings of this work suggest that highly detailed building information is not necessarily required to produce reasonable forecasts of indoor conditions in some of the houses that do not use a central AC unit. This indicates the potential for using IoT devices and machine learning as part of an overheating detection and warning system in buildings. The performance of the proposed approach may be improved by adding the solar radiation data into the models. Specific descriptions of microclimatic differences between the buildings may also enhance the model performance. In future work, the effects of adding these factors on the performance of the models will be investigated.

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REFERENCES

- Baasch, G., Wicikowski, A., Faure, G., & Evins, R. (2019). Comparing gray box methods to derive building properties from smart thermostat data. *BuildSys 2019 - Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*, 223–232. https://doi.org/10.1145/3360322.3360836
- Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, 65, 1–17. https://doi.org/10.1016/j.buildenv.2013.03.011
- Chandra, R., Ong, Y. S., & Goh, C. K. (2017). Co-evolutionary multi-task learning with predictive recurrence for multi-step chaotic time series prediction. *Neurocomputing*, *243*, 21–34. https://doi.org/10.1016/j.neucom.2017.02.065
- Cui, B., Fan, C., Munk, J., Mao, N., Xiao, F., Dong, J., & Kuruganti, T. (2019). A hybrid building thermal modeling approach for predicting temperatures in typical, detached, two-story houses. *Applied Energy*, 236, 101–116. https://doi.org/10.1016/j.apenergy.2018.11.077
- Delcroix, B., Ny, J. Le, Bernier, M., Azam, M., Qu, B., & Venne, J. S. (2020). Autoregressive neural networks with exogenous variables for indoor temperature prediction in buildings. *Building Simulation*. https://doi.org/10.1007/s12273-019-0597-2
- Environment and Climate Change. (2019). *Canada's climate is warming twice as fast as global average*. Environment and Climate Change. https://www.canada.ca/en/environment-climate-change/news/2019/04/canadas-climate-is-warming-twice-as-fast-as-global-average.html
- Government of Canada. (2014). Action for Seniors report. https://www.canada.ca/en/employment-social-development/programs/seniors-action-report.html
- Gustin, M., McLeod, R. S., & Lomas, K. J. (2019). Can semi-parametric additive models outperform linear models, when forecasting indoor temperatures in free-running buildings? *Energy and Buildings*, *193*, 250–266. https://doi.org/10.1016/j.enbuild.2019.03.048
- Gustin, M., McLeod, R. S., Lomas, K. J., Petrou, G., & Mavrogianni, A. (2020). A high-resolution indoor heat-health warning system for dwellings. *Building and Environment*, 168, 106519. https://doi.org/10.1016/j.buildenv.2019.106519
- Gustin, M., Oraiopoulos, A., McLeod, R. S., & Lomas, K. J. (2017). A new empirical model incorporating spatial interpolation of meteorological data for the prediction of overheating risks in UK dwellings. *Proceedings of 33rd PLEA International Conference: Design to Thrive, PLEA 2017, 3,* 3786–3793.
- Laouadi, A., Gaur, A., Lacasse, M. A., Bartko, M., & Armstrong, M. (2020). Development of reference summer weather years for analysis of overheating risk in buildings. *Journal of Building Performance Simulation*, *13*(3), 301–319. https://doi.org/10.1080/19401493.2020.1727954
- Laouadi, Aziz, Lacasse, M. A., Gaur, A., Bartko, M., & Armstrong, M. (2019). Climate resilience of buildings: overheating in buildings: development of framework for overheating risk analysis.
- Lomas, K. J., & Porritt, S. M. (2017). Overheating in buildings: lessons from research. *Building Research and Information*, 45(1–2), 1–18. https://doi.org/10.1080/09613218.2017.1256136
- Loughnan, M., Carroll, M., & Tapper, N. J. (2015). The relationship between housing and heat wave resilience in older people. *International Journal of Biometeorology*, 59(9), 1291–1298. https://doi.org/10.1007/s00484-014-0939-9
- Seem, J. E., Klein, S. A., Beckman, W. A., & Mitchell, J. W. (1989). Transfer functions for efficient calculation of multidimensional transient heat transfer. *Journal of Heat Transfer*, 111(1), 5–12. https://doi.org/10.1115/1.3250659
- Tabatabaei Sameni, S. M., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, *92*, 222–235. https://doi.org/10.1016/j.buildenv.2015.03.030
- Touchie, M. F., Tzekova, E. S., Siegel, J. A., Purcell, B., & Morier, J. (2016). Evaluating summertime overheating in multi-unit residential buildings using surveys and in-suite monitoring. *Thermal Performance of the Exterior Envelopes of Whole Buildings, 2016-Decem,* 135–151.

Smart City Affordable Housing: Reimagining the Way We Live

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ABSTRACT

The unbuilt design presented here was a winner of the 2019 Sydney Alternative Housing Ideas Challenge international design competition. The solution proposes an investment corridor through Sydney's downtown that utilizes data collection systems to deploy population health initiatives. At its heart, the scheme recognizes that data is becoming as impactful on the way we configure cities as water and electricity were 100 years ago.

Individual dwelling units are designed to collect activity and biometric data and transmit this information to an on-site clinic or Living Lab. The technological capability provided by the clinic allows the housing operator to leverage institutional resources by leasing space to university centers or medical research entities. The rental rate far exceeds comparable rates for similar commercial facilities thus subsidizing the housing costs, technology upgrades, and even net zero energy construction.

The ideas here are now being touted as a way of better addressing Covid-related health issues through housing technology. Also presented here is a discussion on how such technology can be useful in creating more covid-resistant housing and strategies allowing seniors to shelter in place and resist the negative health impacts of isolation.

Introduction

The Sydney Alternative Housing Ideas Challenge asked teams to develop housing models that could be scaled and executed by the broader community. The solution presented here proposes an investment corridor through Sydney's downtown that utilizes data collection systems to create more livable neighborhoods and to deploy population health initiatives.

One generally associates the term "Smart City" with a government-driven effort to synchronize the core functions of a city through data collection and actionable analysis. Likewise, Lai et al. (2020) define the smart city as a city that employs technology and data to increase efficiencies, economic development, sustainability, and life quality for citizens in urban areas across three realms: energy, transportation, and health. We seem ever closer to the promise that Smart Cities yield. Yet, a digital divide widens the inequity experienced by marginalized communities. Impoverished and disenfranchised neighborhoods existing in the "data shadow" remain unable to align basic services with the livability and health advantages we expect from a so-called Smart City. (Leonelli et al. 2017, 191-202) Also, the Covid-19 crisis has brought the intersection of urban environments and community health to the forefront of this discussion. The Smart City must operate in a way that allows us to make

headway on the great challenges of our time. Smart and connected cities have the potential to restructure the world and allow us to act critically and strategically within a society we cannot completely remake. One of the most impactful Smart City initiatives is the deployment of population health strategies.

Sensored environments have the ability to collect a wide range of biometric data. The collection and analysis of such data to deliver healthcare more affordably, affectively, and sometimes before we know we need it. (Hibbard et al. 2017, 1297-1309) Even more potent may be the impact on health, wellness, and general livability when this biometric data is aggregated with all the vast amounts of data a Smart City can collect. (Halegoua 2015, 311-316)

The scheme presented here proposes an incentivized investment corridor along George Street, one of Sydney's most vibrant mixed-use corridors. Connecting some of the city's most popular attractions, a light rail line opened on the thoroughfare in December 2019. Like the goals of Transit Oriented Development (TOD), the George Street gigabit investment corridor would prioritize gigabit reception enabling a more robust multimodal transit infrastructure. (Figure 1)



Figure 1: Sydney Alternative Housing Ideas Challenge proposal

Transit alternatives will become increasingly important as demographics shift to an older population. Many suffering from cognitive deterioration will no longer be able to drive safely. (Anstey et al. 2005, 45-65) Electronically hail or "E-hail" services such as Uber or Lyft will become increasingly important to aging drivers as they self-regulate and avoid difficult driving situations. (Molnar et al. 2013, 272-280) Robust transit options become important to the social fabric as well.

The project attempts to create lifelong neighborhoods, those that allow one to thrive at all stages of life. (Ball 2012) They incorporate great parks, great schools, access to multi-modal transit, jobs, cultural districts, and all the amenities needed in later life. Supportive components of a community where one could live their entire life include
connectivity, pedestrian access and transit, neighborhood retail and services, diversity of dwelling types, healthy living, and social interaction. (Keys et al. 2014, 117-130) While every city is looking at how high-speed internet and connected services can increase quality the quality of life for its citizens, affordable dignified housing that is able to leverage this connectivity is becoming increasingly elusive for many. In 2018 Sydney was ranked second worst in urban housing affordability. Its housing prices were 13 times higher than the median income; only Hong Kong was worse. (Cox and Pavletich 2018) There is a need to re-examine both land use and financing regulations to create a downtown that is healthy, vibrant, and accessible to all people. The notion of a lifelong neighborhood, as it is presented here, offers a vision for intergenerational living and the support networks that come along with it.

Problem Statement

One of the fundamental principles of the Sydney solution presented here is monetizing the collection of activity and biometric data. This is not accomplished simply by selling the data to commercial enterprises. Although, today there is little data that one produces that is not bought and sold. In fact, it is argued that the commodification of our data may be the inevitable next step in the growth of the Internet of Things and the most efficient way to spread the wealth created from digital technologies. (Molina et al. 2019) Rather, individual dwelling units are designed to collect activity and biometric data and to transmit this information to an on-site clinic or Living Lab. These sensor-rich environments are able to collect human vital signs, physical activity, environmental conditions, and pharmaceutical regiments. This data can be collected and analyzed to deploy population health strategies. The technological capability provided by the clinic allows the housing operator to leverage institutional resources by leasing space to university research centers or medical research entities. The rental rate far exceeds comparable rates for similar commercial facilities thus subsidizing the housing costs, technology upgrades, and even net zero energy construction. The ground floor Living Lab will collect data not only on willing residents of the housing complex but also that of off-site residents as well. The facility serves as a community amenity able to collect data on a broad section of the neighborhood. Synchronized with like facilities along the George Street gigabit investment corridor, the data is able to be aggregated for implementing population health strategies. Population Health is defined as the health outcomes of a group of individuals, including the distribution of such outcomes within the group. (Kindig 2007, 139-161)

Data privacy is one of the most critical and debated subjects surrounding such technologies. Data privacy laws in Australia vary widely from HIPPA laws in the US where all residents are provided universal health care. The systems here assume data is only collected on residents that volunteer to engage in the building's programs. However, even permission to use de-identified data would be extremely useful for population health initiatives. In fact, the scheme assumes many residents living in sensored units may decline to participate in data collection programs. The model is designed to be plug-and-play. Occupants can opt out of such collection but tap into the existing infrastructure at a later date if they experience changes to their lifestyle or health. One of the most critical health markers is activity tracking accomplished by motion sensors or accelerometers in the floor. Physical activity is one of the most telling indicators of health. Activity trackers detect falls and monitor movements throughout a living unit and also a community. (Evenson and Furberg 2015, 159) One is able to track whether an elderly patient has fallen or has gone into the bathroom and not come out for several hours. Caregivers are alerted when dementia patients susceptible to confusion leave their apartment or the building complex. The

transition to population health strategies enabled by Smart Cities relies on the aggregation of patterns extracted from vast amounts of data.

Other data collecting technologies include sleep sensors, smart mirrors, coloradjusted LED lighting, smart toilets, and automated medicine dispensers. One metric the team focused on more comprehensively was gait analysis.

Methodology

The pattern of one's gait, the characteristics of how one walks, is entirely unique. (Kale et al. 2003) Several factors determine the individuality of gait: body shape and size, posture, and kinesiology. Gait can also be influenced by outside factors such as floor treatment, shoe style, ground slope, moisture, etc. (Lee and Grimson 2002) Gait analysis can be used for identification, tracking, and surveillance. It is also widely used in athletic training and sports medicine. A broadening field of gait analysis is in the clinical environment where variation in stride can predict mental impairments. In the case of such diseases as Alzheimer's and Parkinson's, these physical markers can sometimes present themselves even before neuropsychological tests. (Stone et al. 2014) Typically gait data is collected through worn sensors or 3D cameras in a clinical environment. Subjects are aware they are being observed and cannot help but allow this knowledge to impact their kinesiology. Involuntary changes in body are common when one knows they are being watched. Gait is altered, posture improved, even blood pressure can rise. (Owens et al. 1998, 743-748) The shift in gait analysis presented here moves the sensing technology to the floor assembly, unobtrusively monitoring users with little interaction. The smart floor designed here, is able to collect data over a long period of time and throughout the phases of a 24-hour cycle providing a much richer data set. Similar approaches have been used in sensor-rich shoes fitted with devices that collect data on pressure, speed, rhythm, etc. (Bamberg et al. 2008, 413-423) The potential of floor-embedded sensors is that it synchronizes holistically with other health-monitoring technologies deployed in the housing unit.

One of the fundamental components of the Sydney scheme is gait analysis. Sensors in the floor are able to provide remote detection of falls, the leading cause of injuryrelated deaths among people 65 and older. (Burns and Kakara 2018, 509-514) Such remote monitoring has always been important in the caregiving environment but has been brought to the forefront as critical in the wake of Covid-related lock-down and isolation. The sensors are not only able to detect falls but also limp, shuffling, and a range of gait characteristics. A widening stance, shuffling of feet, or "magnetic" gait is often associated with hydrocephalous, a form of dementia. (Pirker and Katzenschlager 2017, 81-95) Gait patterns related to the ball of the foot striking close to the timing of the heel is a potential sign of neuropathy, a symptom of diabetes. (Wuehr et al. 2014, 852-858) Also, the detection of "toe-walking" and cyclical roaming in learning environments can be indicators of autism. (Barrow et al. 2011, 619-621) The identification of autism in children before language skills have developed would allow for early treatment and intervention. At two-hundred readings per second, the sensors are also able to detect muscle tremor. The implication is that this "smart floor" assembly could be used to detect symptoms of early onset Parkinson's and Alzheimer's disease. The team is currently working with computer scientists and medical researchers to explore the potential for such a system to predict and even prevent falls.

The passive collection and analysis of gait data over time can provide insights into why falls occur. Such insights can allow caregivers to intervene before a serious fall occurs. Perhaps the culprit is furniture arrangement or issues of hoarding, maybe pronounced limp can be tied to the day after a playdate with grandchildren, aligns with changes in a medicine regime, or simply variations in humidity. One strategy for prevention is understanding the activity and patterns that could cause falls, another is to more actively intervene. The team is working with a Parkinson's and Movement Disorder Center on the issue of gait initiation failure. This is an occurrence in Parkinson's patients who suffer a "freezing" of their gait. For some reason their mind is unable to properly assemble the complex motor skills needed to continue walking and the patient falls. (Vercruysse et al. 2012, 1644-1651) Sensors recognizing that gait initiation failure is about to occur are able to instantaneously send a haptic vibration to a wristband or sock to assist the subject in being aware this event is about to occur and helping them to work through it.

The gait data collected from such sensors is not significantly different from that of worn sensors in a human performance lab, however, they are a fraction of the cost. Also, unlike a worn product like an Apple Watch or Fitbit, these sensors act in the background of our lives; embedded in the walls and floor assemblies. There is no need for training, logging steps, or remembering to turn the system on. Also, the data collection is capable of operating 24 hours a day, 7 days a week. Currently, Parkinson's and Alzheimer's patients would need to make an appointment at a performance lab to have such a gait analysis performed. Even then, the subject's gait is often influenced by the recognition that their every movement is being recorded. The embedded systems described here can be opted out of and never engaged, or it can be turned on to collect data in the event of a fall or deteriorating health. It also works for a demographic that may not have the ability to operate smart phones and smart watches or lack the desire to log steps or heel strikes online. A simple prototype unit has been constructed that utilizes simple accelerometers and strain gauges to record heel strike. (Figure 2) The system has been recalibrated from large infrastructure monitoring to detect and identify sensor signals associated with a person moving about a living space.



Figure 2: Completed prototype

The node-based processing minimizes wireless bandwidth communications and enables dense sensorization of the platform. Ten three-axis accelerometers in a plastic casing were screwed into the face of joists at approximately 1/3 span. Forty strain gauges were attached with adhesive to the face of joists at approximately midspan throughout the joists of the floor assembly. All sensors are operated by rechargeable battery power. The sensors were procured from Civionics, Inc., a company whose core technology is licensed from the University of Michigan and relates to the intelligent acquisition and processing of sensor data on wireless nodes. The company's Percev product line provides end-to-end wireless sensor systems. The system features both node- and cloud-based analytics, a web-based dashboard, user configurable statistical over-sampling, user-definable virtual channels, user configurable alerts on all channels, and the ability to embed user-developed code directly in the node. This innovation allows for the system to be realistically deployed at scale. For example, to sample all channels at 1,000 HZ and transmit all of these data to the cloud would require on the order of 1.0 Mbps, with most of the data not being of interest. By using on-node processing, one can send a small window of data around a specific event of interest, such as a fall or gait anomaly, thereby cutting the data transmission rates by one or two orders of magnitude while maintaining all data of interest and increasing battery life significantly. The construction simulates a wood joist structure with crawl space but would be just as effective in concrete or steel structures. Data is collected at each wireless sensor location and sent to the cloud server where it can be aggregated and analyzed. Shifting the care and monitoring that occurs in assisted living facilities to the home and also expanding the possibility of remote monitoring, something that has been revealed to be of critical importance as communities grapple with the vulnerabilities associated with Covid-19. The "smart home" monitoring approach allows for residents to age-in-place longer and at a lower cost than the existing system of Continuing Care Retirement Communities (CCRC).

Conclusion

The potential benefits of the Smart City are clear. Vast literature exists on the impacts of data collection systems on energy usage, safety, communication, and transportation in a city. Here we explore the health benefits presented by the smart city. If we could know that an elderly resident has had limited sleep, impaired reflexes, pronounced limp, and is dangerously dehydrated, one can calculate the probability of a fall. That data can be referenced against environmental data: freezing temperatures and a light rain, high humidity, and high particulate matter in the air. These data sets may allow us to predict that this elderly gentleman has a 99% chance of falling that day. Now imagine that these sensors are imbedded throughout a housing complex with 200 housing units or throughout a community of 10,000 housing units and that some minute fraction has been identified as having a high probability of falling. Identifying those 100 citizens is extremely powerful. Aggregation of such data, even with the subject de-identified, can be useful. Gait markers identifying clusters of diabetes may indicate a food desert or locate areas of a city that have poor walkability, sidewalks in disrepair, or little access to preventative healthcare. This is the potential of a datasynchronized lifelong neighborhood, an equitable deployment of population health initiatives. Finally, it cannot be stressed enough that the monitoring technology presented here is secondary to health and wellbeing. (Colistra 2018) Primary to health and wellbeing is the safety and security one finds in diverse and vibrant neighborhoods, those that nurture social connectivity and interaction. This is the critical point that must not be lost when espousing the advantages of synchronized smart cities. What makes a great city is the diverse, mixed-use, and grittiness of the urban experience. (Jacobs 1964)

We should not allow cities to become so efficient and automated that we eliminate chance encounters on the street or disincentivize one from taking the "long way" home through a park. While the Sydney proposal was created just before the Covid pandemic, the events of 2020 have reprioritized the need to make cities more livable, sustainable, and health-centered. The principles of Smart Cities align with the necessary changes in urban infrastructure that can create more socially just environments where all citizens can thrive.

References:

- Anstey K.J., J. Wood, S. Lord, and J.G. Walker. 2005. "Cognitive, sensory and physical factors enabling driving safety in older adults." *Clinical Psychology Review*, 25 (1):45–65.
- Ball, S. 2012. *Livable Communities for Aging Populations: Urban Design for Longevity*. Hoboken, NJ: John Wiley & Sons.
- Bamberg, S., J. Morris, et al. "Gait analysis using a shoe-integrated wireless sensor system." Information Technology in Biomedicine, IEEE Transactions in 12(4): 413-423.
- Barrow, W.J., M. Jaworski, and P.J. Accardo. 2011. "Persistent Toe Walking in Autism." *Journal of Child Neurology*, 26(5):619-621.
- Burns, E., and R. Kakara. 2018. "Deaths from Falls Among Persons Aged ≥ 65 Years United States, 2007-2016." *Morbidity and Mortality Weekly Report*, 67(18):509–514.
- Colistra, J. 2018. "The Evolving Architecture of Smart Cities." *IEEE International* Smart Cities Conference (ISC2), Kansas City, MO
- Cox, W., and H. Pavletich. 2018. "14th Annual Demographia International Housing Affordability Survey: 2018." Accessed June 2019. http://www.demographia.com/dhi2018.pdf
- Evenson, K., M. Goto, and R. Furberg. 2015. "Systematic review of validity and reliability of consumer-wearable activity trackers." The International Journal of Behavioral Nutrition and Physical Activity, (12): 159.
- Goodspeed, R. 2015. "Smart Cities: Moving beyond Urban Cybernetics to Tackle Wicked Problems." *Cambridge Journal of Regions, Economy, and Society*, 8: 79-82.
- Halegoua, G. 2015. "Calling all 'fiberhoods': Google Fiber and the politics of visibility." *International Journal of Cultural Studies*, 18 (3): 311-316.
- Hibbard, J. H., J. Greene, R.M. Sacks, V. Overton, and C. Parrotta. 2017. "Improving population health management strategies: identifying patients who are more likely to be users of avoidable costly care and those more likely to develop a new chronic disease." *Health Services Research*, 52: 1297-1309.

Jacobs, J. 1964. The Death and Life of Great American Cities. London: Pelican.

- Kale, A., Cuntoor, N., Yeg-nanarayana, B., Rajagopalan, A., and Chellappa, R., 2003. "Gait analysis for human identification." In International Conference on Audioand Video-Based Biometric Person Authentication. Springer Berlin Heidelberg, 706-714.
- Kindig, D.A. 2007. "Understanding Population Health Terminology." *Milbank Quarterly*, 85(1): 139-161.
- Keyes, L., D. Phillips, E. Sterling, T. Manegdeg, M. Kelly, G. Trimble, and C. Mayerik. 2014. "Transforming the Way We Live Together: A Model to Move Communities From Policy to Implementation." *Journal of Aging & Social Policy*, (26) 1-2: 117-130.
- Lai, C.S., J. Youwei, Z. Dong, D. Wang, Y. Tao, Q.H. Lai, R. Wong, A. Zobaa, R. Wu, and L.L. Lai, and L. Loi. 2020. "A Review of Technical Standards for Smart Cities." *Clean Technology*, 2 (3): 290-310.
- Le Corbusier and F. Etchells. 1986. *Towards a new architecture*. New York: Dover Publications.
- Lee, L. and Grimson, W.E.L., 2002. "Gait analysis for recognition and classification." Proceedings of Fifth IEEE International Conference on Automatic Face and Gesture Recognition, Washington, DC: 155-162.
- Leonelli, S., B. Rappert, and G. Davies. 2017. "Data Shadows: Knowledge, Openness, and Access." *Science, Technology, and Human Values*, 42(2):191-202.
- Molina, V., M. Kersten-Oertel, and T. Glatard. 2019. "A conceptual marketplace model for iot generated personal data." arXiv preprint arXiv:1907.03047.
- Molnar, L.J., D.W. Eby, J.L. Charlton, J. Langford, S. Koppel, S. Marshall, M. Man-Son-Hing. 2013. "Driving avoidance by older adults: Is it always self-regulation?" *Accident; Analysis and Prevention*, 61: 272-280.
- Owens, P.E., S.P. Lyons, S.A. Rodriguez, and E.T. O'Brien. 1998. Is elevation of clinic blood pressure in patients with white-coat hypertension who have normal ambulatory blood pressure associated with target organ changes? J Hum Hypertens, 12:743–748.
- Pirker, W. and R. Katzenschlager. 2017. "Gait disorders in adults and the elderly." *Wien Klin Wochenschr*, 129: 81–95.
- Stone, E., Skubic, M., and Back, J., 2014. "Automated health alerts from kinect-based in-home gait measurements." Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE.
- Vercruysse, S., H. Devos, L. Munks, J. Spildooren, J. Vandenbossche, W. Vandenberghe, A. Nieuwboer, and E. Heremans. 2012. "Explaining Freezing of Gait in Parkinson's Disease: Motor and Cognitive Determinants." *Movement Disorders*, 27(13):1644–1651.
- Wuehr M., R. Schniepp, C. Schlick, S. Huth, C. Pradhan, M. Dieterich, T. Brandt, and K. Jahn. 2014. "Sensory loss and walking speed related factors for

gait alterations in patients with peripheral neuropathy." *Gait and Posture*, 39(3): 852-858.

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Predictive Modeling in a Residential Building, Validation of Method in a Passively Conditioned Building Using a Test Cell

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ABSTRACT

Computer simulations of an automated dynamic façade in a passively heated and cooled building by using predictive modeling of short-term future weather conditions show that it is possible to achieve thermal comfort in a passively heated and cooled building in at least 10 of the 15 different climate zones in the United States. A small-scale test cell was used to test the ability to predict the interior operative temperature based on predicted weather forecasts and compared the measured results to simulated results. The test cell ran during the part of the Winter through part of the Summer for approximately 6 months.

The days that were thermally cold might benefit from increasing the number of days for the predictive forecast. Increasing the indoor temperature for the preceding days anticipating low total daily solar radiation might raise the thermal mass temperature enough to have fewer hours of thermally cold indoor temperatures. The test cell might be improved with moveable insulation to slow down the heat loss during the night on days with low solar radiation.

The days that were thermally too hot had high average outdoor temperatures. The simple experiment also only set the ventilation rate and the shading amount for the whole day, but night ventilation only with high temperature cut off during day might have improved the thermal comfort level on those days.

The results of the experiment were promising, and they suggest ways to advance the method of predictive modeling in buildings. The results of both the simulation study and the test cell were similar so modifications to the predicted model and predicted control procedure can be studied further with simulation only.

INTRODUCTION

The main hypothesis for this research work is that an automated dynamic façade can provide whole year thermal comfort in a passively heated and cooled building by using predictive modeling with short-term future weather conditions.

Predictive modeling simulation uses a weather forecast to predict the performance of a building for a range of variable building parameters. Two building parameters that are easily changed on a building's facade are the ventilation rate into the building and the amount of shading falling onto a building's glazing using movable shading. The simulation program optimizes the shading and ventilation schedules to try to achieve building thermal comfort for a single day.

Computer simulations of an automated dynamic façade in a passively heated and cooled building by using predictive modeling of short-term future weather conditions show that it is possible to achieve thermal comfort in a passively heated and cooled building in at least 10 of the 15 different climate zones in the United States (Aksamija and Peters, 2016). The two dynamic facade properties that were investigated in the simulation study were movable shading and variable ventilation.

A test cell with movable shading and variable ventilation was designed and built to validate the computer simulations and test the ability to predict and create a thermally comfortable interior temperature using predicted weather forecasts. Small scale test cells have performed as well as larger test cells. A small test cell should have the same insulation levels as the insulation levels of a large-scale building that would be tested but they must be carefully designed to account for corner conditions and ventilation due to three-dimensional volume differences (Grimmer, 1979).

The test cell (Figure 1) was designed to be highly insulated and used a constructed window. The interior shape of the test cell was based on the approximate shape of the whole year building simulation. The interior dimensions of the cell were width: 0.3m, height: 0.3m and depth: 0.5m. the glazing was 0.3m by 0.3m. The insulation levels, thermal mass amount and window type were preselected from simulation runs that show high levels of thermal comfort. The test cell used a small ventilation fan that was controlled by pulse width modulation to adjust the fan speed and control the ventilation rate. The test cell was surrounded by a plywood box to protect it from extreme weather. The box also served as the shading device. The test cell sat on a moveable table that is controlled by a linear actuator. The linear actuator moved the table and test cell back and forth to control the amount of shading.



Figure 1. Test Cell Components showing Shading and Test Cell

EXPERIMENTAL SETUP

Glazing. The glazing for the test cell was designed and constructed to have a low U-value and a high solar heat gain coefficient. For a passive solar heated building a high solar heat gain coefficient (SHGC) and a low U-value are desirable. Using the software WINDOW 7.3 from NREL (NFRC, 2017) a glazing unit was designed to have a U-value of 1.35 W/(m2 °C) and a SHGC of 0.621.

The glazing unit is made up of 4 layers of 2.4mm Lexan separated by 3 layers of 12.7mm Air with 12.7mm extruded polystyrene spacers at the edges. The SHGC was checked by using the ratio of readings from two pyranometers. One pyranometer was placed on the outside of the glazing and the other was placed on the inside. The measured ratio averaged to 0.61. The calculated U-factor also corresponded to the measured U-factor based on a calibration test of the total test cell.

Insulation. The test cell walls, ceiling and floor were made of 200mm thick polyisocyanate for an U-value of 0.098 W/(m2 °C). The insulation was glued together with overlapping joints and corners to minimize air leakage and thermal bridges. A THERM simulation was performed to verify the minimal thermal bridges at corner conditions (Grimmer, 1979) associated with small test cells.

Thermal Mass. The thermal mass for the test cell were tin coffee cans filled with water.

Test cell controls. The test cell controls comprised of a "raspberrypi" single board computer, a linear actuator and two fans in parallel. The single board computer was used to download data and control the ventilation rate and the amount of shading for the test cell. The amount shading is controlled by the linear actuator which extends and extracts to move a table inside the outer box. The ventilation rate is controlled by

a dual fan that runs at different speeds depending on the calculated optimized ventilation rate.

Test Cell Calibration. The assembled test cell was calibrated by using a small heater (15 watt lamp painted black) in a controlled environment. An accurate EnergyPlus simulation model (DOE, 2016) of the test cell was created based on the calibration results.

EXPERIMENT

The test cell was placed with a south facing orientation in Pawtucket, Rhode Island to test the idea that an automated dynamic façade can provide whole year thermal comfort in a passively heated and cooled building by using predictive modeling of short-term future weather conditions. The thermal comfort standard used for this experiment was the Standard Effective Temperature (SET) model (ASHRAE, 2013). The façade elements that would be modified were the amount of shading on the south facing glazing and the amount of ventilation or volume of outside air brought into the interior of the test cell.

The experiment was expected to last for one half of a year and the procedure was as follows. Once every day, a workstation at another location would run a script that would download a weather forecast from the National Oceanic and Atmospheric Administration and convert it into a one-day EnergyPlus weather file. This weather file was appended to the actual measured weather file for previous days in the experiment. The workstation would run a series of simulations that adjusted the ventilation rate and the amount of shading on the glazing until the SET comfort level inside the simulated test cell averaged between -0.5 predicted mean vote and 0.5 predicted mean vote. The workstation then uploaded the optimized ventilation rate and shading amount to the internet.

Once every day, around midnight, the test cell controller would download the ventilation rate and shading amount data. The controller would use the downloaded data to operate a linear actuator to set the shading depth and to control the speed of a ventilation fan to increase or decrease the rate of ventilation in the test cell. A weather station using an Onset HOBO U30 that measures global horizontal solar radiation, dry bulb temperature, relative humidity, rain depth, and wind speed was used to record actual weather data near the test cell. This data was converted into an EnergyPlus weather file that was used for simulations.

Onset hobo data loggers recorded air temperature, relative humidity and globe temperature inside the test cell. Air temperature and relative humidity are two of the four environmental parameters that are used to predict human thermal comfort. A third parameter, mean radiant temperature, can be calculated from the measured globe temperature. The globe temperature measured with a flat gray painted, 38mm globe has been shown to be a good approximation for indoor operative temperature. (Humphreys, 1977). A licor pyranometer connected to a hobo datalogger using an

amplifier (Phillips and Bond, 1999) measured the incident solar radiation in the plane of the glazing at the outside of the test cell. A digital temperature sensor connected to the "raspberrypi" was used to log the interior temperature in real time and was used to monitor the test cell for problems, since the hobo dataloggers were not internet connected and data was downloaded manually at the test site.

The test cell ran from January 20, 2017, until July 7, 2017. From January 20, 2017 until February 18, 2017 the test cell controller software and simulation calibration were modified to improve the accuracy of the simulation results. From February 18, 2017 until July 7, 2017 the test cell ran on its own with only weekly manual downloading of data. On July 5, 2017, the humidity level of the test cell spiked due to one of the thermal mass water cans leaking water into the test cell. The leak was discovered on July 7, 2017 and the experiment was stopped.

EXPERIMENTAL RESULTS

The test cell did not fall within the range of thermal comfort for all hours. For the 137 days in the experiment, the test cell interior globe temperature was out of the SET operative temperature comfort range during 32 of the days for some of the occupied hours. The potential occupied hours for an office building would be from 8AM until 6PM or 10 hours per day, for a total of 1370 occupied hours during the experiment. Out of the 1370 potential occupied hours, 113 hours (8%) were thermally too cold and 25 hours (2%) were thermally too hot. A residential building has different occupancy than an office building, but this experiment shows the potential for increasing comfort levels using predictive simulation with weather forecasts. A sample of the results of the experiment are plotted in Figures 2 and 3.

The days that were thermally too hot had high average outdoor temperatures. The simple experiment also only set the ventilation rate and the shading amount for the whole day but night ventilation only with high temperature cut off during day might have improved the thermal comfort level on those days. The days that that were thermally cold might benefit from increasing the number of days for the predictive forecast. Increasing the indoor temperature for the preceding days anticipating low total daily solar radiation might raise the thermal mass temperature enough to have fewer hours of thermally cold indoor temperatures. The test cell might be improved with moveable insulation to slow down the heat loss during the night on days with low solar radiation.



Figure 2. Test Cell results 02/18/2017 to 04/18/2017

The results graphs show the following data:

1. The interior globe temperature of the test cell.

2. The operative temperature of the simulation used to set the shading amount and ventilation rate labeled perfect model/real forecast since it shows the results of a predictive energy simulation that models the test cell perfectly and it uses the NOAA weather forecast (NOAA, 2019) to optimize the shading and ventilation but used the measured weather data to run the final simulation.

3. The operative temperature of the simulation used to set the shading amount and ventilation rate are labeled perfect model/perfect forecast since it shows the results of a predictive energy simulation that models the test cell perfectly and it uses the measured weather forecast to optimize the shading and ventilation and the measured weather data to run the final simulation.

4. The predicted outdoor air temperature from the weather forecast.

5. The measured outdoor air temperature from the on-site weather station.

6. The predicted global horizontal solar radiation estimated from the NOAA cloud cover forecast.

7. The measured global horizontal solar radiation from the on-site weather station.

8. The upper and lower SET model of thermal comfort operative temperatures.



Figure 3. Test Cell results 05/19/2017 to 07/04/2017

CONCLUSION

The test cell results show potential for improvements in the predictive modeling algorithms. Advances in weather forecasts, particularly solar radiation prediction might improve the results by increasing the likelihood of achieving indoor thermal comfort.

Comparing a perfect forecast against the real forecast in the case of the two perfect modeled buildings (Figure 4) shows that even with the current solar radiation prediction accuracy, the indoor operative temperature the temperature difference has a standard deviation of 1.3 °C.



Simulated Operative Temp. PF vs Simulated Operative Temp. RF

Figure 4. Comparison of simulated operative temperature with perfect forecast and simulated operative temperature with real forecast.

Improving the building data entered in the simulation model might also improve the results. A comparison of test cell globe temperature and the simulated operative temperature with a perfect forecast, shows the difference in real and modeled buildings and forecasts. The difficulty of creating an accurate simulation model show that even for a very simple test cell with known construction and no occupants, the simulation and experimental data did not match. For more complex buildings the difference could be greater.

Another improvement to the predictive modeling simulation algorithm might be to optimize the predicted mean vote for each individual hour instead of average predicted mean vote for the day.

The results of the experiment were promising, and they do give indications to ways to advance the method predictive modeling in buildings. Improvements to the predictive modeling method could lead to more comfortable buildings that use passive heating and cooling strategies.

REFERENCES

- Aksamija, A., T. Peters, 2016. "Passive Solar Facades, Thermal Comfort and Climate Change: Predictive modelling with near and distant weather patterns", Proceedings of PLEA 2016 Conference.
- ASHRAE. 2013. "ANSI/ASHRAE Standard 55-2013.Thermal Environmental Conditions for Human Occupancy." American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASHRAE Sta: 58.

Department of Energy, US. 2016. "EnergyPlus Engineering Reference."

- Grimmer, DP. 1979. "Theoretical Considerations in the Use of Small Passive-Solar Test Boxes to Model the Thermal Performance of Passively Solar Heated Building Designs." Solar Energy 22 (4): 343–50.
- Humphreys, MA. 1977. "The Optimum Diameter for a Globe Thermometer for Use Indoors." Annals of Occupational Hygiene 20: 135–40.
- NFRC. 2017. "THERM 7 / WINDOW 7 NFRC Simulation Manual," no. July.
- NOAA. 2019. "National Digital Forecast Database (NDFD) Simple Object Access Protocol (SOAP) Web Service." Https://Graphical.Weather.Gov/Xml/.
- Peters, Troy N., 2015. "The potential of predictive modeling and automated building facade elements to attain thermal comfort" Proceedings of ARCC 2015 Conference.

- Peters, Troy N., 2020. "Predictive modeling in an automated building facade" Proceedings of Facade Tectonics World Conference.
- Phillips, N, and BJ Bond. 1999. "A Micro-Power Precision Amplifier for Converting the Output of Light Sensors to a Voltage Readable by Miniature Data Loggers." Tree Physiology 19 (8): 547–49.
- USDOE. 2019. "EnergyPlus Website." https://energyplus.net. (accessed January 1, 2016).

Understanding the Indoor Environment Quality of Institutions of Higher Learning in South Africa: A Physical Building Approach

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ABSTRACT

This study seeks to understand the extent to which the indoor environmental quality (IEQ) of Institutions of higher learning or higher educational institutions (HIEs) in South Africa could be improved through the appropriate management of physical building properties (PBP). In the quest for improving the IEQ standards in HEIs, multiple challenges influencing its success has been documented. However, alternative restitution to the management of IEQ is made possible by considering a hands-on approach. A philosophical post-positivism stance influenced the adoption of a quantitative research approach for the study. The primary data on the views shared by various academic and administrative staff members employed by HEIs across South Africa were collected using a closed-ended questionnaire survey. A review of the literature uncovered 15 influential PBP, which probed the objective of the study. A three-phased analytical approach was employed to the gathered data, which consisted of data reliability and statistical evaluation. The descriptive and inferential statistical evaluation revealed that mechanical heating and cooling systems. number of structural openings and routine building maintenance were key PBP to be carefully considered when seeking to improve the IEQ in HEIs. From a practical perspective, the administrative council of HEIs could consider the identified PBP as an alternative approach to the management of IEQ in their respective institutions. Theoretically, this study contributes to the body of knowledge as it provides a further understanding of the present and future research in PBP, which has been lacking in the current environmental management discourse. As a practical approach, the identified PBP could edify any existing or new facilities management procedures to improve the current individual's perception of workplace comfort, satisfaction, and performance directly associated with their indoor environmental conditions.

Keywords: Indoor environment quality, Higher educational institutions, Physical building properties, Satisfaction, Sick building syndrome.

INTRODUCTION

Higher educational institutions (HEIs) are a pinnacle contributor to developing any country's economic, political and social systems. HEIs can be described as a consortium of institutions that offer conducive facilities to administer learning, content creation and dissemination of knowledge at a higher educational level (Alemu, 2019). In understanding its importance, the failure of HEIs to maintain its objective function, which is education, would delay their transformation within themselves and constant change surrounding themselves (policies, social dynamics and economic growth). Furthermore, modern-day climate change has become a challenge due to health issues affecting occupants who spend most of their time indoors (Al Horr et al., 2016). There are multiple sources of pollutants spreading through various channels that lead to the inhabitable indoor space in buildings of higher learning. Since teaching and learning requires a conducive environment, indoor environmental qualities (IEQ) becomes imperatives in the quest for quality education, optimum productivity and wellbeing of staff members as well as staff members of HEIs environment (Sadick, 2018).

As a comprehensive phrase, indoor environmental quality has played a pivotal function in ensuring the adequate environmental condition of any building by addressing three main environmental factors. These factors include ambient (light) and acoustic (sound) together with air quality (composition of temperature, humidity, odours and pollutants). Since these factors exist within the spatial environment of a building, the magnitude of exposure directly influences its occupants' spatial environment. Occupant productivity and overall satisfaction with their indoor experience are driven by the physical building properties (PBP). The lack of routine maintenance and the inability to provide building occupants with an environmental management system designed to suit their indoor requirements and optimise their teaching and learning function persist in developing nations (Yom et al., 2012; Chiu et al., 2017). Considering the declining quality of education in South Africa (Mlachila and Moeletsi, 2019), it is evident that a gap exists in the literature review.

Previously, there have been limited studies and literature relating to the adequacy of IEQ management of HEIs. Based on this observation, this study explores the critical PBP required to ensure effective IEQ in HEIs of South Africa. The study contributes practically to the body of knowledge on IEQ by revealing major building properties to be considered in the pursuit for ensuring quality education through conducive teaching and learning indoor environment. The structure of the paper comprises a review of the literature and a research methodology write-up. Lastly, conclusions and recommendations are drawn from the study's findings relating to PBP as a management tool for IEQ in HEIs.

LITERATURE

Air pollution has been documented to have a long-term effect not only on global warming but also on humans as high concentration levels presented health concerns (Tham, 2016). Cohen et al. (2017) observed that over 10% of the global mortality rate in 2015 was attributed to air pollution (both indoor and outdoor), which exposed humans to environmental risk factors on their health. This resulted in higher cases of economic

inactivity propelled by more health-related employee absenteeism due to the impact of environmental pollutants (Shezi and Wrights, 2018). The phenomenon of IEQ and the factors concerning the indoor environment have been studied in the past two centuries. Adequate ventilation should be provided in any public or user-centric design structures which learning facilities fail to deliver. As a result, sick building syndromes (SBS) are seen amongst students and staff, which make learning and teaching ineffective and difficult in this regard (Al Horr et al., 2016).

Sick building syndrome (SBS) can be described as a class of random medically-related issues brought on by the various indoor conditions experienced by building users (Al Horr et al., 2016). Similarly, the reconstruction of natural space, the use of office equipment such as computers and printers, the introduction of uncertified alternative construction material together with various types of indoor furniture may lead to more cases of SBS (Singer et al., 2006). It is noteworthy that the observations by the Environmental Protection Agency (EPA, 2017) revealed that occupants who experienced prolonged exposure to poor IEQ are a thousand times more inclined to breathe in pollutants than if they were outdoors. Thus, realising the relationship between the IEQ and the PBP of HEIs and their occupants becomes important (Al Horr et al., 2016). Another study revealed that improved IEQ leads to a direct benefit in reduced medical expenses arising from health problems linked to SBS or indirect benefits linked to the increased performance of building occupants (Brager et al., 2015). Similarly, Fisk (2015) stated that the value of an improved IEQ system might be up to 50% in returns compared to the cost, maintenance and construction or leasing of buildings.

The age of the building and its location (cardinal direction) were reported as important building properties to consider (Yom et al., 2012). Similarly, Laaouatni et al. (2017) mentioned that building materials were to be considered in the construction or refurbishment of any building. Jansz (2011) added that high indoor humidity levels might cause building materials to emit more pollutants, mainly through organic materials that comprise volatile compounds. These compounds, over time, develop health hazards such as microbes, moulds, and contaminants in building furniture, indoor fabrics (curtains), and surrounding internal wall finishes (paints, plasters) (Torres, 2009; Brits, 2011). In addition, previous studies have observed the overall design of the building in terms of its shape and functionality as being an important element of the building (Moon et al., 2014; Chiu et al., 2017; Sadick, 2018). Also, routine maintenance has been stressed to prevent moisture problems that may emanate from the buildings' ventilation systems and outlet vents (Brits, 2011).

The cost of an effective ventilation system is always a big concern for building owners and stakeholders. Natural ventilation through the management of outdoor airflow and ventilation ratios can provide IEQ at minimum cost. However, heating, ventilation, and air conditioning (HVAC) systems provide more airflow management and thermal control applications which uses less outdoor air which may be contaminated (Lundgren and Kjellstrom, 2013; Chiu et al., 2017). Yom et al. (2012) further indicated that the building's floor area, number of openings (windows and doors), together with the thickness of the glass windows were crucial PBP to consider when creating conducive indoor environments for occupants. Moon et al. (2014) further attested that the other indoor heat sources such as office equipment are reduced by the amount of airflow within an envelope of the building determined by its floor size. The larger the floor area, the more occupants the building envelope can accommodate more occupants due to the increased levels of ventilation that eliminate individual carbon footprints. To better understand these variables, a taxonomy of the above detailed critical PBP to the adequate IEQ of HEIs is detailed in Table 1.

Table	1: Physical	Building	Properties
	· · ·		

Roles	Literature			
Age of the building	Yom et al. (2012)			
Building location	Yom et al. (2012)			
Building condition (maintenance)	Cooper and Alley (2010), Brits (2011)			
Building material (brick, timber, etc)	Laaouatni et al. (2017)			
	Moon et al. (2014); Lundgren and			
Design of the building (shape, type, etc)	Kjellstrom (2013); Chiu et al. (2017);			
	Sadick (2018)			
Machanical HVAC systems (aircong bostors)	Lundgren and Kjellstrom (2013); Chiu et			
Mechanical HVAC systems (ancons, nearers)	al. (2017)			
Condition of inlet and outlet vents	Moon et al. (2014)			
Floor area	Yom et al. (2012); Ramprasad and			
	Gnanasambandam (2017)			
Distance from openings (windows and doors)	Yom et al. (2012); Sadick (2018)			
Glazing type (glass window)	Yom et al. (2012)			
Indoor ergonomics (furniture arrangement)	Ramprasad and Gnanasambandam (2017)			
Internal wall finishes (paint, wallpaper, plaster)	Torres (2009); Brits (2011)			
Privacy features (curtains, blinds, etc.)	Brits (2011)			
Heat from electronic equipment (computers, printers, etc.)	Singer et al. (2006)			
Ability to control indoor conditions (temperature, etc.)	Nicol and Humphrey (1973)			

RESEARCH METHODOLOGY

A post-positivism philosophical stance guided the objective of the study due to its quantitative nature. As a measure of data reliability for a larger population, a close-ended structured questionnaire survey was adopted as a data collection tool that measured the 15 variables revealed through literature. The questionnaire was randomly distributed to staff members both in academic and administrative roles in HEIs as previous studies on IEQ in educational institutions focused mainly on students (Chiu et al., 2017; Ramprasad and Gnanasambandam, 2017). Twenty-six public HEIs were surveyed, mainly universities (technikons, traditional and comprehensive) across South Africa. The gathering of the respondent's demographics information formed the first section of the survey, while the second section endeavoured to understand the respondent's views on the influence played by PBP on the management of IEQ in their respective institutions. A five-point Likert scale ranging from 1 to 5, were 1 being to no extent and 5 being a very high extent, was adopted to measure the respondent's views in section two of the questionnaire. The Cochran's

sample size equation was adopted at a 90% confidence level and a \pm 7% margin of error to the large population size of 61,242. A sample size of 413 was derived and a total number of 212 completed questionnaire surveys was collected, which yielded a 51.3% response rate. This was deemed acceptable for the current study as the minimum estimated proportion of 50% was adopted (Kline, 2011).

A three-staged data analysis process was adopted for the study. The first stage involved the screening of the data collected. It is noteworthy that no missing data or outlining information was present in the collected surveys. The second stage involved a data reliability test which revealed an alpha value of 0.780 was derived when conducting the Cronbach alpha reliability test, which was higher than the acceptable threshold value of 0.7 for all PBP (Hair et al., 2010). Lastly, the study administered a descriptive and inferential statistical approach to interpret the measured frequency and percentage data relating to the background information of the respondent. Similarly, mean item score (MIS), standard deviation (SD), and a One-Sample T-test were employed to assess the extent to which PBP are influential to their IEQ according to the respondent's views.

FINDINGS AND DISCUSSION

Background information of respondents

Table 2 presents the demographic data of the respondent. It was revealed that over 76% of the staff members spent more than 30 working hours in their workspaces per week, thus supporting the findings of Kecorius et al. (2018), who noted that more than 50% of building occupants spent on average 45 working hours per week. Over 43% of the respondents worked in an enclosed office with single occupancy, while only 9% were stationed in cubicles, in an open-plan office. The majority of the respondents were in both academic teaching and research roles academic-only research roles were the least represented respondents. Interestingly, 3.3% of the respondents recorded a below-average health status while 47.6% were in very good health. From these findings, it is evident that an overall census of the respondents was fairly represented as a group average of 28 working hours was recorded, making them suitable respondents to opine on the study's objective on IEQ management in HEIs of South Africa.

Demographic Category	Category Description	Frequency	Percentage (%)
Average working hours	Less than 10	7	3.3
17.1	11 - 20	13	6.1
	21 - 30	30	14.2
	More than 30	162	76.4
	Total	212	100.0

Table 2: Background information of respondents

Demographic Category	Category Description	Frequency	Percentage (%)
Workstation Setup	Enclosed office - single occupancy	93	43.9
÷.	Enclosed office - multiple occupancies	54	25.5
	Open plan office – Cubicles	19	9.0
	Open plan office – Desks	46	21.7
	Total	212	100.0
Institutional Role	Academic teaching	49	23.1
	Academic research	29	13.7
	Both academic teaching and research	58	27.4
	Academic support	35	16.5
	Administrative support services	41	19.3
	Total	212	100.0
General Health Status	Excellent	57	26.9
	Very good	101	47.6
	Good	47	22.2
	Fair	7	3.3
	Total	212	100.0

Influence of physical building properties in institutes of higher learning

Descriptive Statistics

15 influential PBP are presented in Table 3. The views amongst the respondents have a relatively low variation as all SD values did not exceed the threshold of 1. The sample size was considered as a true reflection of the general HEIs academic and administrative staff population as all standard error mean values closer to zero. The majority of the academic and administrative staff believe that all 15 of the assessed PBP were deemed influential in improving the IEQ management of their HEIs as these variables had a mean value of 3.0 and above. The three most influential PBP were mechanical heating, ventilation and air conditioning (HVAC) systems (MIS = 3.96), number of windows and doors (MIS = 3.92), and routine building maintenance (MIS = 3.85). The current study's findings were analogous to the findings of previous studies in that HVAC systems were crucial to any building design and its intended purpose, which in HEIs is providing quality education (Lundgren and Kjellstrom, 2013; Chiu et al., 2017).

The global community on IEQ research has been published more in developed nations with more literature required for developing nations like South Africa whose findings will contribute to the body of knowledge. It is noteworthy that the above discussed studies were similar in nature in terms of the broader IEQ research area. However, there has been limited studies conducted on the relationship between IEQ management and the academic and administrative staffs' functionality influenced by the physical building properties of their institutions. In other words, there is limited primary research on how academic and administrative staff in institutions of higher learning perceive their state of IEQ in their indoor environments as most available literature relies on indirect secondary evidence from other teaching and learning environments likes schools.

The findings from this study were in harmony with the previous submissions by Cooper and Alley (2010) and Brits (2011). They acknowledged that routine maintenance is important in preventing building decay from moisture build-up in roofs, structures, and

faulty HVAC systems. Moreover, the study's findings corroborated with those of Nicol and Humphrey (1973), who emphasised that the personal ability to control or regulate indoor air comfort through manually opening and closing of building doors and windows was important in the absence of a mechanical unit that adjusted occupants' thermal and humidity comfort. Even though the design of the building was ranked as the third least influential variable, Moon et al. (2013) and Sadick (2018) stressed the shape and functionality of a structure as a crucial element of any building. The decomposition of volatile compounds found in wall and furniture finishes such as paint, adhesives and wallpaper were mentioned to deteriorate over time and cause health hazards such as microbes and moulds (Torres, 2009; Brits, 2011). Bearing this in mind, the respondent ranked indoor ergonomics, and internal wall finishes as the least influential variables that affected their satisfaction with the quality of their workplace's indoor environment.

Table 3: Physical building properties descriptive results	Table 3: Ph	vsical building	properties de	escriptive results
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Physical Building Properties	MIS	SD	R	Std. Error	
				Mean	
Mechanical HVAC systems (aircons, heaters)	3.96	0.701	1	0.048	
Number of openings (windows and doors)	3.92	0.753	2	0.052	
Building condition (maintenance)	3.85	0.676	3	0.046	
Ability to control indoor conditions (temperature, ventilation,	3.84	0.660	4	0.045	
air velocity, etc.)					
Office location in the building	3.58	0.784	5	0.054	
Degree of personal workspace	3.58	0.747	6	0.051	
Floor area	3.50	0.712	7	0.049	
Building location	3.34	0.734	8	0.050	
Privacy features (curtains, blinds, etc.)	3.29	0.813	9	0.056	
Age of the building	3.27	0.772	10	0.053	
Glazing type (glass window)	3.25	0.778	11	0.053	
Heat from electronic equipment (computers, printers, etc.)	3.23	0.853	12	0.059	
Design of the building (shape, type, etc.)	3.20	0.887	13	0.061	
Indoor ergonomics (furniture arrangement)	3.19	0.805	14	0.055	
Internal wall finishes (paint, wallpaper, plaster)	3.14	0.794	15	0.055	
Overall Cronbach alpha (α) 0.780					
Note : $MIS=Mean$ Item Score, $SD = Standard$ Deviation, $R=Rank$					

A one-sample t-test was also conducted to ascertain the influence of the surveyed PBP to

improve the IEQ management of HIEs. A null hypothesis of PBP being non-influential was set at (H_0 : U \leq U₀), while the alternative hypotheses of them being influential was set to $(H_a: U > U_0)$ with U_0 being the population mean of 3.0 (Ahadzie *et al.*, 2008). A p-value base of 0.05 was derived from an influential confidence interval of 95%. After adopting the alternative hypothesis of (H_a : U >3.0), Table 4 revealed that all influential PBP were examined under a two-tailed significance analysis which yielded a p-value = 0.00, thus rejecting the null hypothesis. Also, a p-value lower than 0.05 signifies that no major deviation was present in the views of the various HEIs occupational groups, thus enabling a collective grouping of their views on the degree of influence of each variable.

Table 4: Statistics results of One-Sample t-test

Physical Building Properties	Test Value=3.0			95% Confidence	
			Interval of the		
			Difference		
	t	df	Sig.	Lower	Upper
			(2-tailed)		
Mechanical HVAC systems (aircons, heaters)	19.986	211	0.000	0.87	1.06
Number of openings (windows and doors)	17.786	211	0.000	0.82	1.02
Building condition (maintenance)	18.385	211	0.000	0.76	0.95
Ability to control indoor conditions (temperature,	18.632	211	0.000	0.76	0.93
ventilation, air velocity, etc.)					
Office location in the building	10.683	211	0.000	0.47	0.68
Degree of personal workspace	11.314	211	0.000	0.48	0.68
Floor area	10.320	211	0.000	0.41	0.60
Building location	6.741	211	0.000	0.24	0.44
Privacy features (curtains, blinds, etc.)	5.153	211	0.000	0.18	0.40
Age of the building	4.361	211	0.000	0.13	0.34
Glazing type (glass window)	4.326	211	0.000	0.13	0.34
Heat from electronic equipment (computers,	3.943	211	0.000	0.12	0.35
printers, etc.)					
Design of the building (shape, type, etc.)	3.562	211	0.000	0.10	0.34
Indoor ergonomics (furniture arrangement)	3.752	211	0.000	0.10	0.32
Internal wall finishes (paint, wallpaper, plaster)	3.808	211	0.000	0.10	0.31

Note: t=t-statistic, df = Degree of Freedom, Sig. = Significance (p-value < 0.05)

CONCLUSION AND RECOMMENDATIONS

The study explored an alternative approach to effective IEQ management through the provision of PBP of HEIs in South Africa. Based on primary and secondary data reviewed, it can be concluded that the failure of appraising building conditions could pave the way for the development of biological markers and moulds that trigger SBS and other health-related hazards for staff members of HEIs. From a practical perspective, the main findings revealed that although building conditions or the maintenance thereof have not been given a comprehensive focus in past studies, the current study amplifies its importance to achieving a conducive working environment. Theoretically, the edification of the study's findings to the existing body of knowledge proposes a sustained alternative to the management of HEIs in other developing countries like South Africa that have limited discourse in the field of indoor environmental studies.

Therefore, it is recommended that effective IEQ management through air purification using air filters and the maintenance through unclogging of outlet pipes where stale air is present would ensure adequate indoor environments conducive to the optimum performance by HEIs staff. The occupants' proximity to the doors and windows influences their overall satisfaction of their indoor workplace as existing outdoor pollutants such as smoke is introduced to the indoor environment through these avenues. Successful IEQ management in HEIs would not only improve the rate of absenteeism due to reduced SBS but will promote a conducive teaching and learning environment attributed to the improved psychological and physiological wellbeing of staff members.

REFERENCES

- Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M. and Elsarrag, E. (2016), "Occupant productivity and office indoor environment quality: A review of the literature", *Building and Environment*, Vol 105, pp.369-389
- Alemu, S.K. (2019), "African higher education and the Bologna Process", *European Journal of Higher Education*, Vol 9 No. 1, pp. 118-132
- Brager, G., Zhang, H. and Arens, E., 2015. Evolving opportunities for providing thermal comfort. *Building Research & Information*, 43(3), pp.274-287.
- Brits, P.J. (2012). Assessment of indoor air quality in an office building in South Africa. Dissertation, University of the Witwatersrand. Available from: http://wiredspace. wits. ac. za/handle/10539/11041 (Accessed on 03 December 2019).
- Chiu, Y.H., Chiang, Y.C., Cheng, Y. (2017). Insights into adaptive thermal comfort on learning efficiency of students a classroom-based case study. *Ergonomics International Journal*, 1(4).
- Chiu, Y.H., Chiang, Y.C., Cheng, Y. (2017). Insights into adaptive thermal comfort on learning efficiency of students a classroom-based case study. *Ergonomics International Journal*, 1(4).
- Cohen A. J., Brauer M., Burnett R., Anderson H. R., Frostad J., Estep K., Balakrishnan K., Brunekreef B., Dandona L. and Dandona R. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), pp.1907-18
- Cooper, C.D. and Alley, F.C., 2010. *Air pollution control: A design approach*. Waveland press.
- Fisk, W.J. (2015). Review of some effects of climate change on indoor environmental quality and health and associated no-regrets mitigation measures. *Building and environment*, 86, pp.70-80.
- Hair, J.F., Jr, Black, W.C., Babin, B.J. and Anderson, R.E. (2010), "Multivariate Data Analysis", 7th ed., Pearson Prentice Hall, Upper Saddle River, NJ
- Jansz, J. (2011). Theories and knowledge about sick building syndrome in sick building syndrome in public buildings and workplaces. S.A.: Springer, 25–58.
- Kecorius, S., Tamayo, E.G., Galvez, M.C., Madueño, L., Betito, G., Gonzaga-Cayetano, M., Vallar, E. and Wiedensohler, A. (2018), "Activity pattern of school/university tenants and their family members in Metro Manila–Philippines", *Aerosol and Air Quality Research*, Vol 18, pp. 2412-2419

- Kline, R.B. (2011), "Principles and Practice of Structural Equation Modelling", Guilford Press, New York
- Laaouatni, A., Martaj, N., Bennacer, R., El Omari, M. and El Ganaoui, M., 2017. Phase change materials for improving the building thermal inertia. *Energy Procedia*, 139, pp.744-749.
- Lundgren, K. and Kjellstrom, T. (2013), "Sustainability challenges from climate change and air conditioning use in urban areas", *Sustainability*, Vol 5 No, 7, pp. 3116-3128
- Mlachila, M.M. and Moeletsi, T. 2019. Struggling to make the grade: A review of the causes and consequences of the weak outcomes of South Africa's education system. International Monetary Fund. Available from: <u>https://www.imf.org/~/media/Files/Publications/WP/2019/WPIEA2019047.ashx</u>. (Accessed 15 May 2020).
- Moon, J.W., Lee, J.H., Yoon, Y. and Kim, S. (2014), "Determining optimum control of double skin envelope for indoor thermal environment based on artificial neural network", *Energy and Buildings*, Vol 69, pp. 175-183
- Nicol J.F. & Humphreys M.A. (1973), Thermal comfort as part of a self-regulating system, *Building Research and Practice* (J. CIB), 6(3), pp 191-197
- Ramprasad, V. and Subbaiyan, G., 2017. Perceived indoor environmental quality of classrooms and outcomes: A study of a higher education institution in India. Architectural Engineering and Design Management, 13(3), pp.202-222.
- Sadick, A.M. (2018), "Assessment of school buildings' physical conditions and indoor environmental quality in relation to teachers' satisfaction and wellbeing", PhD Thesis, University of Manitoba, Canada
- Shezi, B. and Wright, C.Y. (2018). Household air pollution exposure and respiratory health outcomes: a narrative review update of the South African epidemiological evidence. *Clean Air Journal*, 28(1), pp.43-56
- Singer, B.C., Coleman, B.K., Destaillats, H., Hodgson, A.T., Lunden, M.M., Weschler, C.J. and Nazaroff, W.W., 2006. Indoor secondary pollutants from cleaning product and air freshener use in the presence of ozone. *Atmospheric environment*, 40(35), pp.6696-6710.
- Tham, K.W. (2016), "Indoor air quality and its effects on humans—A review of challenges and developments in the last 30 years", *Energy and Buildings*, Vol 130, pp. 637-650
- Torres, E.R. (2009). An evaluation of lead hazards in pre-1978 residental housing within *Clark County*. Nevada, USA.
- Yom, Y.W., Chun, C., Arens, E., Goins, J. and Zhang, H. (2012), "Relation between occupant satisfaction with indoor environmental quality and building characteristics, workspace, and personal factors", *In 10th International Conference on Healthy Buildings* July 8-12, Brisbane, Australia, pp. 725-730

Housing Design Studio: The Case for Social Entrepreneurship

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ABSTRACT

This paper outlines a participatory development strategy first tested and adopted in practice and now being reoriented as an educational studio design process. Two case studies from practice will be explored that provide unique strategies for empowering community. These crowdsourced projects pool resources and expertise in order to design and build projects that resist gentrification, stimulate investment, and build community. Professionals work directly with neighborhood residents to utilize the participatory actions of establishing a pro forma, acquiring land, securing financing, selecting professional engineers and contractors, and ultimately constructing the project all as larger components of community building. The professional models of community development presented here offer an alternative to the traditional designer-client dichotomy and allow the once-clear boundary between architect and client to be redrawn.

We then explore the translation of this process into an educational experience where students in a design studio explore difficult community development issues with building owners and stakeholders. The potential of the educational model is more profound than a traditional design studio in that rather than simulating project constraints fabricated by a studio instructor, actual concerns and issues are brought to the exploration. The studio operates at a scale and scope beyond that which could be accomplished by any one professional firm. It empowers students to chart a path that rejects a discipline rooted in form-making and aesthetics. It teaches the process of architectural design to be one of entrepreneurship. Students act as community organizers in setting up the framework in which community members are able to become active participants in their built environment.

Introduction

Our experience with participatory design reveals a problem with the predominant architecture business model: designers are commissioned exclusively by those with privilege. Design fees are paid by a professional client funding development projects seeking to make a return on investment. However, further examination into a built environment reflective of social justice recognizes that only those affected by an environment have any right to its determination.

In attempting to bring theoretical underpinnings to our participatory design work, one

can examine the increasing number of architects that are finding ways to break free of a practice dependent upon clients paying for professional services. (Feldman et al. 2013) A new 'entrepreneurial' model of practice may loosen the constraints of designers who are torn between the need to operate within a viable business model and the desire to bring design engagement to traditionally underserved neighborhoods. Entrepreneurship is a process by which individuals pursue opportunities without regard to the resources they currently control. (Stevenson and Jarillo 1990) The entrepreneurial architect, then, is one who is able to identify opportunities for change in our communities and *independently* takes constructive action.

The re-framing of the client role that may free the design professional from responding solely to the needs of paying clients, redraws boundaries that may allow us to address more complex challenges: climate change, crumbling infrastructure, lack of access to clean drinking water, food insecurity, disaster response, refugee shelter in areas of conflict, homelessness. Solutions to these and other challenges are rooted in the design and stewardship of the built environment. In an age of opensource architecture, crowdsourced information, and global interconnectedness, today's designer has never been better equipped to meet these challenges head-on.

The modest interventions explored here serve as demonstrated attempts to transition residents from passive bystanders to active participants in the shared process of community redevelopment. In this case, it is the professional knowledge surrounding real estate development and valuation that allows for this transition to active participant. Brazilian educational theorist Paulo Freire's 'banking' concept of empowerment is relevant to this point. His analogy contends that in the traditional educational model, the teacher 'deposits' knowledge into the student as though the student is an empty container. The passive learner is acted upon and the potentially emancipatory process of gaining knowledge (and therefore power) is negated by being reduced to a one-way mechanical transaction. (Freire 2005)

Stakeholders sharing in the visioning process for community redevelopment projects has long been held as a requirement of any sensitive revitalization effort. How can stakeholders be elevated from peripheral players to decision-makers that may be able to invest (even modestly) in a community's transformation and thus directly benefit from shared investment efforts? This mode of shared participation transcends the monetary transaction. The willingness to invest in one's own neighborhood reflects a willingness to invest in oneself and the belief that these actions can allow one to act strategically and critically to restructure a world one cannot wholly remake. (Colistra 2016)

Champa Terrace

The authors' firm, in situ Design, was contacted by a group of neighbors living in the historic Curtis Park neighborhood of Denver, Colorado. An initial group of eight families, all living within a few blocks of the property, formed a Limited Liability Company and purchased the lot for \$40,000. The group then began recruiting other

interested parties within the neighborhood. They set out to construct a viable real estate development while protecting the neighborhood's historic character. As the venture gained momentum, town hall-style design workshops were held to manage the project. The resident group was from a diverse range of economic backgrounds that included such professions as a city planner, a teacher, an historian, a lawyer, and several residents who worked in the construction trades. They were brought together by concerns for the future of their neighborhood. A true example of crowdsourcing, these long-time neighborhood residents put their own homes up for collateral in order to secure a construction loan of \$1 million. This group of twenty-three neighbors recognized the power that came with organizing politically. in situ Design worked with the group over the following months to develop a 4-unit townhouse project that would be called Champa Terrace.

The project sold out within six weeks of the completion of construction and investors realized approximately 65% return on investment. This type of infill project is likely to raise property values. However, a key distinction from typical gentrifying developments where all return on investment leaves the neighborhood, this framework allows all profit to stay within a few blocks of the project. The process also resists gentrification by consciously weighing profit against affordability and setting up a structure in which investors are not driven solely by return on investment but also on community cohesion.

Merchants Row

Champa Terrace was lauded in the local press for its proactive approach to community development. Feeling enfranchised and seeing the opportunity to replicate this development model, the group looked into rolling its returns into a second project. This second self-development model is called Merchants Row Brownstones. This \$2.5 million multifamily housing development is modeled after a rowhome prototype common to the neighborhood. Sensitive of context, the group prioritized the relationship of form, mass, and scale to the surrounding buildings. The primary feature of the exterior is a reinterpretation of the historic bay: a three-story mullionless curtainwall. Figure 1. These not only allow daylight to penetrate deep into the units, they also represent metaphorically the visual connection to openness and transparency.



Figure 1. Merchants Row

This project, like the earlier example, sold out soon after the completion of construction. The pride the group took in witnessing a cultural enterprise emerge from their shared ideas and resources was evident. Open house events and tours were more of a neighborhood celebration than marketing event and extended even after all the units were sold. Several investors, in various structures and configurations, continue to roll over development proceeds into neighborhood investments of various scales.

Social Entrepreneurship Housing Studio

The authors are currently engaged in a studio teaching model at the University of Kansas that engages local neighborhoods to seek out self-development projects. One such project is in Kansas City, Missouri that has the potential to demonstrate a city-wide strategy for the revitalization of underserved communities through the notion of shared economy. In April of 2017, Kansas City voters were asked to approve a one-eighth-cent sales tax to spur economic development in the city's most blighted neighborhoods.

The Central City Economic Development Sales Tax is to be in place for 10 years and provides a projected revenue of \$8.6 - 10 million each year. This citywide tax would only be utilized in an area bounded by Ninth Street to the north, Gregory Boulevard to the south, the Paseo to the west and Indiana Avenue to the east. Essentially, Kansas City's traditionally most underserved neighborhoods. An appointed board made up of designees of such entities as the Mayor's office, the school board, city council, etc.

will oversee the distribution of the tax revenues. The authors, with affiliated faculty from the Kansas City Design Center (KCDC), engaged citizenry from within this established boundary in order to respond to the city's Request for Proposals.

A sales tax is often hurtful to the poor, however, rather than reinvesting the tax revenue in neighborhoods that are well-positioned, the revenue from this initiative will be limited to an area identified with high crime, unemployment, dilapidated housing stock, and a lack of development. (Kades 2016) Leaders of the initiative cited two reasons why this tax makes sense: 1. When a city's core is healthy, the entire city is healthy; and, 2. Residents of these neighborhoods have consistently supported similar tax initiatives that funded major projects outside the core, including a \$1billion airport improvement project. (Gray 2017) The vote was telling. Most neighborhoods voted in favor of the tax despite the reality that it would not directly affect them. (Knox 2017)

Neighborhood Prospects

An advisory committee consisting of city, civic, and professional as well as community residents and stakeholders provided critical guidance towards the project's development; innumerable residents, stakeholders, and city staff also contributed time and advice through participation in public meetings and other conversations. Student-community service-learning projects can be akin to Trojan horses. By throwing earnest and often naïve students into the thicket of community design, we rely on a great number of residents, stakeholders, and community officials to volunteer their perspectives. The student-community project is an opportunity for all to think big – not to abandon the constraints of a project but to hold decision making at bay while engaging students in the project's greater ambitions. Advising students through the essentially academic exercise of inquiry, analysis, and creative design proposals is low risk for all. And, one that comes with the benefit of contributing to the education of the next generation. In this manner, student-community projects can, at their best, draw stakeholders together in a frank discussion that might not be possible where the stakes are higher.

The first iteration of a response to the city's Request for Proposals process has been completed. The proposed self-development project is for a 6-unit townhome project priced in the range of \$170,000. Various solutions have been tested to arrive at a viable development model. Schematic financial analysis utilized construction costs provided by a local contractor. Single family homes were estimated to cost in the range of \$140/sf while the efficiencies of a multifamily structure brought the cost down to about \$110/sf. All proposed options were market-driven and assumed at least 10% profit. This resulted in the required sales price for single-family homes to be approximately \$330,000 while townhomes would need to yield a sales price of \$170,000. Figure 2.



Figure 2. Development Schemes

This difference is significant. Not only is a home price above \$300,000 not compatible with comparable prices in the neighborhood, homes in this price range would almost exclusively be marketed to buyers from outside the community. Units for sale at \$170,000 could serve home buyers with a desire to remain in the community. It is estimated such units would yield monthly payments of \$750 to \$850. This is well within the range of apartment rental rates within the neighborhood. The goal of creating affordable housing is elusive in a neighborhood that has suffered disinvestment that has resulted in depressed property values. Typically, affordable housing can be defined as being able to attain housing at no more than 30% of one's income. Using this standard, a two-income family earning the Area Median Income of \$22,000 could comfortably maintain these anticipated mortgage payments.

The Central City Economic Development Sales Tax Board did not select the project for funding. However, the model that was developed laid the groundwork for the neighborhood group to receive funding in subsequent applications.

Downtown Lawrence Design Center

The pedogogical success of the service-learning experience evolved into several other iterations. Granted modest funding from the University's Center for Service Learning, the School of Architecture & Design was able to secure storefront space in downtown

Lawrence, Kansas. Figure 3. This facility is referred to as the Downtown Lawrence Design Center. Our School's visual presence and our commitment to taking on pressing downtown development issues conveys our University's commitment to our Lawrence community. We engage in master plans, research studies, and design exercises that provide insight to the complex development issues of our downtown. Again, our commitment to community engagement is underpinned by the belief that only those affected by an environment have any right to its determination.



Figure 3. Downtown Lawrence Design Center

Pedagogically, this immersive service-learning experience, uses downtown sites and engages the land owners and community stakeholders to offer real-world experience while being afforded the space to approach design problems with rigorous critical thought. The studio is also "contingent" in nature. Unlike a self-contained introverted studio that has a predetermined and well-defined scope, this somewhat flexible practicum is set up to confront the unforeseen and uncontrollable aspects of architectural practice. The goal is to empower students with the improvisational intelligence necessary to navigate the unknown, and unknowable, that define all realworld endeavors. This approach implicitly embraces the assumption that design extends beyond formal and aesthetic concerns. As such, a contingent pedagogy is one that confronts students with an architectural problem of indeterminate scope in order to expand the potential field of operation beyond conventional academic limits. Reconciling competing opportunities and constraints into a design solution that simultaneaously serves the client and larger community is seldom a straightforward endeavor. Students are challenged to imagine not only new physical environments but also new modes of architectural production in realizing solutions that facilitiate socially and environmentally responsive design.

Design solutions that aspire to goals such as these can rarely be achieved by any stand-alone building design, and they cannot reside the physical realm alone. The process of making architecture may be re-examined and re-imagined to operate in a way that might be referred to as entrepreneurial as it was defined earlier.

The Downtown Lawrence Design Center is the University's only presence in our downtown business district. Projects displayed in the windows attract community statkeholders and passerbys to engage us in discussions. Students are exposed to the critical soft-skills of communication, professionalism, and engagement. Building owners and developers benefit from the University's "neutral" voice being brought to bear on issues facing our downtown. And, design firms appreciate the broad scope of our project approach and our attempt to "tee-up" projects for further professional study. Figure 4.



Figure 4. Design Project, Students N. Acosta and Z. Early

Conclusion

The authors have developed several professional projects that have developed new ideas about entrepreneurship and community participation. These modest projects engage communities to self-develop housing ventures that are not only profitable but provide opportunities for communities to organize and determine the future

development trends of their own neighborhood. The efforts also generate a profound sense of pride as residents witness the emergence of a meaningful enterprise being built using their own resources and ideas.

These strategies for community engagement and community organization are altered to serve as a vehicle for service-learning experiences. The Social Entrepreneurship Housing Studio model implies inclusive participatory input from those affected by a development project. It also suggests that participants have an opportunity to share in the increased value that is brought to their neighborhoods by real estate development. The value created by architectural production has been one of the most stable and well-performing strategies for growing wealth. Yet, participation in real estate development is an impossibility for the vast majority of the population. Through entrepreneurial design thinking, architects have the potential to ease the barriers to such community investment opportunities and share in the transformative act of building community.

Both the studios described here, the downtown Kansas City Design Center studio and the Downtown Lawrence Design Center studio embed design students in a community. Builidng owners, developers, and community stakeholders utilize the physical and theoretical space as a safe and neutral place to discuss broad ideas about community building. The problem fields are perhaps broadened to accommodate the optimistic leanings of ambitious students just beginning to understand the constraints of real-world development. And, community members are more willing to engage in the "academic exercise" of imagining the future without the risk or investment of a true pragmatic proposal.

Students, perhaps for the first time, are beholden to a real estate financial pro forma, zoning codes, and parking requirements. They are able to hear first-hand the concerns and needs of building owners, how these needs may depart from the needs of broader community stakeholders, and facilitate conversations that search for common ground.

Although the scale of the community interventions shared here are small, these professional projects and student explorations are clear territorial demarcations of community empowerment. Participants move through and away from these experiences forever changed from passive occupants of a built environment to citizens armed with the knowledge and resources to act upon the world.

References:

Colistra, J. (2016). Critical Practice: Alternative Modes of Empowerment. *Dialectic IV: Architecture at Service*?, 21–27.

Feldman, R. M., Palleroni, S., Perkes, D., & Bell, B. (2013). Wisdom from the Field: Public Interest Architecture in Practice, A Guide to Public Interest Practices in Architecture. Wisdom from the Field: Public Interest Architecture in Practice, A
Guide to Public Interest Practices in Architecture. Washington, DC: American Institute of Architects.

- Freire, P. (2005). *Pedagogy of the Oppressed*. (M. B. Ramos, Trans.). New York, NY: Continuum.
- Gray, R. (2017, November 17). KCI plan may face unexpected turbulence from federal tax reform. *The Kansas City Star*. Retrieved from https://www.bizjournals.com/kansascity/news/2017/11/17/kci-plan-may-face-unexpected-turbulence-from.html
- Kades, E. (2016). Giving Credit Where Credit is Due: Reducing Inequality with a Progressive State Tax Credit. *Faculty Publications*, *1830*. Retrieved from http://scholarship.law.wm.edu/facpubs/1830
- Knox, R. (2017, May 2). Can Kansas City come together? *Citylab*. Retrieved from https://www.citylab.com/solutions/2017/05/can-kansas-city-come-together/525012/
- Stevenson, Howard and Jarillo, J. Carlos, A Paradigm of Entrepreneurship: Entrepreneurial Management (1990). Strategic Management Journal, Vol. 11, p. 17-27 1990. Available at SSRN: <u>https://ssrn.com/abstract=1505897</u>

Can intergenerational cohousing be a possible living option for aging-inplace: cohousing case studies in the UK

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ABSTRACT

The older population is rapidly increasing worldwide, becoming a global concern. Due to the aging of the population alongside a constant increase in life expectancy, aging in place has emerged as a necessary and valuable guiding strategy in addressing and meeting the needs of the elderly. In this social context, a collaborative living model (cohousing) has attracted the attention of many scholars and social workers. Increasing numbers of researchers and professionals have proposed that cohousing communities have great potential to achieve aging in place via its special co-design procedure and supportive social interactions. This paper aims to investigate whether the intergenerational cohousing model can be a possible and supportive living option for aging in place. The paper demonstrates the advantages and limitations of cohousing communities for aging in place from two aspects: built environment features; and social interactions. This study involved seven cohousing communities in England, accounting for 24 participants. Semi-structured interviews were conducted with project architects and cohousing residents. Focused site observations were carried out in two cohousing communities. The data was collected and analyzed through a qualitative approach to represent cohousers' neighborhood design process, built residential environment and living experience. The findings of this paper highlight fundamental design principles related to aging in place, such as housing adaptability, accessibility and mutual support neighborhoods, and concludes with design recommendations that could guide future neighborhood design and management in order to enable the older population to age-in-place in an age-friendly community setting.

Keywords: aging-in-place, old population, cohousing community, neighborhood design principles, residential environment.

1 Introduction

The older population is rapidly increasing worldwide, becoming a global concern (World Health Organization, 2015). Research by the European Commission shows that the percentage of people aged 65 and over is increasing at an unprecedented speed and is expected to account for over 30 per cent of the European population by 2060 (European Commission, 2015). Therefore, it is fundamental to develop new concepts, systems, and programs to fulfil not only the expectations of older populations, but also for service providers, local governments, and decision makers (Lecovich, 2014). Recently, increasing numbers of scholars are paying attention to the living needs of older people, especially those needs related to their housing environment and social lives. Due to the aging of the population and a constant increase in life expectancy, 'aging in place' has emerged as a necessary and valuable guiding strategy in addressing and meeting the needs of elderly people. The term aging in place is defined as "remaining living in the community, with some level of independence, rather than residential care" (Davey, et al., 2004). To this end, a collaborative residential model named 'cohousing' has drawn great public attention and is seen as a possible living option to age in place because of the nature of collaborative living and its co-design procedure.

The aim of this study is to investigate whether the intergenerational cohousing model (mixed age cohousing) can be a possible and supportive living option for aging in place. A more thorough understanding of aging in place in a cohousing environment could provide knowledge not only for increasing the home-environment adaptation of older residents, but more importantly, the findings of this study are able to enrich the meaning of 'ageing in place' and provide more explanations for cohousing community living. Therefore, this study was guided by the following research question:

• How can intergenerational cohousing be a positive living option to support aging in place for older people?

2 Literature Review

The literature review comprises three parts. First, it introduces the background context of cohousing. Second, it discusses the concepts of ageing in place and age-friendly environment. Third, the literature review outlines the use of the Lifetime Home design standard.

2.1 Background of cohousing

The concept of communal living has existed for millennia (Newsham, 2018). For most of human history, people were hunter-gatherers who lived in large camps and depended on one another for food, child and elder care, and everything else (Strauss, 2016). The form of intentional living based on sharing can be traced back to agricultural times when senior farmers lived in units now called Accessory Dwelling Units (ADUs) or "granny flats" in the United States (Anacker & Niedt, 2019). The term 'cohousing' (synonymous with 'CoHousing' or 'cohousing') is a generic European term for "collaboratively designed and built housing spaces for multiple households that develop 'self-managed social architectures' to share activities and experience" (Nelson, 2018, p.xii). Nowadays, traditional forms of housing no longer address the needs of many people and a lot of people are mis-housed, ill-housed or unhoused due to a lack of adequate housing options (McCamant & Durrett, 1994). Therefore, cohousing has emerged as a new collaborative housing concept, designed to foster meaningful relationships, social interactions, and energy efficiency concepts. Once a cohousing community is established, it is maintained by its residents and functions as a community through shared amenities, facilities, and spaces.

The cohousing phenomenon is now widely extending to many European countries. As pioneers of cohousing scheme - Denmark, Sweden and The Netherland, they have been promoting cohousing for nearly 50 years (The Cohousing Association of The United States, 2007). Particularly, in Denmark, today more than 1 percent of Danish population, about 50,000 people live in cohousing (UK cohousing network, 2021). Recently, research shows that there is a huge interest in cohousing scheme among seniors. According to HERE & NOW (2020), around 80,000 of seniors would be prepared to move into cohousing schemes over the next few years, but there are only around 7,000 co-housing homes. This represents that cohousing is in short supply in Denmark. Meanwhile, Sweden also has long-standing cohousing tradition (UK cohousing network, 2021). Most of the cohousing projects are state-owned, as they were developed as part of a large societal project of an active welfare state. In recent years, cohousing schemes are seen as one of the positive aging options for seniors, many older residents who are experiencing co-living claimed that cohousing scheme decreases segregation and offers a better quality of life (Savage, 2020). However, there is extremely limited access and progress in the UK for all types of community-led housing (e.g., cohousing, housing cooperatives, community land trusts) compared with other countries in Western Europe (e.g., Denmark and Germany).

Through cohousing, residents are committed to living together as a community that, in turn, gains the benefits of a supportive social network (Garciano, 2011; Hagbert, et al., 2020). Typically, a cohousing community is a group of between 15 and 40 households (15-35 families, approximately 50-100 people) who come together and share facilities and belongings (Lietaert, 2009; Hagbert, et al., 2020). As stated by UK Cohousing Network (n.d.), cohousing communities have a common house, with shared facilities such as cooking and dining spaces, meeting and playing areas, laundries, and guest rooms. Sargisson (2012) indicated that cohousing communities are established based on a concept of sharing, not only of physical spaces and resources, but also communities is to minimize living costs, including rent, car ownership, and energy consumption (Thorne, 2015). Community living may enable residents to reduce living costs via shared resources, education, cars, workshops, caring for children and older people, tutoring and training (Priest, 2015; Garciano, 2011).

2.2 Aging in Place and age-friendly environment

The statistics around ageing population are widely known and represented. Nowadays, the UK's population is ageing, According to Agediscrimination.info (2020), 15.2% of the UK population is aged over 70. At the same time, the demands of older people are receiving more attention. Additionally, for older people, their lives not only require sufficient material comfort but also self-value and a sense of belonging. As Wealleans (2015, p.166) stated: "A needs focused view of ageing populations underestimates the value of older people and the contribution they make to society. Obviously, it is a good thing that we are living longer but we need to ensure that people are living stronger for longer and with purpose and a sense of belonging. There are two types of cohousing strongly related to older people: intergenerational cohousing. When discussing older people's needs and their current living status, it is important to understand the term 'aging in place'. As stated on the Senior Resource website, the term has been defined as "living where you have lived for many years, or to living in a non-healthcare environment, and using products, services and conveniences to enable you not to have to move as circumstances change."

When talking about which type of housing design in cohousing community can lead to a healthier and independent lifestyle, it is necessary to define the daily tasks, environmental barriers, functional limitations, and housing preference among the residents, especially for older people. The home environment is a vital consideration and determinant for daily activities and participation for the older generation. Specifically, the physical settings of housing can support independent living, and it is the critical indicator for older people who hope to continue to live a normal life at home as long as possible (Iwarsson & Wilson, 2006). Danziger and Chaudhury (2009) proposed that physical frailty can be delayed if the environmental factors matched the individual's capabilities. Further, it would provide more opportunities to maintain their independence; failure to match the environment would increase their vulnerability and risk for injuries.

Based on this foundation, the key element to meeting the needs of older people and creating supportive housing environments is the physical environment of the home (Hwang, 2011). In other words, the living environment could foster healthy living and subjective well-being (Iwarsson &Wilson, 2006). In this study, the research paid extra attention to the permanent features in the interior spaces or immediate outdoor home environment (e.g. installation of lifts; door widening) to increase accessibility of the home environment. The primary purpose of this section is to explain the home environment barriers and functional limitations in housing

among older people, in order to provide foundational knowledge of difficulties and accessibility issues from a long-term perspective. According to Iwarsson & Wilson (2006, p.63), the environmental barriers can be found in the following places: narrow paths; narrow door openings; poor illumination of walking surface; slippery bathroom surface; no grab bars at shower/ bath and/or toilet; and no level area in front of entrance doors. At the same time, other concerns have been addressed by different researchers, such as the shower tub is too high, the cupboard is too high or too low in the kitchen, lacking storage space in the bedroom, and, the balcony ramp is too small and steep. (Danziger & Chaudhury, 2009).

2.3 Lifetime Homes Standards (LHS)

Lifetime Home Standards (LHS) were established in the mid-1990s to incorporate a set of principles that should be implicit in good housing design (Goodman, 2011). They include 16 design criteria under five categories (Inclusivity, Accessibility, Adaptability, Sustainability and Good Value) that can be widely applied to new build and housing retrofit. These criteria were targeted to improve the property to be flexible for a wide range of people and also introduce adaptability into the housing layout and design. Lifetime homes can provide benefits especially to older people, disabled people, and anyone with physical impairments to make their home more accessible and inclusive.

In the cohousing context, LHS can be applied to benefit both types of cohousing models. Therefore, Lifetime cohousing could become an effective housing model to maximize the opportunities and potentials of housing and neighborhood design for cohousing members and promote better neighborhood sustainability. In addition, LHS also influences social interactions and common activities. As Kelly (2001, p.72) suggested, "flexible, usable and adaptive building design of lifetime home is able to influence social patterns and processes. It will encourage neighborhoods to evolve and flourish [...] they represent the best way to achieve community sustainability". Although this study acknowledges the advantages of LHS, some limitations must also be considered. On the one hand, within the 16 design criteria, LHS do not incorporate sensory factors including room temperature, humidity, air quality, sound, and lighting control. On the other hand, the design criteria may not be fully applied to intergenerational families because they exclude children from consideration and explain the life course period from adulthood to old age (Allen et al., 2002; Imrie, 2006).

3 Methodology

Taking into consideration the research questions mentioned earlier, the position of this study falls firmly within the interpretivist paradigm and is guided by the concepts of environment psychology. As such, it was decided that the inductive approach should be applied in this study using case studies. The methods of this research were divided into data collection and data analysis categories using multiple qualitative methods.

In this research, the term 'older people' is defined as someone over the age of 60. Seven cohousing communities were examined in England (located in Lancaster, Leeds, Sheffield, and Cambridge). In total, 24 participants were involved in this study. Semi-structured interviews were conducted with project architects and cohousing residents (aged from 49-73). Focused site observations were carried out in two cohousing communities: LILAC; and Lancaster cohousing. The observations aimed to capture intergenerational social activities (e.g. common meals), and the design and application of common facilities and community daily routines. Based on the collaborative design process, the study included both parties (architects and building users) of the design process into the research and paid special attention to the future building occupants (future cohousing residents). Specifically, this was accomplished by

interviewing architects, current cohousing residents, and future cohousing residents, investigating their expected needs in various areas of the cohousing community, how the common space (e.g. common house) was to be divided and used to support aging in place and whether any special requirements existed among them (e.g. different building design standards applied for supporting older residents).

In this study, the data were analyzed using Interpretative Phenomenological Analysis (IPA) and a process of Qualitative Content Analysis (QCA), using thematic coding techniques. IPA was applied to analyze the observation date set (Smith & Osborn, 2007; Smith & Shinebourne, 2012). QCA was used to analyze the interviews and secondary data (Mayring, 2014). IPA was carried out through exploring the deeper meaning behind the physical environment (design aspects, quality of community space) and the social environment (social connections, social distance, work relationship, mutual support, and environment for raising children) in the selected cohousing communities. QCA was carried out through various types of coding techniques (Saldaña, 2015). These coding techniques were used to define the main themes and to identify the relationships between the themes.

4 Results

Based on the interview and observation results, all research participants acknowledged that the cohousing living model has a great potential to provide a healthy-aging option for older people. The shared features with the benefits of mutual support from different generations could strongly form social bonding and sense of belonging. However, difficulties remained. In terms of the built environment of the cohousing community, the study found that the criteria of aging in place and older people's living needs (e.g. mobility difficulties and visual impairment) were not fully considered in the process of community design and construction; very few communities considered the needs of the disabled, and the rest of the communities participating in this research did not have corresponding facilities to meet the needs of older residents. Moreover, the flexibility and adaptability of private dwellings in the intergenerational cohousing communities were relatively low. Specifically, the results of this study will be explained in the following two parts:

- Social aspects: mutual support and financial choices.
- Built environment features: adaptability, flexibility, and LHS.

The overall result of this study is illustrated in Figure 1 below:



Figure 1: Intergenerational cohousing and the elderly

4.1 Social aspects: older people and cohousing communities

Why did this research pay close attention to older people as a very special cohousing audience group? The reason for this was based on the investigation of demographic information of the cohousing projects in the UK, older people became the special and biggest audience group of selected cases in this study. Taking Lancaster cohousing as an example, even through the community named itself as an intergenerational group, the majority of residents were older people. When taking senior cohousing model in the UK. The interview results showed that all participants (architects, current residents, and pre-residents) agreed with the concept that "cohousing can be a great housing option for older people". However, the explanations which participants provided for this concept differed. Two aspects were highlighted in the interviews when discussing the housing options for older people: intergenerational living with mutual support; and financial choice. Among these aspects, this study found that intergenerational living and mutual support provided the driving aspect for older people to choose cohousing. The following subsections will introduce how participants perceived the importance of these two aspects when making a housing decision.

Intergenerational living with mutual support

Intergenerational living with mutual support was the driving aspect when discussing cohousing as a housing option for older people. Almost every participant mentioned this point, highlighting that intergenerational living not only benefited older people but also children and young families. Some participants, especially older group members, when comparing intergenerational and senior cohousing, valued the following two viewpoints. First, if people choose to live in a senior cohousing, when people are getting older with declining physical capacities, the interactions in the neighborhood will be reduced, people will have more health difficulties to look after and support each other (Architect AS6, resident RF4, resident RK6). Residents may still rely on services (e.g. too old to drive, unable to carry heavy stuff, thus considered using food delivery services) and care provided from outside of community. Second, living in an age-mixed community, older residents not only could receive 'peer support', but also benefit from the younger generations, such as intergenerational learning. In addition, older people could help out and feel useful when other families needed them, for example, to babysit for a short period of time. If the social aspect was the dominant reason for people to choose a cohousing scheme, then the benefits of mixed age groups and mutual support from different generations were the main reasons why older people choose an intergenerational cohousing. As group members stated:

"I think it is much better being around young people, not just with older people there is more energy there, there is more that different generations to help each other. You know...ignore everyone is physically frail, some people can go and do the shopping and carry the heavy stuff, the older people can be virtual grandparents, then babysit for the kids, which they like the kids a lot" (Resident, RK6).

"You can contribute and feel useful. And you got something to give as well as you receive a lot help and support. So I think for older people is really helpful. I know some cohousing projects are just for older people, I understand why those people want to live just with over 50s. But for me, I prefer multigenerational, I like the mix. It keeps me young and keeps me busy" (Resident, RL13).

Financial Choices

The cohousing model has the potential to bring financial benefits to the group members by developing a financial scheme or benefiting from community sharing. However, cohousing still faces a lot of financial difficulties, for example, the initial costs for developing the community are far too expensive for all group members (sharing the costs of communal areas and investing in some design standards) and a lack of financial support from local authorities and financial organizations. However, the financial situations of living in a cohousing community can be very different when discussing the housing choices for older people. Some older group members highlighted in the interview conversation that they were aiming for an intergenerational group, but young people/ families were having financial difficulties in accessing cohousing. This makes it almost impossible to diversify the population within the group (many intergenerational cohousing groups have little or no young residents). In other words, many mixed age cohousing groups evidenced a pattern similar to the senior cohousing, and in consequence the multigenerational social interactions were largely reduced. From the group members' perspective, because of the developmental procedure of cohousing community (self-funded, collectively buy the land and manage the construction), they have less flexibility to select young people as future residents because the older generations might be the 'only group' able to afford this type of living. This also answered why older people were seen as the largest audience group of the cohousing model:

"I prefer multigenerational. Lancaster cohousing is a group already mainly older people, quite a few retire people here, so we are halfway being senior already. I think it is nice to have intergenerational, but that makes very difficult, because it is not the cheap community to buy, it is difficult for young people to come here, you got less space for your money use, still quite expensive to come and live" (Resident, RL9).

"I think our difficulty here as much we would want to have people are wide range of ages. The physical process is turning these houses (very old English houses) into homes, means they are end up being quite expensive homes. Which means somebody like yourself (less than 30 years), really like the idea of cohousing, want to be part of it, unless you got a lot of money, or your parents got a lot of money, or won the lottery. It is very difficult to join" (Resident, RO18).

Some of the cohousing groups (such as 'On The Brink' cohousing in Sheffield) maintained rental dwellings on site for young people or families to increase the possibilities of involving young people in the group. However, the rental units or flats would not be the final solution to the problem. Key for the developers, decision-makers, and future groups, then, is how to make this type of living more accessible and affordable to a wider range of social groups.

4.2 Physical cohousing design: Lifetime Homes, adaptability, and flexibility for aging in place This section mainly discusses the advantages and disadvantage of cohousing's builtenvironment and physical design for aging in place. This is divided into two parts: Lifetime homes; and, adaptability and flexibility.

<u>Lifetime Homes</u>

The collective design process (co-design) in cohousing communities makes easier for cohousing communities to be well integrated into the design standards which are suitable for the older people. LHS is the most widely considered and accepted design standard in many cohousing communities in the UK. It allows a great deal of flexibility for older residents to age in place. During the interviews, LHS attracted most attention and it was highly valued by the group members. Five participants pointed out the LHS and provided detailed examples to explain the importance of applying this standard. They stated:

"Why we would build houses, that could only fit one particular way of living?... I think, it (applying Lifetime home standard, or build the houses to meet future needs) is just common sense, I never thought about it before. When I saw it, I thought of course this make sense! I thought you have to have the rooms for the person who walking with stick or a wheelchair, or a ramp, we don't have much land, so we got to build things like this. It will make sense. It makes more expensive, of course, but it worth doing in the long run" (Resident, RF2).

"I think... to think about all of these things right to the beginning, because none of us know what is going to happen, we could be absolutely healthy, and suddenly we fall down or have an accident or something. We don't want that to happen, but it is better to think about and it is better to be aware of and better to be planning for it, so I think this design standard is very useful and necessary" (Resident, RF4).

As mentioned above, using this design standard could make buildings more expensive. During the interview, the group members also made suggestions on how to apply this design standard into the community when funds were insufficient:

"We discussed within the group, maybe have one or two dwellings well-equipped, they could specifically meet these kinds of criteria, if somebody needs to go into that... but it is not compulsory for every unit to have something" (Resident, RF5).

In addition, some cohousing communities were considering adopting the LHS for different housing types (e.g., only apply it to three-bedroom houses because the staircase was wide enough), whilst other cohousing communities only applied certain design provisions/ terms instead of using the full standard. These examples provided a practical and more affordable way of adopting design standards in the neighborhood design. At the same time, this study found that even though some of the group members could not accurately identify the name of the design standards, or their specific terms, they were able to describe many items related to the design standards that could be very important to their lives, such as the space for ceiling hoists, wet rooms, stair lifts, ramps, and circulation space for wheelchair users. These design

items were explained in the LHS. This indicated that group members built an awareness of housing adaptability and started to pay attention to the 'future-proof' design features.

Adaptability and Flexibility of the cohousing design in the UK

Intergenerational cohousing is one of a number of cohousing types found in the UK. However, the study found that the living needs of older generation were not fully reflected and addressed in the cohousing design. Due to that fact that all selected cases in this study represented intergenerational cohousing communities, accommodating the living needs of various age groups became extremely important regarding neighborhood design. As mentioned previously, the flexibility and adaptability of private dwellings and special needs of different age groups were neglected in the design. Further, the corresponding future-proof strategies for older residents were not taken into account in the community management. Only one selected case (Five Rivers group) considered and fully addressed the details of intergenerational design principles in the design process. This section will use this case as an example to explain the design principles (physical and social) and elements for older generation.

The study argues that the adaptability and accessibility considerations for older generation should be applied to both communal and private areas in the community rather than just for the private area. The design principles considered by this group fall into the following two categories (Five Rivers Cohousing workbook, 2019):

- 1. Intervention for physical construction:
 - a) Users with specific design requirements: older people, various family types (e.g. couple no children, single-parent family, disabled people in the family, family with children of different ages) and young people (teenagers, young kids).
 - b) Housing types: adaptable houses and purpose-built houses.
 - c) Areas to consider (both communal and private areas): bedroom and communal spaces, bathroom, kitchen, and accessibility measures for people with mobility difficulties (e.g. wheelchair and walking frame users).

2. Intervention for social infrastructure:

- a) Providing opportunities for intergenerationally social interactions: for example, older residents teach young children how to read, and teenagers show older people how to use new technologies.
- b) Respecting the differences of living habits from different age groups, protecting their privacy.

Guided by these principles, this study found that there existed different design priorities for various age groups when selecting the design elements. For example, when designing spaces for families with young children, it focused on adaptable areas that promoted privacy and social interaction with the family via using open layout kitchens, kitchen islands with stools, and sufficient room with non-slippery surfaces. When designing spaces for older residents, health and safety became the priority. Architects considered wider and less steep staircases with handrails, walk-in showers with a built-in seat, non-slip surfaces, wheelchair ramps, suitable heights of kitchen equipment, door levers instead of doorknobs and disabled toilets in the common houses. In order to increase the flexibility of the living space to cope with the changes in family circumstances change, open plan spatial layouts, flexible walls, sliding doors and multifunctional furniture were also considered. These design elements should also be applied to common spaces, including the common house, community workshop and outdoor paths.

Design that is specialized and personalized can provide convenience for the residents. At the same time, it may also challenge community decision-making and financial schemes (e.g. a financial plan to pay off the community mortgage, see Lilac cohousing), which could make the design process longer. Accordingly, the balance between simplified and specialized dwellings should be highlighted to assist the architects and group members for future cohousing design.

To conclude, the following interventions and design principles are fundamental for aging in place in intergenerational cohousing communities:

- Addressing social needs in the cohousing design procedure.
- Emphasizing the significance of mutual support and intergenerational living for physical and mental health for all members.
- Encouraging community participation and engagement from different age groups while protecting privacy.
- Identifying social activities are shaped by the physical infrastructure.
- Physical environment should be designed to foster social activities, for example, placing the common house centrally in the community.

5 Contribution to Knowledge

This research demonstrated the great potential of the cohousing model for aging in place. At the same time, it pointed out the difficulties and limitations of current community living for the cohousing model in the UK. More importantly, the study highlighted a community-based possible aging option for older population by summarizing valuable design principles and age-friendly concepts. The research findings could largely benefit cohousing residents, project architects, policy makers and other related stakeholders for better future cohousing design. Moreover, the results of this study can be applied to other older-people orientated residential settings, such as retirement villages, care homes and home share systems.

6 Conclusion

To conclude, this paper provides an in-depth analysis of cohousing community living for aging in place. The findings suggest that intergenerational cohousing can be a valuable aging option for a broader older population in the UK. Specifically, the research found that social factors have become the biggest advantage for elderly people to choose the cohousing model, However, there exist significant deficiencies in both the aging-related common facilities (e.g. wheelchair ramp) and community management. This suggests that a large amount work is still required in terms of improving the built environment and aging friendly facilities for the living needs of elderly residents. Meanwhile, the cohousing model also requires understanding and support from society, including local government, housing associations, financial institutions, and social workers.

Reference

- Agediscrimination. Info (2020). *The current UK population is 66,435,600*. Available at: <u>http://www.agediscrimination.info/current-uk-</u> <u>population?rq=15.21%25%20of%20the%20UK%20population%20is%20aged%20over%207</u> <u>0.%20</u> Visited site on 27/8/2021.
- Allen, C., Milner, J. & Price, D. (2002). Home is where the start is: the housing and urban experiences of visual impaired children (York, Joseph Rowntree Foundation).
- Anacker, K. B., & Niedt, C. (2019). Classifying regulatory approaches of jurisdictions for accessory cohousing-in-the-uk/ Visited on 27/8/2021.

- Danziger, S. and Chaudhury, H., (2009). Older adults' use of adaptable design features in housing units: An exploratory study. *Journal of Housing for the Elderly*, 23(3), pp.134-148.
- Davey, J.A., de Joux, V., Nana, G. and Arcus, M., (2004). Accommodation options for older people in Aotearoa/New Zealand. Christchurch: Centre for Housing Research.

dwelling units: The case of Long Island. *Journal of Planning Education and Research*, 00 (0), 1–21.https://doi.org/10.1177/0739456X19856068

- European Commission (2015) The 2015 Ageing Report. Brussels: European Commission.
- Garciano, J.L., (2011). Affordable cohousing: Challenges and opportunities for supportive relational networks in mixed-income housing. *Journal of affordable housing & community development law*, pp.169-192.
- Goodman, C., (2011) Lifetime Home Design Guide. Bre Press.
- GOV.UK Government Office for Science, (2016). *Future of an Ageing Population*. Available at: <u>https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/</u><u>file/816458/future-of-an-ageing-population.pdf Visited site on 2/7/2021</u>
- Hagbert, P., Larsen, H.G., Thörn, H. and Wasshede, C. eds., (2019). Contemporary *Co-housing in Europe (Open Access): Towards Sustainable Cities*. Routledge.
- Here & Now, (2020). *Why cohousing is so popular in Denmark*. Available at: https://journal.theaou.org/news-and-reviews/the-popularity-of-cohousing-in-demark/
- Hwang, E., Cummings, L., Sixsmith, A. and Sixsmith, J., (2011). Impacts of home modifications on aging-in-place. *Journal of Housing for the Elderly*, 25(3), pp.246-257.
- Iecovich, E., 2014. Aging in place: From theory to practice. Anthropological notebooks, 20(1).
- Imrie, R., (2006). Independent lives and the relevance of lifetime homes. *Disability & Society*. Routledge. 21:4. pp.359-374.
- Iwarsson, S. & Wilson, G. (2006). Environmental barriers, functional limitations, and housing satisfaction among older people in Sweden: A longitudinal perspective on housing accessibility. *Technology and Disability*, 18 (2), 57-66.
- Kelly, M. (2001). Lifetime home, in: S. Peace & C. Holland (Eds) *Inclusive housing in an ageing society* (Bristol, Policy Press), pp.55-76.
- Lietaert, M., (2010) Cohousing's relevance to degrowth theories. *Journal of cleaner production*, 18(6), pp.576-580.
- Mayring, P., (2014) *Qualitative content analysis: theoretical foundation, basic procedures and software solution.*
- McCamant, K., Durrett, C. and Hertzman, E., (1994) Cohousing. Ten Speed Press.
- Nelson, A., (2018). Small is necessary: Shared living on a shared planet. Glossary, Pluto Press.
- Newsham, B. (2018). Cohousing offers community and a different way to live. Available at: https://www.strongtowns.org/journal/2018/4/18/cohousing-offers-a-different-way-to-live. Strong Towns.
- Priest, I., (2015). "Different kind of living", RIBA Journal, 122(10), pp. 54.
- Saldaña, J., (2015) The coding manual for qualitative researchers. Sage.
- Sargisson, L., (2012). Second-wave cohousing: A modern utopia?. Utopian studies, 23(1), pp.28-56.
- Savage, M., (2020). Could a Swedish housing experiment that forces solo-living renters to spend two hours a week together be a solution to loneliness for young people? Available at: https://www.bbc.com/worklife/article/20200212-the-housing-project-where-young-and-old-must-mingle
- Senior Resource, (n.d.) *Age In Place*. Available at: <u>https://www.seniorresource.com/ageinpl.htm</u> Visited on 2/7/2021
- Smith, J.A. and Osborn, M., (2007). Pain as an assault on the self: An interpretative phenomenological analysis of the psychological impact of chronic benign low back pain. *Psychology and health*, *22*(5), pp.517-534.
- Smith, J.A. and Shinebourne, P., (2012). *Interpretative phenomenological analysis*. American Psychological Association.
- Strauss, I. (2016). The hot new millennial housing trend is a repeat of the middle ages. Available at: https://www.theatlantic.com/business/archive/2016/09/millennial-housing-communal-living-middle-ages/501467/. The Atlantic.

The Cohousing Association of the United State, (2007). *The growth of cohousing in Europe*. Available at: http://oldsite.cohousing.org/node/1537

Thorne, A., (2015). "Different kind of living", *RIBA Journal*, 122(10), pp. 54-56.
UK Cohousing Network, (n.d.), Cohousing in the UK. Retrieved from https://cohousing.org.uk/about/
Wealleans, L.M., (2015). From positive ageing to positive living; a changing perspective from the Beth Johnson Foundation. *Working with Older People*, 19(4), pp.165-169

World Health Organization. (2015). World report on ageing and health. World Health Organization. <u>https://apps.who.int/iris/handle/10665/186463 Visited site on 2/7/2021</u>

Social Living. An experimental project of tall building in Bolzano (Italy)

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Abstract

Social housing has always been an important topic of research in Italy since the post-war period. Starting from the Fanfani plan to the recent laws on social housing, there has been a constant and uninterrupted research within the architectural project.

Each historical period has produced buildings in line with the thought of their time and has led to a variety of housing types that, however, have not always coincided with a high quality of life within the housing.

The current pandemic crisis has only sharpened the approach that architects have increasingly used since the eighties, aimed at a formal and not structural use of technology, leaving unchanged some typological principles of housing and rewriting only the formal aspect.

This approach implies a very precise thought of the project of social housing in which human activities were decomposed through a function and recomposed in monofunctional spaces, minimum, according to a "mechanistic" logic (spaces servants and served) to create housing. The recent pandemic has shown how the functionally designed spaces of our homes do not allow a mixed use and a direct relationship between the external and internal environment.

The design of housing, specifically, is called (today more than ever) to translate the needs, an ecosystem of relationships between objects that refers to natural systems characterized by variability, diversity and redundancy, an interconnected structure and a capacity to "self-adapt". The project of social housing in a tall building, proposed for the company that manages social housing in Bolzano (Italy), suggest a different design system related to the use of a sustainable construction system, (such as load-bearing wooden walls for an earthquake-proof building in height -10 floors-), to the definition of "adaptive" tools for the organization of a space no longer based on the modernist logic of function but on the hybrid use of space, to a different relationship "inside-outside" in the configuration of the spaces of housing, and to the creation of collective spaces dedicated to the inhabitants' community.

BACKGROUND

Modernism has left us a cumbersome inheritance regarding the architectural design of living based on the scientific method.

Developed by Descartes and used throughout the 20th century, the scientific method proposes a coherently logical decomposition, simplification and reduction, from the complex to the simple, – and it has also been used in architecture by some of the Masters of the Modern: Le Corbusier uses the principle of universal determinism with regard to the management that the form establishes with the architectural object in a relationship of continuity with the urban fabric and which allows the predictability of the future based on past events. Mies Van der Rohe employs the principle of disjunction, which disengages the work from the environmental context, so that the work itself it takes on the character of an object structuring the organization of a form, and which isolates and separates objects regardless of their mutual relations, their context, and their relationship with the knowing subject [1] (Guattari, 2013). Aldo Rossi uses the principle of reduction, which suggests interpreting the whole from the basic elements that constitute it, and therefore he builds his popular forms as if they were pieces of the wooden construction boxes used to play with.



Figure 1. Veduta dell'allestimento della mostra 'Modern Architecture: International Exhibition', MoMA, NY, 10 febbraio-23 Marzo 1932. New York, Museum of Modern Art (MoMA). The Museum of Modern Art Archivies, IN 15.1 © 2017. Immagine digitale, The Museum of Modern art, New York/Scala, Firenze

Such considerations have structured a widespread thought about the dwelling project in which human activities had been decomposed through a function and recomposed in monofunctional spaces, minimal, according to "mechanistic" logics (servant and served spaces) and the relationship with the external environment was less and less present.

However, most of the experiments conducted during the last century on housing (both social and nonsocial, with different declinations, from the 'minimal house' to the economic one for all social classes, from the experiments with prefabricated systems to the megaforms of living, from mobile homes to the social house or co-housing) have also affected other topics, with particular regard to the adaptations that technoscience has proposed, but they have not challenged the system of organization of space, except in some rare experiments.

Even in Italy, despite some praiseworthy initiatives on social housing that have occurred from the '50s to the '80s, see the Fanfani plan, the INA casa and some social housing districts designed by some great Italian designers (Adalberto Libera with Quartiere Tuscolano in Rome, Giancarlo De Carlo with Villaggio Matteotti in Urbino, Aldo Rossi with the Gallaratese, just to name a few wonderful examples), the housing project referred to the consolidated functional project of separation of spaces.

But we know how, since the beginning of the new century, the design of housing in general, and of the social one even more so, was no longer able to meet the needs of relationships within the complex family units, which, thanks to the rapid spread of digital technology and the massive influx of immigrants, carriers of other cultures, no longer refer to known models and require much more freedom and speed of change.

The most current experiences have "taken refuge in a formal and non-structural use of technology that keeps unchanged the typological hardware of the house, rewriting only the software in an attractive fashion graphics"[2].

With the beginning of the new century, we are also witnessing a fundamental shift in knowledge and knowing, no longer based on the scientific system but on the complex system [3] (Morin, 2021).

"The disjunctive logic proper to Cartesian analytical theory, which separates and decontextualizes, then becomes insufficient; instead, it is necessary to differentiate and connect, to conceive the project as something that is not exhausted in the juxtaposition or sum of the parts, but as an inclusive system, imbued with links, interactions, transversality, mutation and adaptation" [4] (Ceruti, Bellusci, 2020); composed of elements that in their complexity and constitutive identity constantly contribute to change, nurturing an evolutionary dimension and a co-production of the conditions of reciprocity within the ecosystem, able to "take into account the contexts, interactions and retroactions, to recognize ambivalences and contradictions, to conceive of emergencies and to take into account the circular relationships from global to local and from local to global" [5] (Morin, 2021).

For this reason, it is necessary to look for a new method to face the dwelling project, basing on unknown levels of complexity, such as to make "*coarse and prehistoric*" [6] the past approaches to design the domestic space.

Living is not only a spatial composition of elements assigned to an activity, today, it is much more: it is an interweaving/intersection of daily relationships between people who lead different lives, but who find in their domestic space the key and the answer to their relationship and where they seek their "*shared happiness*" [7]. The recent experience of confinement due to Covid has forcefully clarified how our homes are inadequate for contemporary living.

It has also revealed to us how the functionally designed spaces of our homes do not allow any promiscuous use and the direct relationship between the external and internal environment, typical of Mediterranean culture, completely neglecting the threshold spaces that have always defined the porous margin with the environment.

Moreover, we cannot forget that Italy is a country that unfortunately is subject to strong earthquakes. Since the new century, only in the last twenty years, there have been four major earthquakes: in L'Aquila in 2006, in Emilia Romagna in 2012, in Central Italy in 2016 and in Ischia in 2017, with catastrophic consequences.



Figure 2. Residential building crashed in Cavezzo after the 2014 earthquake in Emilia Romagna land.

The succession of these dramatic events has increased the awareness, not only in designers, but also in public administrations and private individuals, that it was necessary to both improve the seismic regulations and apply them to as many buildings as possible, new and existing ones.

In addition, the issue of sustainability of the intervention, included in an ecosystem-based approach, must be the basis of considerations for a social housing project; not only exclusively referred to a social and economic and of the architectural language sustainability, but also to several environmental aspects such as the reduction of land consumption, emissions, and impacts related to the construction and reversibility of the intervention.

The paper will deal with the design of a multi-storey residential building, developed in height, with wooden load-bearing walls construction system in Bolzano, a city located at the base of the Italian Dolomites mountains.

The notifying body of the design competition, the Popular Institute for Social Housing Bolzano, proposed a call based on five points:

- the building was to be developed in height;
- the design system should allow the reversibility and changeability of housing;
- the use of a lightweight and reversible construction system;
- the need for differentiated housing cuts;
- a low cost of construction;
- the use of green.

AIMS and OBJECTIVES

The social living reflects, basically, what is happening both in reality and in the cultural thought of these years.

Social marginality in recent years has expanded considerably, affecting increasingly large segments of the population, located on the "margins" of the social system, and thus denouncing the inability of society to operate with different degrees of integration/interaction. We are witnessing an everincreasing "social fragility"[8] (Castel, 1997) of individuals who were not initially involved in the phenomenon but who, once any situation of stability has ceased to exist, have become involved in a marginality that has become a daily condition of their existence: separated parents and their children, women and single mothers, elderly people living alone and on low incomes, children removed from their families and, finally, immigrants with no income and of different ethnic groups. These phenomena, more and more extended and complex in their dynamics, induce public institutions to give some answers to the state of discomfort of these families and to provide them with an accommodation that allows both the entry into the Community of these "excluded" and the possibility of living in a low-cost and highly sustainable house.

The concomitance between a possible translation of a complex method for the architectural project and the more focused approach to the solution of social problems, leads us to pursue, for each project of a building dedicated to living, the possibility of creating new relationships for the formulation of the project and between people.

The goal is to create a project - through a polyphonic ecosystemic approach formed by space, landscape and society - that has the attitude of receiving, transmitting and assimilating what comes from the context and from the actors that inhabit it, only after having interpreted and transcribed it within the contemporary world, understanding the latter as a complex reality where both the universalism of contemporary society and the defense of communities and particular identities coexist.

METHODS

The project of living, specifically, is therefore called to translate today more than ever the needs, the instances of a language that goes beyond the sign, or rather, that translates (from *trans-ducere*, "lead

beyond"), through the design sign, a brought relationship between objects which refers to natural systems that have an interconnected structure and an evolutionary ability to 'self-adapt', to introduce by co-option a series of present elements useful for adaptation [9] (Gould, Vrba, 2008), to distribute themselves at different scales. This approach allows to define a new hybrid space between different realities that, as a catalytic agent, can trigger chain reactions within the project of mutation, activating a process of re-signification that favors a *'syntagmatic architectural overwriting'*, in order to shape a new social and architectural identity "*performative and non-representative*" [10] (Irace, 2008), which uses new adaptive tools.

The proposed method unites, and connects different fields, looking for a multidisciplinarity enclosed within the presented project, through the difference, variability and redundancy [11] (Moore, 2021), "derived" from what Herbert Simon said: "[...] *Roughly, by a complex system I mean one made up of a large number of parts that interact in a non-simple way*" [12].

In other words, in an attempt to apply this system to the reality, we proceeded with the constitution of "a multidisciplinary community" that, except for the professional figures helpful to the project and involved in the design process since the beginning, was also attended by people outside the technological system of construction, such as a sociologist, a philosopher, an artist and an activist representing the future inhabitants' Community who, through a series of meetings, first of all stated the overall requirements and later took part in some sessions where the designers explained step by step the result of their work, no longer set on the solution of every single need but on their complex relations: "we have to accept the idea that reality is just interaction" [13] (Rovelli, 2014).

The selected inputs, outcome of the meetings, are the following:

- the integration of a new building in a territory overlooking a mountain landscape must have the aim of a balanced insertion in the land, to ensure that the landscape and the building create a symbiotic and porous relationship able to totally integrate both elements;

- the reduction of the building footprint in order to keep more permeable ground and therefore to use a building in height;

- the will to provide all the accommodations with outdoor but still covered spaces, so as to increase the internal/external relationship and transform the boundary of the wall into "porous margin";



Figure 3. Building placement strategy in the plot

- the need to answer to seismic activity through a lightweight structure;

- the consequent use of a wood structure that, not only answers the previous paragraph correctly, but that also helps the required energy containment performance and the whole sustainability of the intervention;

- the identification of (structural, technological) invariants within the accommodations;

- the possibility to use dry systems especially for the internal walls, in order to easily reconfigure the apartment;



Figure 4. Strategy where it is possible to interlace the structural system, with the invariance of services and the typological mix (same living area exposure but different dimension of flat (See color of module)). The services are collocated near of the main structure for to facilitate the relationship with technological installations and natural ventilation. Are conceived as transitional spaces between the area of social relations and more intimate ones.

- the use of passive sun protection systems for all seasons;

- the necessity to equip the building with spaces for the use of the inhabitants of the Community and of the quartier, such as shared kitchens, rooms for generational interactions, a small library and an area to let the kids play.



Figure 5. Building plans ground floor.

In a second moment, the selected inputs have been translated in the following design choices:

- a square, the simple form of the building able to generate a relationship of almost empathic belonging to the place, of complementarity, but at the same time declaring its formal autonomy, almost iconic, which is expressed both in the simple and compact form of the building and in the external loggias of the housing units. These large loggias (with a width of 1.80 m) run all around the building and define its perimeter, fragmented by dividing diaphragms, of various sizes, colored in various shades of green, differently inclined on the vertical plane and formally reduced to a single structure that generates discreet and reserved spaces, typical of the local farm buildings. These diaphragms are carefully selected views to ensure privacy between people and different accommodations, but they also offer the discovery and contemplation of the extraordinary natural scenery of the surroundings;

- the building has 10 floors above ground: the ground floor and the first floor (with a site area of 19.90x19.90 m) are dedicated to social activities of the neighborhood (internally served by a dedicated stairwell), while a stairwell, placed at the center to optimize the east-south-west views, serves the remaining 8 floors, with residential use;

- the search to maximize the number of housings in relation to the volume and the program provided, through a mix of 4 main types interchangeable, without changing the "hard" part of the building. The proposed project guarantees the possibility to realize the number of 35 lodgings (maximum foreseen);



Figure 6. Available mix of apartments

- the respect of the single room sizes for the optimization, together with the envelope, of the management costs of the single families, with particular attention to the openings in order to favor the shading during the hot summer months and the correct irradiation during the winter months;



Figure 7. Building plans, first floor, roof and plans type.

- the presence of the porch to the south and west, in addition to protecting the entrance from bad weather and the sun, outlines an unconventional place of transition between the open public space and the more private living or community spaces. We think that the different vertical rotation of the pillars can describe and create new relationships;

- the orientation of the living areas always positioned to the east, the south and the west;

- a use of colors derived from the landscape and the given palette, with panels of different shades of green and an outer brownish wall;

- inside, the lightweight composite walls, dry-built, of different colors, the furniture also used as an acoustic barrier between the lodgings and the floors with earth colors give back the impression of a cozy, enveloping and intimate space;

Figure 8. Outside/Inside view of building/apartment

- the opportunity to use the flat roof as an open-air room for relational sharing among the community; - the need to integrate the green as a decorative element also with a discreet presence of some small flower beds in the loggias of the housing where *Abelia grandiflora*, *Pittosporum nana*, *Juniperus old gold*, *Lonicera pileate* can grow, while *Ilex crenata*, *Taxus media hillii*, *Hydrangea annabell* are placed on the roof.

RESULTS

The multidisciplinary approach, helped by the use of BIM system, has allowed to develop, among the various worlds of the project, in its broadest sense, interesting and unpublished reports that were introduced in the final project responding to answer many initial questions.

We believe that the project, conceived as an open and integrated system, will be able to accommodate new and different needs that will emerge in future years.

The project of living this building is therefore subject to a decisive reversal, where the accommodation has been conceived as a space that will contain within it the permanence without a specific function, such as a school accommodation, a Skype backdrop accommodation, an accommodation for smart working or some spare time. From being a privacy protection space, it becomes a shared space between multiple people, for several activities, basing, then, on the possibility of a continuous remapping of the space/activity ratio to be carried out close to the building and within their own home.

But above all, we tried to provide the building with spaces for the community both specialized (meeting room, newspaper library, children's playroom, neighborhood meeting center) and convivial (the rooftop can be used for events), as well as, for housing, porous spaces between the inside and the outside that allow you to extend the accommodation outside and enjoy and relate to the beautiful mountain scenery surrounding the building.

From the technological point of view, having designed a building in height allows a lower consumption of soil; the use of a lightweight and dry construction typology (Xlam, i.e. Cross Laminated Timber panels for walls and slabs too), perfectly meets both seismic (dissipative structure) and reversibility requirements of the building and, consequently, a greater overall sustainability.

At the same time, also considering the climate of Bolzano city (cold in winter and warm in summer), the building has been designed in compliance with the Technical Directive Casaclima for new buildings and it achieves an energy efficiency of envelope EINres \leq 30 kWh/m²a and with an EPSRres (Equivalent Primary Energy Requirement Without RESidential Cooling) \leq 20 kg CO2 eqv /m²a, which corresponds to the definition of "building with nearly zero energy - nZEB", according to the European Directive 31/2010/EU Art.2, paragraph 2. The building has an excellent summer energy performance, due to the fact of using materials for opaque elements with a phase shift > 12 hours and due to the presence of vertical and horizontal projections that allow the shielding of glass surfaces, eliminating, therefore, any active cooling system.

Figure 9. General view of building

REFERENCES

[1] Guattari F., (2013), Architettura della sparizione, Mimesis, Milan

[2] Irace F., (2008), edit by, *Casa per tutti. Abitare la città Globale*, Triennale Electa, Milan, p. 17
[3], Morin E., (2021), *La sfida della complessità*, edit by A. Anselmo, G. Gembillo, L Lettere, Florence

[4] Ceruti M., Bellusci F.(2020), Abitare la complessità, Mimesis, Milan, p. 58

[5] Morin E., (2021), op.cit., p. 48

[6] Coccia E., (2021), *Filosofia della casa. Lo spazio domestico e la felicità*, Einaudi, Turin, p. 27 [7] Coccia E., (2021), op.cit, p. 22

[8] Castel R., (1997), *Diseguaglianze e vulnerabilità sociale*, in Rassegna Italiana di Sociologia, anno XXXVIII, Il Mulino, Bologna, pp. 41-56

[9] Gould S. J., Vrba E., (2008), *Exaptation. Il bricolage dell'evoluzione*, edit by Telmo Pievani, Bollati Boringhieri, Turin, p. 15

[10] Irace F., op.cit., p.17

- [11] Morin E., (2021), op.cit., p. 74
- [12] Simon H. A., (1992), The architecture of complexity, Proceedings of the American
- Philosophical Socierty, 106 (6), ., p. 468
- [13] Rovelli C. E., (2014), Sette brevi lezioni di fisica, Adelphi p. 29

Evaluation of Software Packages for Energy Modeling of Phased Deep Energy Retrofits to Passive House standards

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ABSTRACT

Accurate and timely energy modeling is a crucial and important aspect of the design of high-performance buildings. As such, many software packages have been introduced in recent years. While the large number is a positive and encouraging development, it can also be overwhelming. With so many options available, it can be difficult to determine which software is the right fit for a specific design project. A collection of energy modeling software programs was compiled to create a comprehensive list, which was revised down to ten based on accessibility, energy and financial modeling capabilities, and customization potential of the components. These ten programs were then studied further to determine a final list of three programs, which were used to model a single-family Passive House building. It was concluded that each program required an in-depth understanding of the model, building science, and energy modeling principles, and the deeper the comprehension of these facets, the better and more reliable the ultimate model will be. Since only a simple model was performed for each software, further work will need to be done to explore the additional abilities of the three software programs as well as modeling practice with any or all of the remaining software. This will enhance our understanding of the full capabilities of all the programs available.

INTRODUCTION

It is by now well known within the high-performance building community that the residential sector is a significant consumer of the global energy supply, specifically with regard to the energy allocated for space heating and conditioning. As a result, more stringent building standards have emerged that seek to address these issues. The globally-recognized building standard Passive House, and its retrofit-specific counterpart EnerPHit, focus on insulation, airtightness, and thermal bridges to reduce energy spent on space conditioning to nearly zero (Passive House Institute, 2015; Passive House Institute U.S., 2019).

A deep energy retrofit (DER) is a renovation of an existing building with a focus on drastic reductions in energy use and, in tandem, their costs (Rocky Mountain Institute, 2020). Retrofits of existing buildings have a large number of barriers, not the least of which is cost (The Institute of Engineering and Technology, 2020). In order to mitigate the effects of these barriers, EnerPHit encourages "step-by-step", or phased, retrofit plans, where smaller retrofit projects are done one at a time over a period of many years (Theumer, S., 2016). Exploring how well these phased retrofit projects can address the current barriers requires a method of modeling these projects. Passive House certification requires energy modeling and prescribes certain software already. The Passive House Planning Package (PHPP) and WUFI Passive. These programs, however, have licensure fees that are prohibitive for preliminary and smaller scale studies. As such, there is a need for suitable accessibly (free) software programs that can model building retrofits, at least in an approximate sense.

Whole Building Energy Modeling (BEM), defined by The Rocky Mountain Institute as "the practice of using computer-based simulation software to perform a detailed analysis of a building's energy use and energy-using systems" (Franconi, Tupper, Herrschaft, Shiller, & Hutchinson, 2013), can be and is used for modeling a building's energy consumption, predicting energy and the associated cost, designing retrofits and new construction, sizing building components, providing compliance for codes and certifications, obtaining tax benefits, and shaping public policy (Franconi, Tupper, Herrschaft, Shiller, & Hutchinson, 2013; Passive House Institute U.S., 2019). Therefore, it seems that a BEM software could be an optional substitute for modeling of passive house retrofits, where use of or access to PHPP and WUFI Passive is not an option. Fortunetely, there exists a plethora of available BEM software, each with unique strengths, focuses, inputs, and outputs. Websites have been created, such as the Building Energy Software Tools (BEST) Department, formerly run by the U.S. Department of Energy (BEST Directory, 2020), that compile expansive, but not exhaustive, lists. Closely related papers have looked at the various strengths and skills of a wide variety of BEM software - see (Stumpf, Kim, & Jenicek, 2011), (Gao, Koch, & Wu, 2019) (Sousa, 2012), (Zhu, Hong, Yan, & Wang, 2012), and (Crawley, Hand, Kummert, & Griffith, 2008). With the need of accessible software for small, exploratory projects, and the introduction of new software products to the market, there is space for additional work to be done. This paper is a short preliminary study that explores software that can provide BEM, is free, perform financial analysis, and allowed for customization of building components, features considered useful in the research of the effect of the order of the step-by-step projects on the energy consumption of a single-family home help

SOFTWARE SELECTION

Generic searches based on keywords was performed to identify the existing software options. Public forums and comment sections of articles were also studied as the offered discussions, opinions, and insights into which software was popular and why. 213 different and unique software were identified through sites with searches titled

"building energy modeling software" (Fassbender, 2014; Office of Energy Efficiency and Renewable Energy, n.d.; Smtih, 2016; Kilkelly, 2015; Royapoor, Krishnadas, Lafit, Umar Raji, Banniser, & Gupta, 2015; Azari, 2015),, "building energy software" (BEST Directory, 2020), and "best software for passive house" (RMI, 2020; EnergySoft, 2020; Passive House Canada, 2020; PHIUS, 2020) on a common search engine. Tools and calculators not capable of providing the full BEM and financial analysis desired were not included. The initial list was then narrowed to only software capable of performing whole building energy modeling resulting in 77. This was reduced to 34 programs by removing those that could not be available without a license or that free trials would end after a few weeks. Next, software not capable of performing financial analysis were removed as well as one program that was designed only for commercial use. The final requirement was customization of individual building components. Following such criteria and elimination, which were considered only for this pilot study to illustrate the methodology for side-by-side comparison of software packages for energy modeling of a model house, 10 programs remained.

The final ten were eQUEST (DOE2, 2018), EnergyPlus (EnergyPlus, 2020), National Energy Audit Tool (NEAT) (Oak Ridge National Laboratory, n.d.), HOT2000 (BEST HOT2000, 2018), Manufactured Home Energy Audit (MHEA) (Manufactured Home Energy Audit [MHEA], 2018), Spawn of Energy Plus (Roth & Wetter, n.d), HEED (BEST HEED, 2018), Modelkit (BEST Modelkit, 2018), EDGE (EDGE excellence in Design for Greater Efficiencies, 2018), and BEopt (Building Energy Optimizing Tool[BEopt], 2020). These were researched and subsequently eliminated to reach three that seemed best for phased retrofit analysis.

BEopt uses EnergyPlus as the analysis engine, but adds a simple interface for quick and easy modeling, so BEopt was kept over EnergyPlus(EnergyPlus, 2020; BEopt, 2020 EDGE is a BEM software that can compare costs and energy usage, monitor the usage of a building, can be used for certification, and has a unique app feature (EDGE, 2018; EDGE 2020). However, it is missing climate data for the U.S. and climate data could not be imported. MHEA was removed because it was for mobile homes explicitly (Oak Ridge National Laboratory, n.d.; MHEA, 2018). Spawn, also known as Spawn of EnergyPlus, was removed because it focused on the control systems such as lighting and space conditioning and the algorithms behind them (Roth & Wetter, n.d). Modelkit was deemed a powerful tool, but it required "knowledge of the syntax rules of defining the text-based input file of a building energy model, as well as knowledge of Ruby scripting topics" (BEST Modelkit, 2018) and thus was deemed too rigorous for this study. HEED was eliminated because it could not be downloaded from its website or found on other sites. NEAT was eliminated because it focused too much on selecting conservation measures that should be applied to the home as opposed to offering the ability to test personal ideas of retrofit measures, combinations, and orders (Oak Ridge National Laboratory, n.d.). This left three options as being suitable for this pilot study - eQUEST, HOT2000 and BEopt.

BEopt was selected because it allows for retrofit-specific applications, financial evaluations, and more freedom to design and change individual pieces of a project. HOT2000 has a simple interface and is used in Canada for the actual certification of R-2000 projects (BEST HOT2000, 2018), making it the only software in the list, besides EDGE, capable of providing more than just information. eQUEST is a highly used and popular product that has been around for nearly two decades (DOE2, 2018; BEST eQUEST, 2018). Another strength of this tool that differentiates it from the other programs is its ability to enter CAD drawings into the simulator, potentially allowing for more intricate designs.

As previously mentioned, PHPP and WUFI Passive are the only programs suitable for Passive House Certification, however they are prohibitively expensive. A free version of WUFI Passive exists and can also be used for certification (Passive House Institute US, 2019), but the free version comes with limited functionality, one of them being the inability to create new databases, therefore potentially eliminating customization of building components (WUFI, 2018). However, since the selected software is supposed to help in independent auxiliary Passive House research, it would be pertinent to attempt a model in WUFI Passive Free, if only to better understand what Passive House modeling software is looking for.

METHODOLOGY

A case study was selected to be modeled in WUFI Passive Free, and then again in the three selected software to allow for exploration and comparison across the four programs. The house chosen for the study is located in Eugene, Oregon, USA, and was the subject of a master's thesis on retrofitting existing buildings to the Passive House standard (Hogan, 2011). It is a 1552 ft², 2-story, three bedroom, 1 and $\frac{1}{2}$ bath detached single-family timber home. The long side and front of the house is oriented to the south. The footprint of the house is a rectangle, 31' by 23' with a first-floor backside addition of a 21' by 6' rectangle extended off the backside, offset from the east side by 2'. The east face of this addition holds a second door. The roof over the addition is a shed roof, while the roof on the second floor is a gable sloping north-south. The covered entryway was not modeled. Doors are fiberglass with wood frames and measured 3' by 6.75'. Figure 1 shows the first and second floor plan. Table 1 shows the composition of the wall, roof, and floor. All windows are triple glazed, thermally broken, and insulated. Table 2 provides their schedule, which lines up with the squares shown on Figures 1. The south side windows have high Solar Heat Gain Coefficients (SHGC), the east side has vegetation and no SHGC specification, and the rest of the windows have low SGHC, no precise values given. Appliances are all assumed to be energy star rated or better. The lone occupant is self-described as energy conscious and travels frequently (Hogan, 2011). The construction of and R-values for the wall, floor, and attic of each model, as well as simulated energy consumption of the whole building, is to be compared to that of the case study.

Figure 1: First and second floorplans for the case study building. Adapted from original drawings (Hogan, 2011).

Table 1: Assembly construction compositions.

Floor – R-54 Total	Wall – R 42 Total	Attic – R-60 Total
First floor	Exterior	Exterior
• 2x8 floor joists	• fiber cement board	• asphalt shingle
• Fiberglass	• 1x4 wood furring strips	• felt
Blown-In-Blanket Insulation	• 4" rigid polyiso	• taped ¹ / ₂ " OSB sheathing
(BIBS) R39	• taped ¹ / ₂ " OSB board	• 9.5" TJI joists
 4" polyisocyanurate rigid 	• true 2x4 wood stud wall, 16"	 fiberglass BIBS R-15
insulation. (polyiso)	0.C.	• 2" of rigid polyiso
• Sprayfoam insulation R39,	 fiberglass BIBS R-15 	• 2x4 rafters
along edge.	• gypsum	 fiberglass BIBS R-15
Unfinished basement	Interior	• gypsum
		interior

Table 2: Eugene House Window Schedule

Number	Туре	Frame	Width	Height
Type 1	Awning	Fiberglass	5'-0"	3'-6"
Type 2	Fixed	Fiberglass	2'-4"	2'-9"
Type 3	Awning	Fiberglass	5'-0"	3'-6"
Type 4	Casement	Fiberglass	2'-4"	2'-10"
Type 5	Casement	Fiberglass	2'-8"	4'-4"
Type 6	Casement	Fiberglass	3'-0"	4'-3"
Type 7	Casement	Fiberglass	1'-10"	2'-0"
Type 8	Casement	Fiberglass	2'-8"	3'-0"
Type 9	Casement	Fiberglass	3'-0"	3'-0"
Type 10	Casement	Fiberglass	2'-8"	3'-10"
Type 11	Casement	Fiberglass	2'-5"	3'-10"
Type 12	Casement	Fiberglass	3'-0"	3'-5"

RESULTS AND DISCUSSION

The results of working with the four software programs can be seen in the following tables. Table 3 lists the features of each program in terms of pros and cons. Table 4 displays the Rvalues calculated by each software based on the modeled assemblies. Table 5 shows the energy simulation results. Effort was primarily used to recreate the assemblies, as they had the most given information. Energy schedules and equipment had to be

assumed, often left as defaults. These, along with the varying materials and construction abilities, are likely the causes of the differences seen in the tables.

Table 3: Features as Pros and Cons of the explored software

Software	Pros	Cons
BEopt	 Detailed video tutorials Easy and intuitive click-and-drag building input Easy to change footprint between floors Able to specify different spaces on each floor Building components are easy to access and edit. Large material database Allows for PHI levels of airtightness Window area for each wall can be specified Warnings given before results to allow for modifications and more complete designs Easy to obtain, read, and compare results Multiple types of results available Able to compare results across building designs 	 Building design limited to right angles No building design wizard Space types and roof shapes/orientations are limited to what is available Construction of components limited by the program, not free to build entire component from scratch. Examples include not being able to have both cavity and continuous insulation in the floors, and not being able to create 2 sets of rafters in the roof. Windows could not be placed nor could the building support multiple types of windows.
НОТ2000	 Customization of components Building wizard present Building geometry is simple and flexible Unique perimeter and floor area for each floor Windows with thermal breaks available Details could be specified within the "tree view" Analysis shows areas of greatest heat loss Ability to upload weather files 	 Limited construction design templates inhibit complete modeling of wall, floor, and roof designs Limited materials database Limited weather data present within software Airtightness inputs less than 1.5 not allowed Unable to reopen building wizard once closed
eQUEST	 Design Wizard Present Customizable components R values could be specified for components instead of constructing them Up to 3 types of doors and windows allowed Custom window placement possible Ability to import cad drawings to help create floorplans Very detailed building wizard 	 Does not have a residential single-family home option for building type, though the area activity of the whole building can be set to residential later Limited materials database Constructions limited by number of layers allowed Insufficient options for many things, including foundation type, heating system, and hot water Custom placement may be lost if building geometry is edited Building wizard doesn't allow for differentiation of building footprint between floors

WUFI	 Building Wizard present Floorplans can be customized on each level using vertices Complete customization of wall, roof, and floor components, including structural members Windows can be designed and placed individually Software guides user towards all information needed Hovering over the data entry area will often give tips on trained defoult unlose 	 Re-entering the building wizard will erase any building geometry entered manually Floorplans can only be modified outward, meaning floorplans must start smaller as vertices cannot be moved inward nor can walls be removed. Climate data is nearly impossible to find without a paid membership to PHAUS and default location is in Germany Databases climate and CAD files cannot be imported
	• Hovering over the data entry area will often give tips on typical and default values	 Databases, climate, and CAD files cannot be imported
	• Is suitable for PHIUS certification	• Will not generate reports unless all information is entered
	Very helpful tutorial videos	Will not assume values

Table 4: Assembly R values (ft²F*hr/BTU)

	Original	BEopt	HOT2000	eQUEST	WUFI (overall/homogenous)
Wall	R-42	R-27.2	R-24	R-45.5	R-40.2/43.2
Roof	R-60	R-51.9	R-43.8	R-55.6	R-65.1/70.6
Floor	R-54	R-27.2	R-34.8	R-63.5	R-52.3/55.5

Table 5: Energy Simulation Results

Passive House Planning Package Criteria	Original	BEopt	HOT2000	eQUEST	WUFI
Specific space heat demand kBTU/(ft ² yr)	4.69	1.68	18.37	10.40	12.29
Specific primary energy demand kBTU/(ft ² yr)	35.4	16.03	38.27	37.38	20.33
Heating load BTU/(ft ² hr	2.85	0.19	2.09	1.19	6.37
Cooling load BTU/(ft ² hr)	1.80	0.08	0.00	0.00	1.08
Airtightness ACH50	0.6	0.6	1.5	0.96	1.1

CONCLUSION

This pilot study was carried out for selecting, exploring, and comparing building energy modeling software that could potentially aide in the future research of phased passive house retrofits. BEopt, HOT2000, and eQUEST were selected out of a list of over 200 software and were compared with WUFI Passive Free. WUFI had the best construction capabilities, was easy to use, and can actually be used for PHIUS certification, but the inability to freely find the required climate data makes it very difficult to generate useful results. BEopt had the best options for geometry input, being easy to visualize and customize, and it was the best for comparing designs, but it was limited in its construction capabilities. eQUEST can input CAD drawings to help create more complex models, but the floorplan could not change among floors using just the wizard. It also was not designed for single-family residential designs in mind. HOT2000 has the simplest geometry input requirement, with basic shape, area, and perimeter being the descriptors, but had the worst construction capabilities. eQUEST and HOT2000 did not allow Passive House levels of airtightness and none of the software packages seem to have BIBS, so blown fiberglass was used with modified R values. For construction, only WUFI is without limitations. WUFI, eQUEST and HOT2000 have easy design wizards, but BEopt's layout allowed for easiest navigation and visualization of changes. In terms of Passive House analysis, WUFI is most likely to be trusted due to its PHIUS connection, but the original model was following PHI standards, so differences would be expected. BEopt could not replicate the assembly R-values and yielded energy results furthest from the original values, but the ability to quickly generate and compare two designs at once can prove handy for research such as comparing the effects of phased retrofit project order on energy consumption.

The software packages may not seem complicated, but the differences in results show they are designed for users competent in the knowledge of building science, energy modeling, and the model in question. Expanding this knowledge will lead to better and more accurate simulation results. In addition, it is understood that the full capacities of these four software packages were not explored, and that many suitable software were likely eliminated due to the cost restraint for this pilot comparative study. Continued work with these and other software applications through similar and broader projects is required for a deeper and more comprehensive understanding, but this paper provides an initial exploration method of study into the capabilities and potential uses of the explored four.

REFERENCES

- "EDGE Excellence in Design for Greater Efficiencies," BEST Directory, 18 July 2018. [Online]. Available: https://www.buildingenergysoftwaretools.com/software/edge-excellencedesign-greater-efficiencies.
- "EnergyPlus," National Renewable Energy Laboratory, 27 March 2020. [Online]. Available: energyplus.net. [Accessed July 2020].

- "Manufactered Home Energy Audit (MHEA)," BEST Directory, 25 August 2018. [Online]. Available: https://www.buildingenergysoftwaretools.com/software/manufactured-homeenergy-audit-mhea. [Accessed July 2020].
- A. L. Stumpf, H. Kim and E. M. Jenicek, "Early Design Energy Analysis Using Building," US Army Engineer Research and Development Center, Champaign, 2011.
- Azari, E. (2015, September 18). Question: What's the best energy analysis software for energy analysis? ResearchGate. Retrieved July 14, 2020, from https://www.researchgate.net/post/Whats_the_best_energy_analysis_software_for_energy_analys
- BEST Directory, "Software Listing," BEST Directory, 23 June 2020. [Online]. Available: https://www.buildingenergysoftwaretools.com/software-listing. [Accessed 7 July 2020].
- BEST, "eQUEST," BEST Directory, 19 September 2018. [Online]. Available: https: //www.buildingenergysoftwaretools.com/software/equest. [Accessed June 2020].
- BEST, "HEED," BEST Directory, 29 August 2018. [Online]. Available: https://www.buildingenergysoftwaretools.com/software/heed-home-energy-efficientdesign. [Accessed July 2020].
- BEST, "HOT2000," BEST Directory, 25 August 2018. [Online]. Available: https:/ /www.buildingenergysoftwaretools.com/software/hot2000. [Accessed July 2020].
- BEST, "Modelkit," BEST Directory, 11 October 2018. [Online]. Available: https:// www.buildingenergysoftwaretools.com/software/modelkit. [Accessed July 2020].
- Building Energy Optimization Tool (BEopt), "Home," BEopt, 2020. [Online]. Available: https://beopt.nrel.gov/. [Accessed 2020].
- Center for Global Development. (2016, March 30). Ratio of household electricity use to national electricity consumption by country. Retrieved August 13, 2021, from https://www.cgdev.org/media/ratio-household-electricity-use-national-electricity-consumption-country.
- D. B. Crawley, J. W. Hand, M. Kummert and B. T. Griffith, "Contrasting the capabilities of building energy performance simulation programs," Building and Environment, vol. 43, no. 4, pp. 661-673, 2008.
- D. Zhu, T. Hong, D. Yan and C. Wang, "Comparison of Building Energy," Ernest Orlando Lawrence Berkeley National Laboratory, 2012.
- DOE2, "the Quick Energy Simulation Tool (eQUEST)," James J Hirsch & Associates, 4 October 2018. [Online]. Available: http://www.doe2.com/equest/. [Accessed July 2020].
- E. Franconi, K. Tupper, B. Herrschaft, C. Schiller and R. Hutchinson, "Building energy modeling for owners and managers: A guide to specifying and securing services," Rocky Mountain Institute, Boulder, 2013.
- EDGE, "About," International Finance Corporation, 2020. [Online]. Available: edgebuildings.com. [Accessed July 2020].
- EnergySoft. (2020). Software sales. EnergyPro. Retrieved July 16, 2020, from https://www.energysoft.com/.
- Fassbender, R. (2014, May 14). What is the Best Energy Modeling Software? [web log]. Retrieved July 13, 2020, from http://energy-models.com/blog/what-best-energymodeling-software.
- H. Gao, C. Koch and Y. Wu, "Building information modelling based building energy modelling: A review," Applied Energy, vol. 238, pp. 320-343, 2019.
- Hogan, M. (2011). A Design Approach to Achieving the Passive House Standard in a Home Energy Retrofit (Master). University of Oregon.
- J. Sousa, "Energy Simulation Software for Buildings: Review and Comparison," in Information Technology for Energy Applications 2012, Lisbon, 2012.

- Kilkelly, M. (2015, December 8). Five digital tools for architects to test Building Performance. Architect. Retrieved July 13, 2020, from https://www.architectmagaz ine.com/technology/five-digital-tools-for-architects-to-test-building-performance o.
- Oak Ridge National Laboratory, "Software Description NEAT and MHEA," Oak Ridge National Laboratory, [Online]. Available:

https://weatherization.ornl.gov/softwaredescription/. [Accessed July 2020].

Office of Energy Efficiency and Renewable Energy. (n.d.). Building energy modeling project portfolio. Energy.gov. Retrieved July 13, 2020, from https://www.energy.gov/eere/buildings/building-energy-modeling-project-portfolio.

Passive House Canada. (2020). PHPP and designPH software. PHPP and designPH software for Passive House design. Retrieved July 16, 2020, from http://www.passivehousecanada.com/phpp-and-design-ph-software/.

- Passive House Institute US, "PHIUS+ 2018 Passive Building Standard Certification Guidebook Version 2.1," PHIUS, Chicago, 2019.
- Passive House Institute, "Passive House Home," Passive House Institute, 2015. [Online]. Available: https://passivehouse.com/. [Accessed 20 7 2020].
- PHIUS. (2020). Additional modeling tools. Other Modeling Tools: Passive House Institute U.S. Retrieved July 13, 2020, from https://www.phius.org/software-resources/wufi-passive-and-other-modeling-tools/additional-modeling-tools.
- RMI (Rocky Mountain Institute). (2020). Deep Retrofit Tools and resources. RMI. Retrieved July 16, 2020, from https://rmi.org/buildings/deep-retrofit-tools-resources/.
- Rocky Mountain Institute, "The Retrofit Depot," Rocky Mountain Institute, 2020. [Online]. Available: https://rmi.org/our-work/buildings/deep-retrofit-tools-resources/deep-retrofitcase-studies/. [Accessed 20 7 2020].
- Roth, A; Wetter, M, "Spawn-of-EnergyPlus (Spawn)," Office of Energy Efficiency & Renewable Energy, [Online]. Available: https://www.energy.gov/eere/buildings/downloads/spawnenergyplusspawn#:~:text=Spawn%2Dof%2DEnergyPlus%20(Spawn)%20is%20a%20next%2D,uni

fy%20BEM%20with%20control%20workflows. [Accessed July 2020].

- Royapoor, M., Krishnadas, H., Latif, E., Umar Raji, A., Bannister, P., & Gupta, R. (2015, August 9). Question: Which software is best for performing building energy analysis?
 ResearchGate. Retrieved July 13, 2020, from https://www.research
 gate.net/post/Which-software-is-best-for-performing-building-energy-analysis.
- Smith, M. (2016, March 27). The energy Modeling breakdown. the Energy Modeling Breakdown. Retrieved July 13, 2020, from https://www.verdicalgroup.com/the-energymodeling-breakdown.
- The Institution of Engineering and Technology; Nottingham Trent University, "Scaling up retrofit 2050," 2020. [Online]. Available: https://www.theiet.org/media/5276/retrofit.pdf. [Accessed 20 7 2020].
- Theumer, Susanne.S. (2016) Step-by-step retrofit to achieve EnerPHit Standard, the example of a single-family home. International Passive House Association/Passivehouse Institute [Brochure]. Retrieved from https://passipedia.org/_media/picopen/microsoft _word_-___06_fachinfo_schrittweise_modernisierung_sth.pdf. Website: passipedia.org/planning/refurbishment_with_passive_house_components.
- WUFI, "Product Overview," WUFI en, 2018. [Online]. Available: https://wufi.de/en/software/product-overview/. [Accessed 19 12 2021]

Design and construction approaches of foundations in permafrost with an application for a 3-D printed habitat in the Arctic

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ABSTRACT

Design and construction of buildings on the permafrost in remote areas of the circumpolar regions are a significant engineering challenge due to the complexities of the harsh and frigid environments, degrading permafrost, and limited construction materials and equipment. A novel exploration is to build habitats through 3-D concrete printing. This paper presents the initial design and construction approaches of various foundations for the 3-D concrete printed habitat in Arctic Alaska. First, based on the available literature, the typical design and construction of shallow and deep foundations on permafrost are reviewed, which inform the design parameter selection for the case under study. Based on the recommended foundation design practice in permafrost regions, conventional shallow and pile foundations for 3-D concrete printed habitats are explored. The initial design and construction approaches for slurried pile foundations, driven piles, and shallow foundations are discussed and examples for such foundations are presented. Besides the structural loads transmitted to the soil, thermal effects are also considered in the specification of design parameters to reduce heat transfer to the permafrost. This paper serves as a preliminary design document for foundations in permafrost for 3-D concrete printed habitat in the Arctic.

Keywords: foundations; permafrost; 3-D printing

INTRODUCTION

Permafrost is any soil that has remained continuously frozen for at least two consecutive years. It is widely distributed in the high latitude regions of both the northern and southern hemispheres. Permafrost occupies two main zones: continuous and discontinuous (Zhang *et al.*, 2000), and the discontinuous permafrost provides the greatest engineering challenges (McFadden, 2001). Due to the current trend of global warming, the rate of permafrost thawing is accelerating (Linell and Johnston, 1973; Romanovsky and Osterkamp, 1997). Inadequate technical solutions have been applied as a result of lack of awareness of degrading permafrost and its potential impacts (Bommer *et al.*, 2010). This is significant for Arctic Alaska, where surface infrastructure such as energy extraction and transport assets (pipelines), buildings,
roadways, and bridges are supported by degrading permafrost. As air temperature in the Arctic increases, ground temperature rises, resulting in thawing of the permafrost nearest to the ground surface, causing severe damages of the built infrastructure (Yang *et al.*, 2021; Osterkamp, 1994).

The permafrost temperature is of great concern in designing foundations on frozen ground sites. In warm permafrost, a small temperature increase may be sufficient to cause extensive thawing settlement. The terms "thaw-stable" and "thaw-unstable" have been adopted to describe the two groups of permafrost, and the thaw stability is dependent on the amount of water contained within the frozen soil. During the construction, because the permafrost around the pile foundations can warm or thaw due to the thermal distribution of pre-drilling and concrete hydration heat (You et al., 2017), the thermal state of permafrost needs to be considered in foundation design. After construction, the stability of foundations on permafrost is affected by the temperature increase in permafrost during service life, which is known as the thermal effect (Nixon, 1990). Hence, climate change induced permafrost degradation is also inevitably to be considered in foundation design approaches (Wu and Zhang, 2010), such degradation can result in thickening of the active layer and permafrost thinning. In this context, although various foundation types have been developed in new construction in permafrost sites since decades ago, the approach to foundation design diverges widely over the years.

Developments in permafrost engineering have mainly taken place at high latitudes (e.g., Andersland and Ladanyi, 2004). The northern latitudes where permafrost is encountered have a short construction season and are usually long distances from supply points, requiring flexibility of construction (Clarke, 2007). Given the high socioeconomic relevance, new recommendations have been developed to limit both cost and uncertainties in the future by focusing particularly on on-site investigation and the choice of appropriate foundation designs (Bommer et al., 2010). In this regard, 3-D printing seems to be a promising technique to build complex structures without the need of formwork and significant human intervention (Tay et al., 2017). Currently, three main categories of this technology are found in public domain, including D-shape (Cesaretti et al., 2014), contour crafting (Khoshnevis, 2004), and concrete printing (Lim et al., 2009). A novel exploration is to build habitats in the Arctic through 3-D concrete printing. Concrete printing is an extrusion-based manufacturing process that fabricates complex geometries layer by layer without the use of labor-intensive formwork. Like conventional construction with concrete, 3-D printed habitat in the Arctic is constrained by freezing weather. Alaska's freeze periods vary from one area to another due to its vast geographic size. Concrete should be poured after frost dates to prevent ice in the concrete that will melt causing concrete damage.

The U.S. Federal Government envisions the Arctic as a new frontier that will thrive due to global warming. Extensive new public infrastructure will need to be built to support the envisioned opportunities. Although various types of foundations have been developed for building construction in the Arctic, some geohazards still have been observed in construction. How to enhance the resilience of the existing and future infrastructure in a changing Arctic environment is crucial to the Arctic region's socioeconomic development (Yang *et al.*, 2021). In this study, based on the review of typical deep and shallow foundations used in permafrost, the approaches to permafrost foundation design and construction are discussed.

TYPICAL FOUNDATION CONSTRUCTION APPROACHES IN PERMAFROST

There are two types of pile foundations typically used in permafrost regions: slurried piles and driven piles. For slurried pile foundation (Figure 1a), predrilling is required, and freeze-back time is required to fully freeze the slurry before loading can be applied. Freeze-back time depends on the amount of slurry that must be frozen. When a slurried pile is placed, the portion of the pile in the active layer is typically wrapped with three layers of polyethylene film. In Alaska this has been found to be effective to reduce the active layer's adfreeze grip (McFadden, 2001). Adfreezing is known as a process by which two objects adhere to each other via ice. Driven piles (Figure 1b) can be driven into frozen soil without pretreating the permafrost. The ice and frozen soil are viscoplastic materials, so the loaded pile will gradually settle as the ice in the adfreeze bond deforms. The deformation of the ice in the adfreeze bond is called "creep" (McFadden, 2001). There are three categories of creep: primary creep, secondly creep and tertiary creep. The pile must be designed to keep the secondary creep rate low enough so that the accumulated creep will not exceed the maximum deformation criteria for the structure during its lifetime. To keep the loads low enough to stay in secondary creep, more piles can be added, the pile's depth into the permafrost can be lengthened, or the load lowered.

Pilings (either slurried piles or driven piles) is usually preferred if they are feasible. Piles have several advantages. Piles can be anchored into the permafrost so that they do not move during the coming and going of seasonal frost, they provide good lateral support for the building to resist wind loads and earthquakes, and some types of piles can be refrigerated if the permafrost is fragile and needs additional strengthening to support the building loads. The choice of pile type is largely decided by the availability of equipment. If pile-driving equipment is available and the soil conditions are favorable, then driving may be the most economical method. On the other hand, if soil is frozen and the cost mobilizing the driving equipment is prohibitive, or the site is immediately adjacent to nearby structures, then slurried piles may be preferred and possibly less expensive.

Piles are usually made of steel pipe, steel "H" columns, treated wood poles or timbers, and even concrete (Andersland and Ladanyi, 2013). Timber piles are generally the least expensive solution in some northern countries, where they are locally available. Steel piles are generally the most common types used in permafrost. Pile foundation designs should meet the following minimum specifications (McFadden, 2001): (1) the foundation must raise the building above the surface high enough to promote uninhibited air circulation beneath the building; (2) heavy insulation must be placed on the floor of the structure so that heat loss through the bottom of the building is minimized; (3) in the active layer, the adfreeze bond must be eliminated or reduced

between the supporting pilings, posts, or piers; and (4) the pile must be stabilized against lateral loads to safely withstand wind and/or earthquake loads.



Figure 1. Typical deep foundations in permafrost regions (modified after McFadden, 2000): (a) typical slurried pile installation in permafrost; (b) preparation of pilot hole in preparation for driving a pile into permafrost

When piles foundation cannot be used, a conventional shallow foundation might be considered. They are subjected to the heaving and subsiding effects of seasonal frost Also; these foundations do not provide significant lateral support. Shallow foundations are used in permafrost much less than piles. But shallow foundations may be more economical in many cases and could be an acceptable alternative to piles foundation. Figures 2 illustrates the typical shallow foundations used in permafrost. Slab-on-grade foundations are often used for homes and for buildings with large floor loads such as heavy equipment garages and aircraft hangars. The construction procedure (McFadden, 2001) is as follows. First, a layer of clean compacted sand of 6 to 8-inch-thick should be placed as bedding directly on undisturbed ground surface. Then, ventilation tubes are placed on the clean sand bedding and must be checked to ensure that the tubes are supported along their entire length, and they do not "bridge" any holes or voids. Next, sand should be compacted around the tubes in layers with 3 to 4 inch per layer until the tubes are covered to a depth of about 6 inches. This allows adequate heat transfer between the soil and the pipes. Then, an insulation layer of extruded polystyrene (XEPS) foam with 2 to 4 inch in thickness should be placed over the area directly beneath the structure to reduce the heat flow into the frozen soil. The rigid insulation should be buried in the granular fill at least 12-inches below finish grade, deeper embedment may be warranted in areas with heavier loads and traffic areas. The rigid insulation should be direct surface drainage away from the structure perimeter walls. Altogether, a

minimum of 18 inch (including minimum 4-inch XEPS foam) of support should be placed beneath the slab-on-grade.



Figure 2. Typical shallow foundations used in permafrost regions (redrawn after Johnston, 1981): (a) typical shallow foundation footing in permafrost, embedded in a thick, insulated gravel pad placed on the ground surface; (b) typical shallow foundation footing in permafrost, placed in backfilled pits excavated below the original ground surface; (c) shallow foundation on permafrost with typical timber sill surface foundation; (d) shallow foundation on permafrost with typical insulated concrete floor slab placed on duct-ventilated compacted fill

DISCUSSIONS

Weaver and Morgenstern (1981) suggested that foundation design in frozen ground must satisfy both thermal and serviceability considerations. Pile foundations are commonly used to support superstructures situated on permafrost in Arctic, since they can be installed to a greater depth and provide larger resistance against both structural load and frost heave loads. The bearing capacity of piles embedded in permafrost mainly comes from the adfreeze forces between the pile surface and permafrost (You *et al.*, 2017; Andersland and Ladanyi, 2013). The adfreeze strength depends on permafrost temperature, soil type, ice content, surface roughness of piles (Weaver and Morgenstern, 1981), and salinity of pore water in permafrost (Biggar and Sego, 1993a, b). The ice and frozen soil are essentially visco-plastic materials and, as such, exhibit creep. Recent investigations (*e.g.*, Nixon and McRoberts, 1976; Morgenstern *et al.*,

1980) suggested that the adoption of bearing capacity criteria for pile design in permafrost without taking creep behavior in consideration may be improper. Therefore, it is highly recommended that the design of pile foundation in permafrost region should be based on both settlement and adfreeze strength criteria (Weaver and Morgenstern, 1981). In general, pile foundation should meet the following condition for construction design in permafrost:

$$P + \tau_f A_f + \tau_d A_d > Q - \tau_h A_h \tag{1}$$

where *P* is the end bearing capacity of piles; τ_f is the adfreeze bond between pile and soil; A_f is the pile-soil interfacial contact area in permafrost; τ_d is the frictional stress between pile and soil in the active layer; A_d is the pile-soil interfacial contact area in the active layer; *Q* is the structural load; τ_h is the stress due to frost heave in the active layer; and A_h is the pile-soil interfacial contact area in the frozen active layer.

Slurried pile has been the most commonly used foundation in Alaska (McFadden, 2001). Considering the critical role of thermal regime in foundation design, we suggest pressure-treated all-weather wood be used for the slurried piles to limit heat transfer from the house to the permafrost foundation soil. It is assumed the slurried pile is 6 inch in diameter and a hole of 12 inch in diameter is first drilled. The larger end of the wooden pile is at the bottom of the hole. The open space (annulus) between the pile and the drilled hole is filled with clean sand-water slurry and compacted using preferably vibratory compactor. If vibratory compactor is unavailable, careful tamping using long rods can be used. The clean sand-slurry should have 6-inch slump in order to achieve workable consistency and develop strong adfreeze bond. If clean sand is not available, the auger cuttings that are removed from the hole should be used for the slurry. In this case, wood, peat, or other organic materials should be removed from the cuttings that are used for the slurry. A concrete mixer can be used to prepare the slurry. Water should not be allowed to enter the hole. Local timber, generally spruce, Douglas fir, or pine, is most commonly used. They have length from 18 to 45-ft and diameters from 6 to 10-inch at the top and 12 to 14-inch at the bottom. The timber piles usually remain well preserved in permafrost, but they must be protected in the active layer against deterioration and decay. Several wood preservatives may be used for that purpose, but some of them may reduce the adfreeze bond between pile surface and frozen soil (Andersland and Ladanyi, 2013). In the North Slope Borough, Alaska where the soil is colder and has high moisture content, difficulty of pile driving increases. It may also be difficult to access pile driving equipment. Driven piles are usually steel piles, which may be difficult or expensive to obtain in remote areas. Accordingly, driven piles may not be the best choice for construction similar to the one reported here.

When soil freezes around the pile, a bonding force between the ice in the soil and the pile surface develops, known as adfreeze bond. Such bond is temperature-dependent and increases with the decrease of temperature. Since the active layer becomes much colder than the permafrost in the winter, the adfreeze bond in the active layer is higher than that in the permafrost layer. Frost heave of the active layer can uplift the pile. The depth of the pile embedment in the permafrost layer must be greater than the active

layer thickness. Most piling designs attempt to reduce or eliminate the adfreeze bond in the active layer by using sleeves or coating on the pile in the active layer. We recommend the pile in the active layer be wrapped with three layers of 6-mil thick black polyethylene film to reduce the active layer's adfreeze grip.

Some air space is needed between the bottom of the house and the surface of the ground to provide air circulation and avoid or minimize heat transfer to the ground surface. The airspace between the bottom of the house and the surface of the ground must be enough for unimpeded circulation of cold air in the winter. The height of the airspace depends on the size of the building and amount of wind. A small home of approximately 30-foot width should have 3 feet height of the airspace, and the minimum height is 2 feet. The aspect ratio of the minor dimension of the building to the airspace height should be less than 10 (McFadden, 2001). For the habitat to be constructed in this project, the length of post above ground should be 2 ft. It is assumed the width of the habitat is 12 ft; thus, the aspect ratio is 6 and fulfills the requirement. A natural convection cooling device is commonly used to keep the ground frozen. Either closed single-phase convection tube (where working fluid transfers heat out of the ground with phase change) can be used. The working fluid will depend on the recommendation of the contractor who will install the cooling device.

Pile's bearing capacity evaluation plays a role in the design and construction approaches. The cavity expansion theory, based on nonlinear isochronous stress-strain and strength curves of frozen soil (Ladanyi and Johnston, 1974; Ladanyi, 1975; Phukan and Andersland, 1978) can be used to determine the ultimate point (end) bearing capacity of a pile foundation in permafrost (Andersland and Ladanyi, 2013). The ultimate point bearing capacity of a pile is:

$$q_{ult} = p_0 N_q + c N_c \tag{2}$$

Where p_0 is average initial total stress at the bottom of the foundation; *c* is temperature-dependent cohesion; N_q and N_c are bearing capacity factors. For circular pile foundation these parameters can be determined from the following equations:

$$N_c = 1 + \frac{4}{3} \left(n + \ln \frac{2}{3\varepsilon_f} \right) \tag{3}$$

$$N_q = (1 + \sin\phi) \left(1 - \frac{n}{k}\right)^{\frac{n}{k} - 1} \left(\frac{2}{3}\right)^{\frac{1}{k}} (kI_r \tan\phi)^{\frac{n}{k}}$$
(4)

$$k = \frac{3}{4}(1 + \csc\phi) \tag{5}$$

$$I_r = \frac{4N_{\phi}^{0.5}}{3\epsilon_f^{1/n}[1 + (p_0/c)\tan\phi]}$$
(6)

$$N_{\phi} = \tan^2 \left(45^o + \frac{\phi}{2} \right) \tag{7}$$

Where *n* is the exponent of stress in power law equation, n > 1 and *n* is determined experimentally; ε_f is the failure strain, corresponding to the strain at the minimum creep rate or at the start of tertiary creep; I_r is the rigidity index; and ϕ is the internal friction angle of the permafrost.

As an application for project reported here, the weight of one 3-D printed habitat model in this study is approximately 83 kips. All these 3-D printed constructions are divided into foundation, grounding, slab, walls, and roof. Walls are the vertical elements on the slab that enclose the interior space. Because of the vaulted shape of the roof, the printed walls can be short, providing just a basis for the roof. Two possibilities will be considered for the structure of the walls: solid (single shell) or hollow (double shell). It is assumed the habitat has 16 piles; each pile carries 5 kips. Considering seismicinduced eccentric loading, the finite element analysis shows the worse axial load on a perimeter pile is 21 kips in compression and 14 kips in tension. Thus, the stress at the base of such a pile of 6 inch in diameter is 26,700 psf. However, under gravity alone, the stress is 6600 psf. Based on the previous sections, we can use the following parameters in the pile's bearing capacity evaluation: 1) ϕ is 20° for sandy permafrost; 2) c is 100 kPa (or 2089 psf), as a conservative value for sandy permafrost; 3) γ is 95 pcf for unit weight of soil; 4) ε_f is 0.1 (Andersland and Ladanyi, 2013); 5) the exponent of stress in power law equation, n is 2; 6) pile diameter is 6 inch; 7) total weight of habitat, W is 82,870 lb; 8) number of piles, N is 16; 9) stress on each pile, q is 6,600 psf. We assume the habitat may be built in three locations in Alaska (North Slope Borough, Fairbanks, Anchorage). Table is prepared for the pile foundation's bearing capacity evaluation, and it shows the factor of safety by dividing ultimate bearing capacity for each region by the pile stress 6600 psf. For gravity load only, the factors of safety are all larger than 3, which is conservative. For seismic load, however, the least factor of safety would be 1.15 under compression. To consider potential tension in pile, we can simply determine the friction in the permafrost region by multiplying the cohesion coefficient of 2098 psf by the surface area of the pile in permafrost region, say 12 ft embedment, which results in approximately 40 kips, significantly larger than the potential tension due to the seismic effect.

Locations	L_a (ft)	L_{p} (ft)	L_t (ft)	q_{ult} (psf)	FS
North Slope Borough	3	12	15	20,300	3.07
Fairbanks	4	12	16	20,700	3.13
Anchorage	5	12	17	21,100	3.20

(*Note*: L_a is active layer thickness; L_p is embedment of pile in permafrost, which at least 2 times of L_a to resist heaving; L_t is total pile embedment; q_{ult} is ultimate bearing capacity of pile; FS is the factor of safety, FS = q_{ult}/q)

CONCLUSIONS

This paper reviewed the conventional types of foundations adopted in the Arctic region and discussed the design and construction approaches for pile foundation and shallow foundation in permafrost. The objective is to identify appropriate foundation types that are proven effective in permafrost regions for a 3-D printed habitat in the Arctic. Pile foundation is the most reliable approach and widely used in the Arctic. Considering the thermal effect between pile-soil interface in permafrost and adfreeze grip effect between interfacial zone in the active layer, slurried pile using pressure treated allweather wood seems to be the preferred choice for this project, and the pile in active layer is recommended to be wrapped with three layers of 6-mil thick black polyethylene film. Driven pile does not seem to be as desirable because of the difficulty in pile driving process and the steel driven pile is less economical. Based on the cavity expansion theory, the bearing capacity of the designed slurried pile foundation is evaluated, with the consideration of the loading of the 3-D printed habitat. The factors of safety in three general regions in Alaska (North Slope Borough, Fairbanks, Anchorage) show that the preliminary design and construction approaches for pile foundation in permafrost may be sufficient to support the habitat structure.

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REFERENCES

- Andersland, O. B., & Ladanyi, B. (2013). An introduction to frozen ground engineering. Springer Science & Business Media.
- Andersland, O.B., Ladanyi, B. (2004). Frozen Ground Engineering. John Wiley & Sons.
- Biggar, K. W., & Sego, D. C. (1993). Field pile load tests in saline permafrost. I. Test procedures and results. *Canadian Geotechnical Journal*, 30(1), 34-45.
- Biggar, K. W., Sego, D. C., & Noel, M. M. (1993). Laboratory and field performance of high alumina cement-based grout for piling in permafrost. *Canadian Journal of Civil Engineering*, 20(1), 100-106.
- Bommer, C., Phillips, M., & Arenson, L. U. (2010). Practical recommendations for planning, constructing and maintaining infrastructure in mountain permafrost. *Permafrost and Periglacial Processes*, 21(1), 97–104.
- Cesaretti, G., Dini, E., De Kestelier, X., Colla, V., & Pambaguian, L. (2014). Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronautica*, 93, 430-450.
- Clarke, E. S. (Ed.). (2007). Permafrost Foundation: State of the Practice. *American Society of Civil Engineers*.
- Johnston G.H. (1981). Permafrost Engineering Design and Construction. John Wiley & Sons
- Khoshnevis, B. (2004). Automated construction by contour crafting—related robotics and information technologies. *Automation in construction*, 13(1), 5-19.
- Ladanyi, B. (1975). Bearing capacity of strip footings in frozen soils. Canadian Geotechnical Journal, 12(3), 393-407.

- Ladanyi, B., & Johnston, G. H. (1974). Behavior of circular footings and plate anchors embedded in permafrost. *Canadian Geotechnical Journal*, 11(4), 531-553.
- Lim, S., Le, T., Webster, J., Buswell, R., Austin, A., Gibb, A., & Thorpe, T. (2009). Fabricating construction components using layered manufacturing technology. *In Global Innovation in Construction Conference*. pp. 512-520.
- Linell KA, Johnston GH (1973). Engineering design and construction in permafrost regions: a review. North American contribution to the 2nd international conference on permafrost. National Academy of Sciences, pp 553–575
- McFadden, T. (2000). "Design Manual for New Foundations in Permafrost," *Permafrost Technology Foundation*. <u>http://www.uaf.edu/ces/energy/housing</u> <u>energy/resources/PermafrostNewFoundations.pdf</u>
- McFadden, T. (2001). "Design Manual for Stabilizing Foundations on Permafrost," *Permafrost Technology Foundation*. <u>http://www.uaf.edu/ces/energy/housing</u> <u>energy/resources/Permafrost-design-manual.pdf</u>
- Morgenstern, N. R., Roggensack, W. D., & Weaver, J. S. (1980). The behaviour of friction piles in ice and ice-rich soils. *Canadian Geotechnical Journal*, 17(3), 405–415.
- Nixon, J. F. (Derick). (1990). Effect of Climatic Warming on Pile Creep in Permafrost. Journal of Cold Regions Engineering, 4(1), 67–73.
- Nixon, J. F., & McRoberts, E. C. (1976). A design approach for pile foundations in permafrost. *Canadian Geotechnical Journal*, 13(1), 40–57.
- Osterkamp TE. (2005). The recent warming of permafrost in Alaska. *Glob Planet Chang* 49(3-4):187–202
- Phukan, A., and Andersland, O. B. (1978). Foundations for Cold Regions. *Chap. 6 in Geotechnical Engineering for Cold Regions*, pp. 276-362. O. B. Andersland and D. M. Anderson (Ed). McGraw-Hill, New York.
- Romanovsky, V. E., & Osterkamp, T. E. (1997). Thawing of the Active Layer on the Coastal Plain of the Alaskan Arctic. *Permafrost and Periglacial Processes*, 8(1), 1–22
- Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping*, 12(3), 261–276.
- Weaver, J. S., & Morgenstern, N. R. (1981). Pile design in permafrost. *Canadian Geotechnical Journal*, 18(3), 357–370.
- Wu, Q., Zhang, T., & Liu, Y. (2010). Permafrost temperatures and thickness on the Qinghai-Tibet Plateau. *Global and Planetary Change*, 72(1-2), 32–38.
- Yang, Z. J., Lee, K. C., & Liu, H. (2021). Permafrost thaw and ground settlement considering long-term climate impact in northern Alaska. *Journal of Infrastructure Preservation and Resilience* 2(1), 1-17
- You, Y., Wang, J., Wu, Q., Yu, Q., Pan, X., Wang, X., & Guo, L. (2017). Causes of pile foundation failure in permafrost regions: The case study of a dry bridge of the Qinghai-Tibet Railway. *Engineering Geology*, 230, 95-103.
- Zhang, T., Heginbottom, J. A., Barry, R. G., & Brown, J. (2000). Further statistics on the distribution of permafrost and ground ice in the Northern Hemisphere1. *Polar Geography*, 24(2), 126–131

Impact of the COVID-19 Pandemic on Single Family Homes' Electricity Consumption in the Rural Iowa

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ABSTRACT

The COVID-19 pandemic and its associated lockdown have caused significant changes in lifestyle all around the globe. The combined effect of business and school closures as well as restrictions on travel during this period introduced unprecedented changes in occupancy presence and behavioral patterns in buildings. Electricity consumption in residential buildings can be affected by such changes in occupancy. However, the majority of the research activities which have attempted to quantify the aforementioned impacts of the COVID-19 lockdown on electricity consumption have been at the grid level; there have been limited efforts to study the impact of the pandemic on electricity consumption at the building level. Moreover, even fewer studies have focused on analyzing the change in electricity consumption patterns in rural residential buildings. Accordingly, in this study, electricity consumption data from more than 9,000 detached single-family homes in Cedar Falls, Iowa during the COVID-19 pandemic (2020) are compared against corresponding calendar normalize electricity consumption data for prior years (2010-2016). These comparisons support an improved understanding and quantification of how the lockdown during the 2020 COVID-19 pandemic affected the electricity use patterns of residential energy users in the rural Iowa.

This study's findings show that 54% of buildings in our database had a significant change in their non-weather-related consumption in 2020 when compared to previous years. From these, 62% of homes decreased in consumption, and 38% increased consumption. Those with increased consumption increased by a larger amount on average. The magnitude of changes in electricity consumption in this dataset was also found to be impacted by certain housing characteristics such as building size, vintage, and number of bedrooms. Accordingly, larger and newer homes were less impacted by the COVID-19 pandemic in 2020 as compared to the rest of the building stock.

INTRODUCTION

On March 11th, 2020, the World Health Organization (WHO) declared the novel coronavirus (COVID-19) outbreak a global pandemic (Cucinotta & Vanelli, 2020). Accordingly, governments across the world established lockdown measures to slow the

spread of this virus and protect their citizens. In the U.S., at least 316 million people in at least 42 states, three counties, 10 cities, the District of Columbia and Puerto Rico were urged to stay home (Mervosh et al., 2020). These lockdown orders were accompanied by prolonged school and business closures as well as imposed travel restrictions (Gostin & Wiley, 2020). These measures had a profound impact on daily life routines. Conventional in-person learning environments were replaced by online learning, and non-essential workers had to adapt to a new work from home model. The imposed measures also resulted in a dramatic reduction in transportation, as more people spent the majority of their time at home instead of traveling to and from school, work, or other activities (Conway et al., 2020). These substantial changes in lifestyle cause by the COVID-19 pandemic and lockdown significantly impacted when and how electricity was consumed.

In residential buildings, both HVAC and non-HVAC related loads can be impacted by occupant presence. HVAC use may be impacted since, in many homes, occupants adjust temperature setpoints and/or schedules of their HVAC systems based on whether or not there are occupants present in their home (Kawka & Cetin, 2021). For non-HVAC loads, the added loads may include those associated with the use of homes as substitutes for the office, classrooms, restaurants, and entertainment (Kawka & Cetin, 2021). Accordingly, a number of recent studies have focused on changes in energy and electricity consumption due to the COVID-19 pandemic and lockdown (e.g. Chen et al., 2020; Elavarasan et al., 2020; Kawka & Cetin, 2021; Rouleau & Gosselin, 2021). However, the majority of these research activities have attempted to quantify the impacts of COVID-19 at the grid level (e.g. Abu-Rayash & Dincer, 2020; Prol & Sungmin, 2020). There have been limited efforts to study the impact of the pandemic on electricity consumption at the building level (e.g. Kawka & Cetin, 2021). Even fewer studies have focused on analyzing changes in electricity consumption patterns in rural residential buildings.

Accordingly, in this study, several years of metered residential electricity consumption data from rural households located in Cedar Falls, IA (ASHRAE Climate Zone 6A (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), 2020)) is used to study the comparative electricity consumption of single family homes, including pre-pandemic (2010-2016) and during the COVID-19 pandemic, in 2020. First the data is quality controlled to calendar normalize meter readings and eliminate substantial missing or outlier data. Then, assessors' data is matched with electricity consumption data according to the unique parcel IDs to enable analysis with respect to housing characteristics.

METHODOLOGY

Multiple years of metered electricity consumption data (monthly billing data) for nearly 12,000 residentials customers were obtained for Cedar Falls, Iowa. This data included two datasets, one representing the period between 2010 and 2016, and the other for 2020. The electricity consumption data obtained from Cedar Falls Municipal Utilities included meter readings at irregular time periods (billing cycles), lasting between 8 to 46 days, which is typical of most utility billing data. To normalize this data to a common data frequency for analysis, a customized R script was developed and utilized.

This code assigned the daily average of a billing period to each one of the days that fell into that period. Then these daily averages were summed to form monthly and annual consumption values for each property in the database. All months with zero consumption were removed, since meter readings are subject to errors and vacant homes were not of interest in this study.

Next, the data was filtered to only include single family homes and to remove outliers based on estimated minimum and maximum monthly consumption from the Residential Energy Use Survey (RECS) data (U.S. Energy Information Administration (EIA), 2015a). These outliers were found by dividing the minimum and maximum annual consumption in the RECS dataset by 12 which limits the monthly consumption values to a lower bound of 4.9 kWh and an upper bound of 5,268.1 kWh. Then, the two datasets were combined and parcels that only existed in one dataset were removed as this limited the potential for comparison.

In addition to the datasets discussed above, the assessors' dataset from the selected location was also obtained and used. The assessors' data included information on the buildings' age, size, type, and other variables describing the properties of the residential building stock. Table 1 presents summary statistics for the 9,016 parcels in the resulting data.

Variable	Mean	Min	25th Percentile	50th Percentile	75th Percentile	Max
Home Age (years)	56.03	6	30	59	70	191
Number of Bedrooms	3.1	0	3	3	4	8
Home Area (m ²)	105.2	23.4	80.3	97.5	124.9	456.9
Monthly Consumption (kWh)	881.3	4.93	504.8	764.1	1117.8	5267.9

Table 1. Overview of the acquired dataset.

Removing Non-Weather-Related Electricity Consumption

Electricity consumption data for each meter reading was divided into a weather-related and a non-weather-related component to allow for comparison across different years and seasons. Accordingly, in addition to the data discussed thus far, temperature data for Cedar Falls in intervals from one hour to one day, based on availability, were also collected from the National Solar Radiation Database (NSRDB) (US Energy Information Administration (EIA), 2021). This data was used to distinguish the nonweather-related component of electricity consumption for each home, by removing the variation in consumption due to changes in local weather. To do so, first heating degrees days (HDD) and cooling degrees days (CDD) were calculated from a base temperature of 18.33°C (65°F) for each observation in the NSRDB and summed up for each month. Next, two linear regression analyses between the calculated degree days and consumption were used to determine how much of the electricity consumption is related to changes in local weather conditions. Accordingly, for each home, months May through August were used for the CDD regression analysis, and all other months were used for the HDD analysis. The resulting model coefficients were then used to remove weather-related consumption for each individual observation of monthly consumption. To determine the non-weather-related consumption for each home, Equation (1) was utilized,

$$C_n = C - (D_h * C_h + D_c * C_c)$$
 (1)

where C_n is the non-weather-related consumption, C is consumption, D_h and D_c are month's HDD and CDD respectively, and C_h and C_c are heating and cooling degree day coefficients. A consideration made in this analysis was related to the number of observations available for each home. Figure 1 shows the relationship between HDD coefficients and number of observations used in regression analysis. Homes with less than 26 observations (7.4%) generally were not found to have realistic HDD coefficients and were thus removed.



Figure 1. Relationship between the number of observations and heating degree day (HDD) coefficients

Next the 95% mean confidence intervals of non-weather-related electricity consumption were found for each month and year across all parcels and plotted to visually compare the consumption of 2020 to previous years.

RESULTS & DISCUSSION

To compare the electricity consumption during the COVID-19 lockdown in 2020 against previous year, the 95% confidence interval for monthly non-weather-related electricity consumption was identified for all studied years across all homes (2010 to 2016 and 2020). As seen in Figure 2, all months are used in this analysis except for the month of December which had missing data in the year 2020 and was thus not suitable for analysis.



Figure 2. 95% mean confidence intervals for non-weather-related electricity consumption by month and year for all residential parcels in Cedar Falls, IA.

From these data, confidence intervals for percent change in non-weather-related electricity consumption were derived (Figure 3). Here, the months January and February in 2020 appeared to have had significantly lower consumption levels compared to previous years. Similar trends can be seen in the Monthly Energy Review reports published by the EIA, which shows that electricity consumption by the U.S. residential sector in the first three months of 2020 were lower than the comparative period in previous years (U.S. Energy Information Administration (EIA), 2021b).

During these three months, the weather was relatively warmer than average in the U.S. and HDDs on average were 15% fewer (U.S. Energy Information Administration (EIA), 2021a). It has been suggested that because of this warmer weather, residential energy consumption of several heating fuels, including electricity, in the first three months of 2020 was lower than previous years (U.S. Energy Information Administration (EIA), 2021a). However, since this analysis considers non-weather-related electricity consumption, and the majority of residential space heating in the State of Iowa is not powered by electricity (76.3%), it is suggested that further investigation is needed to understand the root cause of the relatively lower consumption witnessed in January and February of 2020 (U.S. Energy Information Administration (EIA), 2015b; US Energy Information Administration (EIA), 2021).

Regardless, assuming that percent change for each parcel is considered significant when zero does not fall within the interval, non-weather-related electricity consumption for most other months in 2020 appears to be within the range of previous years. This suggests that changes in monthly non-weather-related electricity consumption between the lockdown period and previous years were not significant for most months in this dataset. Similar trends were found when studying the nationwide residential electricity consumption, according to which most months' consumption values were within a 10% range difference from the mean of previous year (2010-2016). The annual electricity consumption in this sector was only 3.8% more than the mean of the control period (U.S. Energy Information Administration (EIA), 2021b).

The higher annual electricity use for residential buildings is mainly believed to be driven by HVAC and appliance use during daytime hours, and thus relates to both weather and non-weather related electricity loads (Krarti & Aldubyan, 2021).



Figure 3. The change in 95% mean confidence intervals for non-weather-related electricity consumption between 2020 and previous years for all residential parcels in Cedar Falls, IA.

The homes with a significant change in annual non-weather-related electricity consumption between 2020 and previous years of data (54%) were then analyzed more closely to determine the drivers of this witnessed change in consumption. Figure 5 shows the distribution of these parcels based on the change in their 95% mean confidence intervals for non-weather-related electricity consumption between the year 2020 and the 2010-2016 period. It can be seen that of the 54% of homes with a significant change in consumption during the COVID-19 lockdown, 62% witnessed a decrease in consumption. However, the average change of significance decreasing homes was calculated to be 42.3%, whereas the average change of significance increasing homes was calculated to be 87.8%. This means that although more parcels had witnessed a decrease in consumption, those with increased consumption had a larger amount of change on average.



Figure 4. Distribution of homes by percent change in non-weather-related consumption (*Note: Only parcels IDs with statistically significant percent change in 95% mean confidence interval 95% mean confidence intervals are shown*).

Other studies on the impact of COVID-19 on the electricity consumption in residential sector have concluded that the magnitude of the increase in home energy use depends on the household and housing characteristics (Krarti & Aldubyan, 2021). The parcels with significant change were thus analyzed with respect to select building characteristics based on data obtained from the assessors in Cedar Falls (Figure 5). This figure shows the (left) positive and (right) negative change in 95% mean confidence intervals for non-weather-related electricity consumption between 2020 and previous years based on (a) building size, (b) building age, and (c) number of bedrooms.





Figure 5. The (left) positive and (right) percent change of non-weather-related electricity consumption between 2020 and previous years for homes in Cedar Falls, IA based on (a) building size, (b) building age, and (c) number of bedrooms.

It can be seen that the variance in percent change for all three groups of buildings attributes is substantial. For the analysis involving the number of bedrooms specifically, there appears to be a negative correlation between the percent change in households with relatively higher consumption levels in 2020 with regards to an increase in the number of bedrooms. Similarly, a positive correlation was found between consumption values for homes that had lower consumption in 2020 as compared to previous years. Table 2 summarizes the regression metrics for this set of analysis and shows that home area was the only non-significant factor when analyzing homes with increased consumption in 2020. All other factors were statistically significant in both reduced and increased consumption models. Overall, the data suggests that larger homes with respect to both area and number of bedrooms were less affected by changes in lifestyle experience during the COVID-19 pandemic. Prior research had also suggested that the relative influence of occupants differs for varied building characteristics (van den Brom et al., 2019). However, all R-squared values are low, suggesting that the regression models built using the selected housing characteristics can explain little variance in changes in electricity consumption between the year 2020 and previous years with available data.

Variable	Type of change	R squared	p-value	95% CI coef lower	95% CI coef upper	Coef
Bedrooms	+	0.003	0.022^{*}	-11.238	-0.876	-6.057
Bedrooms	-	0.007	0.000^{***}	1.062	2.749	1.906
Home Area	+	0.001	0.216	-0.018	0.004	-0.007
Home Area	-	0.011	0.000^{***}	0.003	0.007	0.005
Year Built	+	0.014	0.000^{***}	-0.478	-0.203	-0.341
Year Built	-	0.040	0.000^{***}	0.105	0.151	0.128

 Table 2 . Housing characteristics-based regression metrics for changes in electricity consumption.

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

CONCLUSIONS

In this study, electricity consumption data from more than 9,000 detached single-family residential meters in Cedar Falls, Iowa during the COVID-19 pandemic (2020) were compared against corresponding calendar normalize meter readings consumption data for prior years (2010-2016). The study's main objective was to understand and quantify how the lockdown during the 2020 pandemic affected the electricity use patterns of residential energy users in the rural Iowa. The findings showed that 54% of buildings in our database had a significant change in their non-weather-related consumption in 2020 when compared to previous years. From these, 62% of the witnessed changes in consumption were classified as a decrease. However, although more parcels had witnessed a decrease in consumption, those with increased consumption had a larger amount of change on average. Assessors' data was also studied to characterize the homes with significant change in electricity consumption between the year 2020 and the 2010-2016 period. We found that overall, larger homes, homes with more bedrooms, and newer homes were less affected by the changes in lifestyle experienced during the pandemic.

The limitations inherent in the sample of this study are related to the unavailability of household size and demographics characteristics. Future studies can benefit from such data to control for socio-economic status. Another set of limitations are related to the unavailability of data for the 2017-2019 period which created a gap in the analysis. It may be possible that renovations or changes in ownership happened over this period for certain homes which might have affected its housing and household characteristics.

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REFERENCES

- Abu-Rayash, A., & Dincer, I. (2020). Analysis of the electricity demand trends amidst the COVID-19 coronavirus pandemic. *Energy Research & Social Science*, *68*, 101682.
- American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE). (2020). *Standard 90.1 User's Manual (Based on ANSI/ASHRAE/IES Standard 90.1-2019)*.
- Chen, C., de Rubens, G. Z., Xu, X., & Li, J. (2020). Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. *Energy Research & Social Science*, *68*, 101688.
- Conway, M. W., Salon, D., da Silva, D. C., & Mirtich, L. (2020). How will the covid-19 pandemic affect the future of urban life? early evidence from highly-educated respondents in the united states. *Urban Science*, *4*(4), 50.
- Cucinotta, D., & Vanelli, M. (2020). WHO declares COVID-19 a pandemic. Acta Bio Medica: Atenei Parmensis, 91(1), 157.

- Elavarasan, R. M., Shafiullah, G. M., Raju, K., Mudgal, V., Arif, M. T., Jamal, T., Subramanian, S., Balaguru, V. S. S., Reddy, K. S., & Subramaniam, U. (2020). COVID-19: Impact analysis and recommendations for power sector operation. *Applied Energy*, 279, 115739.
- Gostin, L. O., & Wiley, L. F. (2020). Governmental public health powers during the COVID-19 pandemic: stay-at-home orders, business closures, and travel restrictions. *Jama*, *323*(21), 2137–2138.
- Kawka, E., & Cetin, K. (2021). Impacts of COVID-19 on residential building energy use and performance. *Building and Environment*, 205, 108200.
- Krarti, M., & Aldubyan, M. (2021). Review analysis of COVID-19 impact on electricity demand for residential buildings. *Renewable and Sustainable Energy Reviews*, 110888.
- Mervosh, S., Lu, D., & Swales, V. (2020, April 20). See Which States and Cities Have Told Residents to Stay at Home. *The New York Times*. https://www.nytimes.com/interactive/2020/us/coronavirus-stay-at-homeorder.html
- Prol, J. L., & Sungmin, O. (2020). Impact of COVID-19 measures on short-term electricity consumption in the most affected EU countries and USA states. *Iscience*, *23*(10), 101639.
- Rouleau, J., & Gosselin, L. (2021). Impacts of the COVID-19 lockdown on energy consumption in a Canadian social housing building. *Applied Energy*, 287, 116565.
- U.S. Energy Information Administration (EIA). (2015a). *Residential Energy Consumption Survey (RECS)*. https://www.eia.gov/consumption/residential/data/2015/
- U.S. Energy Information Administration (EIA). (2015b). Residential Energy Consumption Survey (RECS).
- U.S. Energy Information Administration (EIA). (2021a). Despite more people staying at home, U.S. residential energy use fell 4% in 2020. https://www.eia.gov/todayinenergy/detail.php?id=47976
- U.S. Energy Information Administration (EIA). (2021b). *Monthly Energy Review*. https://www.eia.gov/totalenergy/data/monthly/
- US Energy Information Administration (EIA). (n.d.). *National Solar Radiation Database (NSRDB)*. https://nsrdb.nrel.gov/
- US Energy Information Administration (EIA). (2021). *Iowa State Energy Profile*. https://www.eia.gov/state/print.php?sid=IA
- van den Brom, P., Hansen, A. R., Gram-Hanssen, K., Meijer, A., & Visscher, H. (2019). Variances in residential heating consumption–Importance of building characteristics and occupants analysed by movers and stayers. *Applied Energy*, 250, 713–728.

Overview of common residential wall construction methods applied to achieve a continuous air-barrier and their material properties

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Abstract

One-third of the energy used to heat a typical house is lost by air leaking through the building envelope, which includes the slab on grade, exterior walls, and roof. Consequently, new houses built to codes and standards that require minimal energy to provide thermal comfort rely on airtight building envelopes. While the efficacy of the air barrier in these houses is tested during construction and prior to initial occupancy, there is a lack of research conducted into the resiliency of these air barriers to displacements caused by earthquakes, wind, or other forces. A literature review and documentation of case study projects was conducted to determine the types of wall assemblies, air-barrier methods and materials that are used in Passive House (PH) construction of single-family and low-rise multifamily construction in the Pacific Northwest. This region was selected because it was an early adopter of PH building methods and his high seismic risk. This research presents wall types in high-performance construction as documented by the Building Science Corporation and in several PH case study projects. The sheathing substrate materials for the walls and materials used for sealing gaps between material panels are identified. The most used exterior wall sheathing materials, in respect to the study, are gypsum board, plywood, OSB and ZIP[®] Board. Two of the studied methods of providing air barriers include: (1) the use of specialized tape at the intersections of exterior sheathing panels and (2) fluid-applied air barrier. Manufacturer literature for three commonly used flashing tapes and one liquid barrier are reviewed herein to understand the mechanical properties of the air barriers and to speculate on their performance if subjected to seismic loads.

Keywords: Passive House, Air Barriers, Envelope Design, Resiliency

1. Introduction

Passive House (PH) certified construction¹ employs a high-performance building envelope. "In order to maintain comfortable indoor conditions in low-energy buildings, the entire building envelope needs to be perfectly insulated and prevented from air leakages." (PassiveHaus Institute, n.d.) If PH standards are to be widely adopted for high-performance buildings, these highly insulated walls with minimal air leakage must be designed and proven to resist wind and earthquakes (lateral loads) without compromising their thermal and airtightness performance. For example, if a small earthquake shakes a wall so that it is not damaged structurally but there is a tear in the layer functioning as an air barrier, then the thermal performance of the envelope may be compromised with no visible exterior signs. This could lead to higher energy use and, more critically, mold in the wall cavity which can affect the health of the occupants (e.g., allergy or asthma). Failures of this type would likely lead to resistance in adopting the PH standard widely.

This is a multi-phase research initiative to understand the integrity of airtightness in highperformance PH walls when exposed to seismic forces. During the initial research, reported on in this paper, we identified wall construction methods commonly used in Passive House certified residential buildings and uncovered various products used. The interaction between sheathing systems and products used to seal gaps between wall sheathing, products identified in this paper, were tested in small-scale samples under monotonic forces (see Abdelwahab et al. (2022) in these proceedings). Cyclic loading tests of the selected sheathing and air sealing products is underway. As a next phase of this research, full scale wall assemblies will be tested under earthquake forces. The products and systems identified in this paper are typical to construction practices often seen in the Pacific Northwest (Oregon and Washington, USA). We discovered that companies who specialize in PH construction in this region most often use half inch thick oriented strand board (OSB) for exterior wall sheathing; OSB is also used in many Structurally Insulated Panels (SIP), sometimes used as a prefabricated component of highly insulated walls. Ultimately, three sheathing types were selected for further study.

2. Background on Passive House Construction

Investigation of high-performing buildings aligned with PH standards started in North America in response to the oil embargo in the 1970s and was formalized in the 1980s. Physicists Bo Adamson and Dr. Wolfgang Feist refined the principles and developed the PassivHaus performance metrics in Europe in the early 1990s. The first test project was an apartment block at Darmstadt Kranichstein and Dr. Feist established the Passivhaus Institut (PHI) in 1996 (Bere, 2013). Since then, PH principles have been tested in the United States, all European climates, Canada, and even in warm Asian climates where cooling is required. PH standards can be used in all building types including low-cost buildings, new construction, and retrofit in an existing building of any type or size.

¹ There are two organizations that promote passive building principles, Passive House International (PHI) originating in Germany and PHIUS, established in the United States. Airtight envelopes are essential for both and therefore the term Passive House is used to describe both for the purposes of this paper. For more information see Melton (2019). Passive House is also a specific designation that differs from passive solar building principles.

PH standards associated with PHI were reintroduced in the United States in 2002-'03 by Katrin Klingenberg, a German-trained architect, when she constructed a home in Urbana, Illinois. The Illinois home was constructed using passive building energy standard, leading the research of PHI for the United States. After investigation and positive outcomes, PHIUS was established in 2007 in collaboration with Building Science Corporation to establish cost-effective climate specific metrics for the United States. Although metrics and approaches vary, both PHI and PHIUS continue to promote passive building principles.

Corner et al., in the book *Passive House Details Solutions for High-performance Design* (2018), recognizes that "the building envelope shapes all of the other opportunities, the high-performance envelope greatly reduces capital expenditures on mechanical systems, tons of cooling, volumes of ducts, diameters of pipes…" and adopts PH building standards as the benchmark for optimal envelope design. Five building science principles are core to Passive House design, including "extremely airtight envelope, preventing infiltration of outside air and loss of conditioned air" (Corner et al., 2018). Since this study is specific to North America, with a focus on the Pacific Northwest, PHIUS certified buildings are further explored.

3. Materials and Methods

Materials and methods used to achieve air sealing in building envelopes have significant implications for the durability of the envelope, which will impact the adoption of PH. To better understand these methods, single-family residential buildings designed and constructed to PHIUS certification standards were analyzed. Four are detailed in the section below with particular attention paid to identifying the exterior sheathing material and the air sealing employed at the seam between wall sheathing panels.

3.1 Case Studies

Pumpkin Ridge PHIUS was completed in 2014 in North Plains, Oregon. It is included in this study for its use of the Prosoco[®] fast flash system, wall structure, and location. This project was completed in 2014 in North Plains, Oregon. Like other PH projects, Pumpkin Ridge utilizes 2x6 wall studs with joists. In this case, $9\frac{1}{2}$ " I-joists are used on the exterior side of the envelope. High density cellulose insulation is installed to accomplish PHIUS Standards for superinsulation; the air barrier consists of $\frac{1}{2}$ " OSB sheathing using fast flash fluid applied air barrier. (source: Hammer & Hand, 2019)

The Karuna House is in Newberg, Oregon and is 3,500 square-feet and also utilized the previously mentioned wet flash system to maintain an air-tight envelope. The wall construction consists of ¹/₂" plywood sheathing with a continuous layer of Prosoco[®] Cat 5 roll-on fluid membrane (wet flash system). Additionally, it has 2x6 wall studs that are supported with z-trusses on the exterior of the wall structure and utilizes blown high density cellulose insulation to address the PHIUS standards. (Source:Karuna PHIUS details)

The PHIUS certified Delphi Haus in Olympia, Washington, is smaller than the previous projects with a square footage of 2,250. Delphi Haus was completed in 2017, using 2x6 wall studs, dense-packed fiberglass insulation in addition to six-inch foam insulation. This project used ½" OSB Sheathing with Siga acrylic tapes at the seams on the interior side of the OSB. Typically, the tape

is on the exterior side of the sheathing, however the designer of the project chose to have it installed on the interior to maintain an air-tight envelope from the inside. (Creative, n.d.).

Palatine Passive House in Seattle, Washington was completed in 2016. It is 2,700 square-feet in size. The Palatine PHIUS uses a ZIP[®] prefabricated wall system that consists of 2x8 wall studs and dense packed fiberglass insulation and three-inch poly-isocyanurate insulation. The ZIP[®] system has its own adhesive tape to maintain the air-tight envelope desired for PHIUS construction. The Palatine PHIUS uses the ZIP[®] tape at the seam between ZIP sheathing panels to achieve air tightness (source: *HomeWorldDesign,n.d.*).

		Case Studies	5		
	Pumpkin Ridge Passive House	Karuna House	Delphi Haus	Palatine Passive House	
Location	North Plains, OR	Newberg, OR	Olympia, WA	Seattle, WA	
Size	4,400 sq/ft	3,500 sq/ft	2,250 sq/ft	2,700 sq/ft	
		Prosoco Cat 5 Fluid	Siga tapes on interior		
Air Barrier	Fast Flash Fluid Barrier	Barrier	OSB		
Sheathing	1/2" OSB	1/2" Plywood	1/2" OSB	Zip Sheathing	
Completion Date	2014	2013	2017	2016	
		Blown high density	DP Fiberglass & 6"	DP Fiberglass & 3" Poly-	
Insulation	High Density Cellulose	cellulose insulation	Foam	Isocyanurate	**DP is Dense-Pack
	2x6 wall studs with	2x6 wall studs with z-			
Wall System	9.5" I-joists	truss	2x6 wall studs	2x8 stud wall	
	Passiv	e House Wall	Systems		
		2x6 Advanced-			
	Standard Wall	Framed Wall			
	Construction	Construction	Larson Wall Truss	SIP Wall System	
Interior	Gypsum Board	Gypsum Board	Gypsum Board	Gypsum Board	
Sheathing			Plywood/ OSB		
Sheating	n/a	n/a	Sheathing	OSB Sheathing	
			2x4 or 2x6 Studs 24"		
Structure		2x4 or 2x6 Studs 24"	on center, 2x3 exterior		
	2x4 or 2x6 Studs	on center	truss	Panel	
Insulation	Fiberglass or Cellulose	Fiberglass or Cellulose	Fiberglass or Cellulose	EPS insulation core	
Exterior Sheathing		XPS insulating exterior	Plywood/OSB		
Extenor Sheatning	OSB or Plywood	sheathing	sheathing	OSB Sheathing	
Air Barrier	House Wrap	Taped XPS insulation	House Wrap	House Wrap	
Exterior Finish		Cladding attached to Furring Strips	Cladding attached to Furring Strips	Cladding attached to Furring Strips	

Table 001 Case Studies and Wall Systems

Per the examined case studies, the 2x6 Advanced-Framed Wall system is the most common base construction type used in the PH projects studied. This wall, especially combined with exterior insulation, has a high R-value that is ideal for the climate of the Northwestern United States. These wall types are summarized, along with the case study homes reviewed, in Table 1 above.

3.2 Wall Systems

Common high-performance wall construction assemblies used in PHIUS buildings are outlined below and compared with a base case, considered "standard wall construction." Assemblies are analyzed from information provided by the Building Science Corporation (BSC). It is important to note that the Building Science Corporation (BSC) wall systems included were selected because they provide good hygrothermal performance necessary for high-performance, passive buildings; they are not necessarily designed for earthquake regions and may need to be modified based on best practices for earthquake regions (e.g., lateral bracing, etc.). Resources such as those available from the National Institute of Building Sciences (NIBS) Building Seismic Safety Council (NIBS, n.d.) will need to be considered in future work.

Standard Wall Construction

Standard or traditional wall construction is often used today. The double top plate provides more structural strength, and the wood studs are placed at 16 inches on center (o.c.). Depending on the type of the insulation material (fiberglass batt or cellulose), the R-value of this assembly can be 10.0 or 13.7, respectively. Many high-performance walls include exterior insulation, increasing thermal resistance and reducing thermal bridging.

2x6 Advanced Framed Wall Construction

Advanced Framed walls, popular in residential construction today, use less lumber than standard framing (24 inches o.c. instead of 16 inches o. c.). This wall system has a higher R-value, making it a better candidate for colder climate zones. It is a 2x6 stud wall with fiberglass or cellulose insulation in the wall cavities and uses XPS exterior insulation. The seams at the sheathing, exterior insulation, or both are taped to establish a continuous air, moisture, and vapor barrier (ETW: Walls - 2x6 Advanced Frame Wall Construction High R-value). The single top wood plate and bottom of the wall assembly is insulated with spray foam at rim joist.

Larson Truss Wall System

The Larson Truss Wall System consists of a 2x6 interior framed wall and a 2x3 exterior truss that allows a large central cavity for cellulose insulation. The truss system allows the insulation on the exterior to eliminate thermal bridging at the rim joist, studs, and top plate. This system can be used in new construction and in a retrofit scenario. (ETW: Wall - Truss Wall Construction)

Structural Insulated Panel (SIP) Wall System

This system is being tested to ensure the airtightness remains at the seams of the panels in the event of a natural disaster. SIP is sometimes referred to as sandwich panel. OSB panels are placed on both sides of insulating foam and vertical stiffeners holds them together. The foam core is commonly composed of EPS as insulation; it could also be used by XPS and PIC to increase R-value. SIPS construction is considered as having less architectural flexibility than wood framing because of panel attachment requirements and minimum panel widths (ETW: Wall - Sips Wall Construction). Studies indicate that care must be taken to avoid moisture issues/condensation problems with SIPs in high-performance buildings in cold climates. Solutions for continuous insulation are available but might increase the cost of the assembly.

3.3 Air Barriers

Of particular interest in this study is the sheathing layer of the wall, common to all types above and of importance because if not detailed properly, the gaps between sheathing panels can compromise the airtightness of the building envelope.

Seams in a building envelope occur where exterior sheathing ends and begins, at window openings, and at door openings, allowing moisture and air to penetrate if they are not properly sealed. These seams need to be addressed to have successful PHIUS construction. Once the wall assembly is complete, seams are hidden and difficult to access. However, long-term viability of

the air sealing at these gaps is essential to maintaining the performance of the wall. There is a lack of information concerning how tapes and other sealants perform during and after natural disasters such as earthquakes. A research initiative to fill this gap in knowledge is undertaken with the support of Penn State's Institutes of Energy and the Environment (IEE). As a first stage of this work interaction between wall sheathing and air barrier materials are considered.

Sheathing

Based on the case study analysis, OSB and plywood sheathings² are more universal and commonly used in all construction and is found in many PHIUS projects. Some additional case studies utilized ZIP System[®] sheathing. ZIP System[®] sheathing is paired with the company's tape sealing system. In our study, we will only be pairing the ZIP[®] tape with the ZIP[®] sheathing as per the manufacturer's recommendation.

Air Barrier Assemblies

Although mechanically fastened building wraps continue to be the most popular type of air barriers, fully adhered air barrier materials applied at sheathing seams are a rising practice in highperformance construction. For PHIUS buildings, applying self-adhered sheet products or fluidapplied membranes ensures more control over the air sealing process. The tape and liquid air barriers that were chosen for this study were selected from various case studies discussed in this report. Additionally, insight from Green Hammer Design Build, a company located in Portland, Oregon, aided the decision in air barriers to study. From the studies conducted, we included in this research air barriers outlined below: Siga Wigluv pressure sensitive adhesive tape, 3M tape, ZIP[®] acrylic adhesive tape, and Prosoco R-Guard liquid barrier were selected as appropriate for application at the sheathing seams to achieve airtightness³. The material summaries below are provided from the manufacturers' websites.

Air sealing tapes include an adhesive that is either peel and stick or applied directly from the roll; liquid air barriers are applied by brush, spray or roller. The website of *Hammer and Hand* presents a system for sealing a building envelope using a paint roller (Swinford, 2012). This is called a wet flash system. This system can be used for multiple purposes like filling joint seams, penetrations through the walls, and seal the window openings and may be applied in a continuous layer covering the surface of the sheathing. A video of the air barrier system applied to the 2x6 wall at Karuna Passive House (https://vimeo.com/44143840) demonstrates the application of the wet flash system. After the system is applied, rigid insulation can be attached to the exterior face then the rainscreen for siding to be installed.

² It is important to ensure that the substrate is airtight, otherwise sealing at the seams only (the scope included in this research) will not adequately provide the airtightness standards necessary for PHIUS certification. Material properties may vary widely and should be selected based on best hygrothermal and structural properties. ³ For this phase of the research study, the interaction between wall sheathing and materials adhered to the seam between sheathing panels are considered. Further research is needed to determine the entire assembly.

3.4 Summary of air barrier products selected for further study

Siga Wigluv

Siga Wigluv is described as strong and elastic with pressure sensitive adhesive protected by a peel-off backing. The acrylic adhesive maintains its strength in high and low temperatures. The tape has a reinforced mesh backing to aid the structural integrity of the product. Siga Wigluv is known to allow the builders to reach their airtightness goals with its vapor-permeable polyolefin (PO) film. This product can be exposed directly to the weather conditions for up to 12-months without damage to the adhesion. This illustrates the strength and durability of this tape, and it gives the builders a flexibility once the exterior finish material attached.

3M

This tape is described by the manufacturer as being durable during hot and cold conditions and can be applied in weather as cold as 10°F and as hot as 185°F. The adhesion for the tape is promoted as being very strong and able to stick to the surface of most substrate materials. This property reduces the chances of the material peeling off or curling at the edges. In addition to use at the sheathing seams, the 3M tape can be applied to other building applications including foam board insulation, covering the seams of the polyethylene vapor barriers, and repairing holes in the exterior building wrap.

ZIP®

ZIP[®] tape has a strong acrylic adhesion and intertwined polymer chains for strength and durability. "the tape's advanced acrylic adhesive is made of highly polar molecules," pulling the tape into the ZIP System® panel and helping the tape to "wet out, and flow into panel ridges and produce a permanent bond" (Huber, n.d.). When the tape is applied, it takes approximately seventy-two hours for it to fully adhere and create the bond and seal desired. This product can withstand higher temperatures than others and be applied in weather as cold as 0°F.

Prosoco R-Guard FastFlash

The Prosoco R-Guard® FastFlash® is a liquid barrier "that combines the best characteristics of silicone and polyurethane" (Prosoco, n.d.), which bonds to common building materials like OSB. It is easily applied to the sheathing, creating a seamless layer of air protection but allowing the building to "breathe" with respect to vapor permeability despite the liquid creating a continuous layer. The R-Guard is specified to be a durable product with adhesion thought to last a long period of time, making this an attractive product to test.

The documentation regarding adhesives and their attributes is available, but not consistent. One important aspect of the adhesives is how they cure. The three main ways, or curation, are by physically hardening, chemically curing, and using pressure. Pressure sensitive adhesion (PSA) tapes either peel and stick directly to the sheathing or comes in a roll without a backing. Adhesives that physically harden are used in liquid-based adhesives and become hard when they dry. Chemical curing, unlike PSA, uses an additional product to make the tape adhere to the sheathing. There are different backing materials for the adhesive tapes. These are typically rubber, fabric, and fibers. The fiber backing material can be used with the roll-on barrier to aid

the strength of the material. The backings can aid in the durability, pliability, and strength of the product.

								-	
	Tapes	Tapes	Tapes	Tapes	Spray on	Rollon	Rollion	"Note: One of the tapes will be elimi	nated
OSB	Siga	Proclima	3M		Aerosana	Prosoco	Visconn Fibre	Alternative for the spray on is listed	below (Aerosana
Plywood	Siga	Proclima	ЗM		Aerosana	Prosoco	Visconn Fibre		
ZIP	-			Zip					
	Adhesive Type	Life	Material	Temp Resistance	Thickness	Dimensions	Strength	Ndes	
Siga Wigluv	Pressure Sensitive Acrylic Adhesive		vapor-permeable polyolefin (PO) film, reinforcing mesh, and pressure-sensitive glue	-40 to 212	14milis	2.4" x 131' 4", 6", 9'x 82		high permanent adhesive strength, non-drying and non-embritting since without caoutchouc, resin or solvent, can reliably and durably absorb structural movements	10 Year Limited warranty
Proclima Tescon Vana	waterproof SOLID adhesive	Reliable for up to 100 years See document in folder	special PP fleece	-40 to 194			The bands should not be subjected to templic shows	wall lining membrane: pro clima SOLITEX: TESCON PRIMER is required	
зм	Pressure Sensitive Acrylic Adhesive	Shelf 24 months from manufacturer date	biaxially oriented polypropylena (BOPP)	14 to 185	3mils	3,9" or 37,5"	38 lb/in	used on Type V construction	
Zip	Pressure Sensitive Acrylic Adhesive		vapor-permeable polyciefi n (PO) fi lm, reinforcing mesh, and pressure- sensitive glue,	0 to 120	12mils	3 3/4"(30' and 90'), 6" (75'), 9", 12" (50')	938 psi tensile strength		
Aerosana Visconn	Water-based Acrylic	3 month esposure to climate without being covered	modified aqueous acrylate polymer dispersion	-40 to 194	8-39 (wet) mils			If the seam is wider than 1/8" need Aerosanna Fleece	
Prosoco R Guard Cal 5	Silicone	Shelf 12 months if stored at or below 80 degrees	Silyl-Terminated-Polymer	32 to 110 (for application)	12 (wet) mils	roll on	>100psi		
Aerosana Visconn Fibre		3 month esposure to climate without being covered	modified aqueous acrylate polymer dispersion, fibre- reinforced	-40 to 194	24-55 (wet) mils	brush on		Can cover up a 3/4" seam without additional materials	

Table 2: Summary of technical specifications for materials

4. Summary and Conclusions

This study is part of a broader research study to understand how air sealing in PH construction performs when subjected to earthquakes. Available literature and case study projects were explored to better understand the most common wall assemblies and methods for air sealing used in PH residential construction. Manufacturer specification and product literature was used to speculate on performance. These products were examined and chosen for their adhesive type, durability, their application, and the elasticity of each product.

The barrier types chosen, Siga Wigluv, Proclima: Tescon Vana (later changed to Prosoco R-Guard FastFlash®), 3M, and ZIP[®] are strong materials per specifications, with adhesion properties that are desired for the research. Additionally, they all are thought to perform well in very cold climates and very hot climates. They are not fragile materials that need to be applied in one climate zone, they are versatile. The sheathing materials in Table 2 are commonly used in PH construction in North America: OSB, Plywood, and ZIP[®] sheathing. Further research is needed to understand the long-term performance of the combination of sheathing and air sealants, especially to know whether the viability of the air sealing at gaps in the sheathing would be compromised if the wall assembly is affected by a minor earthquake where damage to the wall assembly may not be immediately obvious. As a next stage of this research, small scale samples of selected sheathing and sealants were tested. For results of this initial testing, please refer to the paper by Abdelwahab et al. (2022), also included in the conference proceedings.

Study limitations and future work: this paper identifies common sheathing and air sealing products used in Passive House certified projects in the Pacific Northwest and consistent with best practices for high-performance well construction. It was intended to identify a limited study case for small-scale testing and is not a comprehensive review of all products. Moreover, sheathing is only one component of the exterior wall assembly. A holistic approach that considers interaction of forces on components of exterior wall assemblies, including the air barrier, and related hazards affecting residential construction in earthquake regions will be addressed in future work.

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References

- Abdelwahab, K., Gracie-Griffin, C., Memari, A., and Iulo,. L.D. (2022). "Small-scale Testing of Air Barrier Systems Adhered on Sheathing Panels Under In-Plane relative displacement Simulating Seismic Effect." In Proceedings of the 6th Residential Building Design and Construction Conference, March 2022, University Park, PA.
- "Air Barrier: Waterproof Barrier PROSOCO R-Guard Cat 5." Prosoco, prosoco.com/product/cat-5/.
- BCS, Building Science Corporation, "Building Enclosures that Work," https://www.buildingscience.com/documentsearch?term=&field doc topic tid=All&type%5B%5D=9 Accessed September 2021.
- Bere, Justin. An Introduction to Passive House. RIBA Publishing, 2013.
- Corner, D. B., Fillinger, J. C., Kwok, A. G. (2018). *PHIUS Details Solutions for High-Performance Design*. Routledge.

Creative, E. (n.d.). *Delphi haus:* Artisans Group - Modern architecture revolutionary comfort. Retrieved September 15, 2021, from https://artisansgroup.com/portfolio/delphi-haus.

- Detail Inspiration (2007), "Community Centre in Ludesch," Detail 06/2007.
- Ehrlich. "Seal, Tape, Gasket: A Sticky Search for Better Materials." *BuildingGreen*, BuildingGreen, 12 July 2019, <u>www.buildinggreen.com/feature/seal-tape-gasket-sticky-search-better-materials</u>.
- "ETW: Wall Sips Wall Construction." Building Science Corporation, 15 Nov. 2014, www.buildingscience.com/documents/enclosures-that-work/high-r-value-wall-assemblies/high-rwall-sips-wall-construction.

- "ETW: Wall Truss Wall Construction." Building Science Corporation, 15 Nov. 2014, www.buildingscience.com/documents/enclosures-that-work/high-r-value-wall-assemblies/high-rwall-truss-wall-construction.
- "ETW: Walls 2x6 Advanced Frame Wall Construction High R-Value." Building Science Corporation, 10 July 2015, <u>www.buildingscience.com/documents/enclosures-that-work/high-r-value-wall-assemblies/high-r-value-wall-advanced-wall</u>.
- Hammer & Hand (2019) "Pumpkin Ridge PHIUS by Portland BUILDER Hammer & Hand." 08 Jan. 2019. Web. 10 Sept. 2021.
- *HomeWorldDesign (n.d.).* "Palatine PHIUS in North Seattle by Malboeuf Bowie Architecture." Web. 10 Sept. 2021.
- Huber Engineering Woods (n.d.) "Zip System[™] Flashing Tape," product specifications. Downloadable from https://www.huberwood.com/uploads/documents/technical/documents/Product-Data-Sheet-Flashing-Tape-ZIP-System_2021-03-09-153355.pdf
- "Karuna PHIUS Details: Wall Assembly: Hammer & Hand: NW Green Home Builder." *Hammer & Hand*, hammerandhand.com/portfolio/karuna-house/wall-assembly/.
- Melton, P. (2019) "The Two Passive Houses: A Comparison," News Analysis, BuildingGreen, published August 6, 2019.
- Mission & History: Passive House Alliance U.S. <u>https://www.phius.org/about/mission-history. Accessed</u> 12 Jan. 2022.
- NIBS (National Institute of Building Sciences (n.d.). "Building Seismic Safety Council," (<u>https://www.nibs.org/bssc#resources</u>). Accessed January 07, 2022.
- PassivHaus Institute, Passipedia: A PHIUS Resource, "Building Envelope," (https://passipedia.org/planning/thermal_protection). Accessed September 2021.
- PHIUS , PHIUS Alliance website. "PHIUS Principles." <u>https://www.PHIUS .org/what-is-passive-building/passive-house-principles</u>. Accessed: September 2021.
- Prococo (n.d.) R-Guard® FastFlash® product data sheet. Available at: https://prosoco.com/Content/Documents/Product/RG_FastFlash_PDS_011121_C.pdf
- Skylar Swinford (2012). "New Videos Highlight Liquid Applied Window Flashing and Air Barrier System Used at Karuna Passive House. Hammer & Hand Construction | Woodcraft. June 16, 2012. (<u>https://hammerandhand.com/field-notes/new-videos-highlight-liquid-applied-window-flashing-and-air-barrier-system-used-at-karuna-passive-house/</u>) Accessed September 2021.

ACHIEVING CONSTRUCTION QUALITY USING AN INTEGRATED WORKMANSHIP BENCHMARKING FRAMEWORK

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Abstract

Several studies have been conducted on construction quality and workmanship performance of building and construction projects. Consequently, a lack of experience and competency, language barriers and a lack of communication, unsuitable construction equipment, poor weather, limited time and limited costs, among others, have been identified to be amongst notable factors contributing to poor workmanship. Unfortunately, assessment factors required for workmanship performance appraisal at both project and organizational levels are yet to be identified. As such, this study is aimed at using an integrated benchmarking framework to assess and model the workmanship performance of building projects to ensure construction quality. The study undertakes a comprehensive questionnaire survey and expert assessment of selected projects and organizations for workmanship performance modelling. The study outcomes showed the framework was effective in assessing workmanship at both organizational and project levels. Besides, the framework could also serve as a versatile tool for the building and construction industry towards developing a universal workmanship performance standard for project evaluation, assessment, and tendering.

Keywords: Workmanship, Performance, Framework, Construction, Projects, Appraisal, and Benchmarking

Introduction

The most significant and re-occurring factor responsible for the substandard performance of construction projects is the lack of a comprehensive performance framework for Workmanship Performance Assessment (WPA) at all stages of the project. Therefore, there is an urgent need to develop a system to determine current workmanship performance, resolve problems, and benchmark them against best practices to fulfill the stakeholders' expectations. Furthermore, the lack of a workmanship management tool presents a significant issue facing the construction industry in most Caribbean countries, resulting in a building collapse as experienced in Trinidad and Tobago. Unfortunately, the construction industry within the Caribbean and other developing nations have no specific workmanship quality management system.

The Problem of Poor Workmanship and Building Failure in Developing Countries

Building failure associated with poor workmanship is a significant concern in the construction industry (Agwu 2014). The author further states that building collapse has become a frequent phenomenon for residential and commercial buildings, with many crumbling while being occupied, resulting in loss of properties and death. For example, in Nigeria, loss of lives was recorded due to building collapse resulting from poor workmanship and inferior materials (Opara 2006 and Agwu 2014). In other parts of the world, building failure has become a critical issue affecting construction quality. For instance, an eight-story factory building in Dhaka, Bangladesh, collapsed and killed over a thousand people in 2013 due to poor construction supervision, workmanship, and systemic corruption in the building industry (Agwu 2014). Similar findings were reported by Folagbade (2001) and Chinwokwu (2000) that many cases of poor construction workmanship-related building failures occurred between 1980 and 1999. Furthermore, Makinde (2007) also identified fifty-four cases of building failures occurring between 2000 and 2007. These cases occurred across varying building categories: 39.7% of poor construction workmanship-related buildings, 14.3% with commercial buildings, 12.7% for assembling buildings (Churches and Mosques), and 8%, 6.3%, and 4.7% for institutional, mercantile, and mixed occupancy buildings, respectively (Windapo and Rotimi 2012). Agwu (2014) further discovered that 50% of poor construction workmanship-related building failures were attributed to design defects,

40% to construction defects, and 10% to material failure. According to Chinwokwu (2000) and Windapo (2006), approximately 37% of the building failures were connected to carelessness and greed by construction professionals, while 22% were attributed to design defects.

Governments and policymakers have done little to address building failures and collapse in developing countries. Baiden and Tuuli (2004) stated that defects and variation in construction projects remain a problem of concern in the construction industry in Ghana. Kazaz and Birgonul (2005) indicated that quality satisfaction in construction projects in Turkey was not achieved consistently. These deficiencies were attributed to defects, mainly human factors, in most construction projects, including forgiveness and carelessness (63%), lack of knowledge (29%), and intentional (8%) (Chong and Low 2005). In a survey conducted on twenty-seven building projects by Atkinson (1999), inferior quality was attributed to lack of skill, inadequate knowledge, carelessness, difficulty in construction, and ambiguous project information. These causes reflected the existence of substandard quality of workmanship in the construction industry. Similarly, Nima et al. (2002) and Atkinson (1999) showed that the construction industry faced problems attributed to lack of skill, inadequate knowledge, building defects, rising cost, and time delays. These workmanship problems can affect the quality performance of construction projects if not addressed.

The evidence of poor workmanship in building construction includes incorrect proportioning, drying cracks, workmanship defects, decreasing bond strength, and poor material handling. According to Josephson and Hammarlund (1999) and Sookoo, Iwaro, Mwasha (2017), 32% of defects originated from client and design, 45% from management, and 20% from materials and machines. In addition, the authors stated that 58% of workmanship defects originated from faulty design, 35% from operational and installation, 12% from poor materials and systems, and 11% from unexpected user requirements. Furthermore, Atkinson (2002) claimed that managerial errors accounted for 82% of all building defects, while the Building Research Establishment indicated that 90% of building failures occurred due to workmanship defects, design, and construction stages (Thamilarasu, Rajprasad, and Ram Prasanna Pavan 2017).

Defects occur because of poor workmanship arising from a lack of knowledge, information, and quality workmanship. Most defects in the building occur due to human factors and errors. Moreover, Ali and Wen (2011) and Sookoo, Iwaro, Mwasha (2017) concluded in their studies that construction projects suffered from poor workmanship, resulting in frequent building failure and collapse. Therefore, there is a need to investigate the existing workmanship management techniques in Trinidad, the Caribbean region, and other developing nations.

Workmanship Performance Assessment Technique and Models

The construction quality must be assessed and evaluated to ensure quality in the constructed buildings and housing provided for the public. Despite the rapid development in housing construction and government quality control efforts, as stated above, the existence of widespread defects in the provided housing is a considerable public concern. According to Ani et al. (2014), the quality of provided housing in most developing countries today is far below standard as most of the defects are related to architecture workmanship problems. These defects were noted to be strongly associated with poor workmanship quality (Chong and Low 2005). Therefore, to ensure economic development, workmanship quality should be assessed and enhanced to reduce building defects. These include monitoring contractors and consultants to prevent the generation of low-quality buildings. Several models and procedures have been suggested for evaluating project performance on-site and at the project level (Aziz and Hafez 2013). Some of these models aimed at predicting project performance, while others aimed at measuring. However, these traditional models offered and adopted a limited set of measures for performance assessment. Most of these models limit their analyzes to measure factors, such as cost, schedule, labor, and productivity. The fundamental shortcomings of these traditional workmanship control systems are inappropriate for measuring current performance elements.

Moreover, several important quality management systems and programmes have been developed since the 1980s for quality management, such as ISO 9000, Total Quality Management (TQM), Six Sigma, re-engineering, and lean programmes (Metri 2005). Most of these quality systems have been adopted by various industries around the world. Employees must be familiar with the quality systems adopted and know how to implement the related

practices. To help the construction firms in undertaking this task, this study described the meaning of quality, the evolution of quality management, quality management practices, concepts, and develop a flexible integrated quality system for workmanship management. Among the quality management systems, TQM and Six Sigma were recognized as the most widely adopted. In some cases, firms implemented both quality management systems simultaneously. To implement these two-quality management programmes effectively, it is necessary to integrate TQM with Six Sigma, even with other quality practices such as safe practice. Safety is considered a crucial component of quality management in a construction project (Yang 2004 and Metri 2005). According to Yang (2004), based on the integrated TQM and Six Sigma model with other quality practices, a holistic workmanship management model can be developed. The conceptual framework that combined the principles and capabilities of TQM, Six Sigma, and Safety Management System (SMS) frameworks was developed in this study (Figure 1.1). The concept, if well implemented, can undertake a comprehensive workmanship assessment of both construction organization and project.



Figure 1.1: Conceptual Integrated WPA Framework

Methodology

This section demonstrates the application of the integrated benchmarking framework to assess the Iere Concepts Limited workmanship performance. To achieve this objective, the study developed questionnaires that were administered to professionals in the field not affiliated with the Iere Concepts Limited organization. The study selected a group of experienced professionals to undertake this assessment at Iere facilities using the questionnaires developed for these purposes. These professionals were selected based on their experience, workmanship knowledge, and willingness to participate in the study. The professionals used include contractors, engineers, environmentalists, project managers, quality surveyors, supervisors, consultants and safety experts.

1. Organization Workmanship Performance Assessment

This section of the data collection involved using record analysis and survey methods to evaluate organizational workmanship performance. Fifteen professionals from different backgrounds, with over five years of experience, were selected from various companies to assess Iere Concepts Limited organizational workmanship performance utilizing the organizational workmanship performance questionnaire. Each professional is required to visit the company for 3 to 5 days to evaluate the organization's workmanship performance. Thereafter, professionals were required to complete the application questionnaires after appraising the organization's performance, base on the established set of performance criteria. The professionals were given sufficient time to review each document

provided by the organization for review. The assessment was completed after approximately five days. Subsequently, the questionnaires were submitted to the document control coordinator in the company to be reviewed. The documents assessed by the professional include project execution documents, safety records, customer feedback, certification status, progress/project reports, tender documents, quality records, management structure, and standard compliance.

2. Project Workmanship Performance Assessment

The professionals that completed the organizational workmanship performance questionnaires were also selected to complete the project workmanship assessment. The professionals were requested to visit three project construction sites in various completion stages: Digicel civil work project, Servus roof repair project, and Port Authority pile installation project. The three projects were construction tendered projects. The Servus construction project was completed in December 2020. However, the Digicel and the Port Authority construction projects are ongoing. Similar to the organizational assessment, fifteen professionals from different backgrounds, with over five years of experience, were selected from various companies to assess Iere Concepts Limited project workmanship performance, utilizing the application questionnaire developed for project workmanship performance assessment. The professionals were given sufficient time to appraise each project and documents. Subsequently, the questionnaires were submitted to the document control coordinator. The documents assessed by the professionals include tender documents, design/drawings, bill of quantities, project specifications, progress reports, pictures of projects (before, after, and during) and customer feedback. In terms of workmanship performance assessment, the professional assessed the three projects visited and the overall company project workmanship performance using the main and sub-criteria provided in the application questionnaires. The criteria were developed to measure project workmanship performance in terms of quality performance, defect performance, variation performance, and standard compliance performance.

Iere Concepts Limited Workmanship Performance Modeling

This section of the study applied the integrated benchmarking framework to assess and model the workmanship performance of Iere Concepts Limited concerning their project execution and organizational management. The workmanship performance assessment covered all relevant aspects of the firm, including project, organization, management, quality, defect, and safety. Table 1.1 presented the major workmanship performance criteria used for the assessment along with the assigned weights.

Notation	WPA Factors	Weight
RM	Risk Management	0.270
OC	Operational Control	0.280
ТМС	Top Management Commitment	0.290
СР	Competency Profile	0.320
SC	Safety Climate	0.200
РМ	Project Management	0.280
PN	Project Nature	1.100
EI	Economic Investment	0.600
CS	Customer Satisfaction	0.460
PM	Performance Measurement System	0.340
РР	Process Planning	0.300
ICS	Information and Communication	0.260
ES	Environment and Society Impact	0.240
SCM	Supply Chain Management	0.220
SQM	Strategic Quality Management	0.220

Tabla 1.1	Main Organizational	WPA	Factor V	Woight
Table 1.1	Main Organizational	VV F A	ractor	weight

Iere Project Workmanship Performance Modeling

In undertaking the workmanship performance assessment of Iere Concepts Limited, some important sub-criteria factors were assessed under each of the main criteria factors to enable the project workmanship performance modeling. These sub-factors performances and their weights aided the modeling of the main factors, which determine the project workmanship performance. Therefore, Table 1.2 presents the project workmanship performance modeled for each main assessment factor based on the sub-criteria factors' performance scores and the weights. According to Table 1.2, modeled project workmanship performance values, the results showed that Iere Concepts Limited recorded better project workmanship performance in over 90% of the sub-criteria factors assessed. Notably were sub-factors under Risk Management (RM), Top Management Commitment (TMC), Competency Profile (CP), and Safety Climate (SC). Others include Project Nature (PN), Economic Investment (EI), Customer Satisfaction (CS), Project Management (PM), Process Planning (PP) and Information Communication System (ICS). Among the factors that were assessed, the sub-factors under PN, EI, and CS recorded better workmanship performance when compared with other sub-factors (Table 1.3 and Figure 1.2). This means that project nature, top management commitment, customer satisfaction and competence profile are major determinants of project workmanship performance.

Main Factors	Sub-factors	Performance Score	Weight	WPI
RM	1.1	56	0.019	7.182
	1.2	52	0.020	7.020
	1.3	60	0.018	7.290
OC	2.1	44	0.018	5.544
	2.2	34	0.019	4.522
	2.3	42	0.018	5.292
	2.4	45	0.019	5.985
	2.5	54	0.018	6.804
ТМС	3.1	47	0.019	6.474
	3.2	51	0.016	5.916
	3.3	60	0.019	8.265
	3.4	54	0.019	7.439
	3.5	60	0.019	8.265
СР	4.1	59	0.018	8.496
	4.2	51	0.018	7.344
	4.3	56	0.017	7.616
	4.4	50	0.017	6.800
	4.5	61	0.018	8.784
SC	5.1	60	0.020	6.000
	5.2	63	0.020	6.300
	5.3	47	0.020	4.700
	5.4	52	0.018	4.680
	5.5	45	0.019	4.275
PM	6.1	49	0.019	6.517
	6.2	40	0.019	5.320
	6.3	48	0.019	6.384
	6.4	51	0.019	6.783
	6.5	52	0.019	6.916
PN	7.1	35	0.015	14.438

 Table 1.2
 Project Sub-factors Workmanship Performance

	7.2	63	0.018	31.185
	7.3	45	0.017	21.038
EI	8.1	33	0.013	6.435
	8.2	48	0.017	12.240
CS	9.1	58	0.021	14.007
	9.2	54	0.019	11.799
	9.3	42	0.019	9.177
	9.4	54	0.020	12.420
PM	10.1	49	0.018	7.497
	10.2	46	0.016	6.256
	10.3	57	0.019	9.206
PP	11.1	63	0.018	8.505
	11.2	50	0.018	6.750
ICS	12.1	55	0.017	6.078
	12.2	46	0.019	5.681
	12.3	61	0.018	7.137
	12.4	45	0.018	5.265
ES	13.1	69	0.019	7.866
	13.2	40	0.017	4.080
SCM	14.1	51	0.017	4.769
	14.2	36	0.020	3.960
	14.3	53	0.014	4.081
	14.4	59	0.016	5.192
SQM	15.1	47	0.018	4.653
	15.2	57	0.019	5.957
	15.3	57	0.019	5.957

Table 1.3 Project Main Factors Workmanship Performance Summary

Main Factor	Notation	Weight	Project Workmanship Performance
Risk Management	RM	0.270	21.490
Operational Control	OC	0.280	28.150
Top Management Commitment	ТМС	0.290	36.360
Competency Profile	СР	0.320	39.040
Safety Climate	SC	0.200	30.000
Project Management	PM	0.280	32.000
Project Nature	PN	1.100	66.660
Economic Investment	EI	0.600	18.680
Customer Satisfaction	CS	0.460	47.400
Performance Measurement System	PM	0.340	22.960
Process Planning	РР	0.300	15.250
Information and Communication	ICS	0.260	24.160
Environment and Society Impact	ES	0.240	11.950
Supply Chain Management	SCM	0.220	18.000
Strategic Quality Management	SQM	0.220	16.560



Figure 1.2 Summary of Iere Project Workmanship Performance

In addition, it suggests important factors to be assessed for poor project workmanship performance as issues associated with top management commitment, such as cost spent on safety, allocation of human resources, allocation of time for project activities, and safety policy development. Other important project-related issues to be addressed for poor workmanship performance include customer satisfaction and competency profile. Major sub-factors assessed under competency profile main factor include personal quality of safety manager, personal competency of the safety manager, training and education of project manager, safety behavior and safety leadership of the project manager. The high project workmanship performance values recorded could be attributed to the impact of the organizational certification efforts, such as the ISO standard.

Iere Concepts Limited Organizational Workmanship Performance

In the case of organizational workmanship performance, the Iere Concepts Limited workmanship performance assessed in Figure 1.3 suggested that the organization recorded better workmanship performance results under top management commitment, safety leadership, safety training, process planning, training and education and supply chain management. Other factors with Iere Concepts Limited considerable workmanship performance include quality culture, employee empowerment, information, and communication. This suggests critical areas to appraise in addressing the problem of poor workmanship in the construction organization.


Figure 1.3 Iere Concepts Limited Organizational Workmanship Performance

In addition, Table 1.4 provided a more in-depth analysis of the workmanship performance accrued from subfactors assessed for the Iere Concepts Limited organizational workmanship performance. The results, depicted in Table 1.4, revealed important workmanship sub-issues that could be assessed in providing a solution for poor workmanship. Leading among them were the sub-factors under TMC, Safety Leadership (SL), Training and Education (ETE), Supply Chain Management (SCM), Process planning and Safety Training. Also included in this category were Quality Culture and Information and Communication sub-factors.

Main Factors	Sub-factors	Performance Score	Weight	WPI
	1.1	44	0.018	10.49
	1.2	45	0.021	12.52
	1.3	51	0.019	12.84
	1.4	57	0.013	9.82
	1.5	54	0.016	11.45
SL	2.1	42	0.019	8.18
	2.2	34	0.018	6.27
	2.3	45	0.019	8.76
	2.4	47	0.014	6.74
	2.5	46	0.016	7.54
РР	3.1	61	0.016	7.08
	3.2	60	0.019	8.27
SQM	4.1	47	0.018	4.65
	4.2	45	0.02	4.95

 Table 1.4 Organizational Sub-factors Workmanship Performance

	4.3	49	0.019	5.12
ЕТЕ	5.1	40	0.016	3.36
	5.2	34	0.02	3.57
	5.3	54	0.019	5.39
	5.4	54	0.019	5.39
	5.5	54	0.014	3.97
	5.6	54	0.01	2.84
SCM	6.1	46	0.017	4.11
	6.2	51	0.021	5.62
	6.3	51	0.013	3.48
	6.4	36	0.014	2.65
CS	7.1	59	0.02	8.85
	7.2	51	0.019	7.27
	7.3	46	0.02	6.90
	7.4	40	0.02	6.00
IC	8.1	50	0.018	6.30
	8.2	63	0.018	7.94
	8.3	40	0.02	5.60
	8.4	54	0.018	6.80
	8.5	46	0.018	5.80
PMS	9.1	65	0.02	11.70
	9.2	55	0.015	7.43
	9.3	48	0.02	8.64
CI	10.1	40	0.018	6.12
	10.2	53	0.018	8.11
	10.3	51	0.017	7.37
QC	11.1	40	0.017	5.61
	11.2	40	0.019	6.27
	11.3	42	0.019	6.58
ST	12.1	40	0.02	6.00
	12.2	48	0.018	6.48
	12.3	61	0.017	7.78
EE	13.1	61	0.016	7.08
	13.2	46	0.016	5.34
	13.3	63	0.02	9.14
	13.4	52	0.019	7.16
	13.5	55	0.017	6.78
PMS	14.1	63	0.02	7.88
	14.2	55	0.02	6.88
	14.3	51	0.016	5.10
	14.4	46	0.018	5.18
	14.5	42	0.021	5.51

Overall Iere workmanship Performance

The overall Iere Concepts Limited workmanship performance was modelled using the integrated workmanship performance index. The index combined project workmanship performance index with organizational workmanship performance index. The project workmanship performance of Iere Concepts Limited was modelled to be 428.660 as shown in Table 1.5 while that of the organization workmanship was found to be 380.23.

The workmanships performance index is:

$$WPI_{ij} = \frac{PW \times RSF_{ij} \times RMF_j}{4} \times 100$$

Where $WPI_{ij} = Workmanship$ Performance Index of ith sub-factor under jth main factor

PW = Weighted score of different workmanship performance

Project Workmanship Performance		Organizational Wo	Organizational Workmanship Performance	
Main Factor	WP	Main Factor	WP	
RM	21.490	TMC	57.12	
OC	28.150	SL	37.50	
TMC	36.360	PP	15.34	
СР	39.040	SQM	14.32	
SC	30.000	ETE	24.51	
PM	32.000	SCM	15.86	
PN	66.660	CS	29.02	
EI	18.680	IC	32.44	
CS	47.400	PMS	27.77	
PM	22.960	CI	21.60	
PP	15.250	QC	18.46	
ICS	24.160	ST	20.26	
ES	11.950	EE	35.49	
SCM	18.000	PMS	30.54	
SQM	16.560	-		
	428.660		380.23	
Iere Workmanship Performance			808.89	

 Table 1.5
 Overall Iere workmanship Performance

Discussion of findings

The results showed that Iere Concepts Limited recorded better project workmanship performance in over 90% of the sub-criteria factors assessed. Notably were sub-factors under Risk Management (RM), Top Management Commitment (TMC), Competency Profile (CP), and Safety Climate (SC). Others include Project Nature (PN), Economic Investment (EI), Customer Satisfaction (CS), Project Management (PM), Process Planning (PP) and Information Communication System (ICS). The findings from the study revealed important workmanship sub-issues that could be assessed in providing a solution for poor workmanship. Leading among them were the sub-factors under TMC, Safety Leadership (SL), Training and Education (ETE), Supply Chain Management (SCM), Process planning and Safety Training. Also included in this category were Quality Culture and Information and Communication sub-factors. Among the factors that were assessed for project workmanship performance, the sub-factors under PN, EI, and CS recorded better workmanship performance when compared with other sub-factors. This means that project nature, top management commitment, customer satisfaction and competence profile are major determinants of project workmanship performance. Furthermore, it means that poor workmanship in construction projects can be resolved by addressing workmanship issues associated with project nature, site selection, project size, complexity, subcontractors, foundation, design, tender, procurement, environment, material quality, material selection, material handling, labour, construction, defect, and cost overall.

The findings from the Iere Concepts Limited workmanship performance assessed using integrated workmanship performance index suggest that the organization recorded better workmanship performance results under top management commitment, safety leadership, safety training, process planning, training and education and supply chain management. Other factors with Iere Concepts Limited considerable workmanship performance include quality culture, employee empowerment, information, and communication.

Finally, the findings revealed the comprehensiveness and effectiveness of the integrated workmanship performance index in modelling the workmanship performance of construction projects and organizations. In this study, the project workmanship performance of Iere Concepts Limited was modelled to be 428.660, while that of the organization workmanship was found to be 380.23. it means that knowing the workmanship performance status of an organization and project will help to ensure compliance to standard, quality, durability, elimination of defect and building collapse.

Conclusion

This study provides a comprehensive analysis approach to construction company workmanship performance at both organization and project levels. This approach combined the methodological framework from TQM, SMS, and Six Sigma techniques. Therefore, the established benchmarking system could be applied at the tendering stage for project evaluation and award. Additionally, it could assist contractors in making informed decisions on construction workmanship performance. Potential defects and safety hazards could be identified at an early stage of the construction projects to ensure necessary measures were implemented to minimize financial loss and failure. Moreover, the framework application has shown that the integrated benchmarking framework developed in this study and applied to the Iere Concepts Limited workmanship performance assessment can effectively and comprehensively undertake the workmanship performance assessment of construction projects and organizations in the construction industry. However, it is important to validate and verify the outcomes from the framework and ensure effectiveness. The implications of this study include the findings that can be projected into developing a universal workmanship standard and guide for the Caribbean and developing countries. Besides, it provides tremendous opportunities for the construction industry and managers to measure project and organization level of compliance to the standard, level of defective workmanship, and it can significantly aid elimination or detection of building collapse.

Reference

Agwu, Mba Okechukwu. 2014. "Perception Survey of Poor Construction Supervision and Building Failures in Six Major Cities in Nigeria." *British Journal of Education, Society & Behavioural Science* 4(4): 456-472.

Ali, Azlan Shah, and Kam Hui Wen. 2011. "Building Defects: Possible Solution for Poor Construction Workmanship." *Journal of Building Performance* 2(1): 59-69.

Ani, A., Norngainy Mohd Tawil, Suhana Johar, Mohd Razak, and Hasnah Yahaya. 2014. "Building Condition Assessment for New Houses: A Case Study in Terrace Houses." *Jurnal Teknologi* 70(1): 43-50.

Atkinson, Andrew. 1999. "The Role of Human Error in Construction Defects." Structural Survey 17(4): 231-236.

Atkinson, Andrew. 2002. "The Pathology of Building Defects: A Human Error Approach." *Engineering, Construction and Architectural Management* 9(1): 53-61.

Aziz, Remon, and Sherif Hafez. 2013. "Applying Lean Thinking in Construction and Performance Improvement." *Alexandria Engineering Journal* 52(4): 679-695.

Baiden, B. K., and Martin Morgan Tuuli. 2004. "Impart of Quality Control Practices in Sandcrete Blocks." *Journal of Architectural Engineering* 10(2): 53-60

Chinwokwu, G. 2000. The Role of Professionals in Averting Collapse. In: Proceedings of a 2 Day Seminar of the Nigerian Institute of Building-on-Building Collapse, Causes, Preventing and Remedies, 3-4 May, 2000, 12-28. Ikeja, Lagos.

Chong, Wai-Kiong, and Sui-Pheng Low. 2005. "Assessment of Defects at Construction and Occupancy Stages." *Journal of Performance of Constructed Facilities* 19(4): 283-289.

Folagbade, S. O. 2001. Case Studies of Building in Nigeria. Proceedings of a Workshop on Building Collapse Causes, Prevention and Remedies. The Nigerian Institute of Building, Ondo State Chapter, 23-24 October, 2001.

Kazaz, Aynur. and M. 2015. Birgonul. "Determination of Quality Level in Mass Housing Projects in Turkey." *Journal of Construction Engineering and Management* 131(2): 195-202.

Josephson P., and Y. Hammarlund. 1999. "The Causes and Costs of Defects in Construction: A Study of Seven Building Projects." *Automation in Construction* 8(6): 681-687

Makinde, F. A. 2007. Minimizing the Collapse of Building in Nigeria. Seminar Paper, Faculty of Environmental Studies, Osun State College of Technology. Esa-Oke; 20-21 August.

Metri, Bhimaraya. 2005. "TQM Critical Success Factors for Construction Firms." Journal of Contemporary Management Issues 10(2): 61-72.

Nima, Mekdam, Mohd Abdul-Kadir, Mohd Jaafar, and Riadh Alghulami. 2002. "Constructability Concepts in West Port Highway in Malaysia." *Journal of Construction Engineering and Management* 128(4): 384-356.

Sookoo, Rakesh, Joseph Iwaro, and Abraham Mwasha. 2017. "The Impacts of TQM Practices on Construction Workmanship in Developing World: A Case Study of Trinidad and Tobago." Master's thesis. The University of the West Indies, St. Augustine, Trinidad and Tobago

Thamilarasu, V., J. Rajprasad, and T. Ram Prasanna Pavan. 2017. "A Case Study on Requirements of Quality Workmanship in Construction Projects." *International Journal of Civil Engineering and Technology* 8(4): 1061-1067.

Yang, Ching-Chow. 2004. "An Integrated Model of TQM and GE-Six-Sigma." *International Journal of Six Sigma and Competitive Advantage* 1(1): 97-111.

Windapo, Abimbola. 2006. "The Threat of Building Collapse on Sustainable Development in the Built Environment in Nigeria." In: *Proceedings of National Conference on Sustainable Development and the Built Environment*, 9-12 August, 2006, 59-67. Nigerian Institute of Bulding.

Windapo, Abimbola, and James Rotimi. 2012. "Contemporary Issues in Building Collapse and its Implications for Sustainable Development." *Buildings* 2(4): 283-299.

Opara P. 2006. "Building Collapse in Lagos State: Causes and Recommendations." *Journal of Technology and Education in Nigeria* 11(1): 58-65.

Review of Structural Load Resisting Systems for Cross-Laminated Timber Multi-story Residential Buildings

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ABSTRACT

Sustainable construction has been the main motive in positioning wooden-based building systems as a favorable construction choice. Various engineered wood systems are now being employed in low-rise, mid-rise, and high-rise building construction. Extensive research findings in the last decade have helped establish viability of engineered wood products for multi-story building application in general, and crosslaminated timber (CLT) in particular, for mid-rise buildings. Also known as mass timber, CLT has been gaining wider acceptance as an alternative to conventional masonry and concrete construction. In particular, there is growing interest in constructing taller than 10- to 15- story residential and non-residential buildings using CLT systems. However, while greater focus of recent research has been on establishing viability of CLT systems for mid-rise construction in general, there is still not enough understanding of various gravity and lateral load resisting systems appropriate for such residential, commercial, or mixed-use buildings. This paper presents a review of the research conducted on CLT systems in several aspects such as connections, using damper or dissipating energy devices in these structures, CLT rocking systems, and Timber-Based Hybrid Structural Systems. The paper also presents some case studies on low-rise and mid-rise residential and non-residential buildings to illustrate different systems used in practice. Furthermore, the paper reviews some of the available experimental test studies, including shaking table tests. Since for practical application of CLT systems performing experimental tests would be cost prohibitive, numerical modeling and analysis is the preferred approach to predict the behavior of the designed building. Accordingly, the paper also illustrates an example of such numerical simulation for a CLT building using ABAQUS and OpenSEES software packages.

Keywords: cross-laminated timber (CLT), Seismic performance, Finite-Element numerical modeling, Timber-Based Hybrid Structural Systems, OpenSEES

INTRODUCTION

Concrete and steel have been the most important building materials for over a century. The favorable properties of these materials have made them continue to be used in the construction of high-rise buildings. Until recently, there was no specific reason to challenge concrete and steel in the construction industry. However, today because of

global climate change, researchers are trying to reduce emission of greenhouse gases, and one way is to use more sustainable construction materials. On the other hand, due to population growth and urbanization, the use of alternative materials like framing lumber, has attracted the attention of researchers and builders (Bhat 2013).

Mass timber products such as cross-laminated timber (CLT) is a relatively new building material with its unique construction system, which is becoming popular in medium rise buildings all around the world especially in North America today. CLT is conventional mass timber panels that are glued in several layers that it characteristics are different from light wooden frames (Benedetti et al. 2019). Although mass timber products have less variety in mechanical properties compared to conventional wood products, they are produced in larger dimensions, have higher strength and rigidity and have better performance in terms of fire resistance (Bhat 2013). Compared with precast concrete panels, CLT systems have several advantages, including lighter weight, good heat resistance, and good sound insulation (Karacabeyli and Douglas 2013). In fact, the reason for the rapid growth of the use of CLT is due to increased speed of erection. drv manufacturing process in comparison with concrete, and reduction in carbon dioxide emissions (Follesa et al. 2013). Also, CLT construction system is a suitable solution as a complementary system for conventional wood systems and can even replace concrete, masonry, and steel in some cases in the construction of residential and non-residential structures (Bhat 2013). This new product was introduced in the early nineties in Germany and Austria, and in Europe, it was used in the construction of residential and non-residential structures. In the early 2000s, the widespread use of CLT system was due to its better efficiency as well as its alignment with the green building movement. (Karacabeyli and Douglas 2013). This paper aims to review the recent research studies on application of CLT system in buildings in general and tall buildings in particular, considering experimental studies and numerical modeling/analyses.

CONNECTIONS IN CLT SYSTEMS

The mechanical behavior of CLT systems under lateral loads depends mainly on the performance of the connections between the CLT panels to each other and to the foundation (D'Arenzo et al. 2021). Mechanical connections in CLT systems are usually divided into two categories, one using metal plates/brackets, and the other using finger joint, slot and insert, or stepped edge joints. The first category is to prevent rocking and sliding of walls (Izzi et al. 2018), which is done by three-dimensional nailing plates, e.g., hold-down and angle brackets, as shown in Figure 1. Both of these connector types use small diameter threaded nail or screw fasteners, are conventionally used for lightframe systems (Polastri et al. 2017). This has led to interest in improvement of the behavior of angel brackets and hold-downs. For example, some experiments under monotonic and cyclic loading were conducted to evaluate the performance of angle brackets and hold-downs in shear and uplift directions (Gavric et al. 2015). To study the impact of uplift displacement on the shear behavior of angle bracket joints, Liu and Lam conducted an experimental test such that joints were under monotonic and cyclic shear loadings (Liu and Lam 2018). A coupled uplift-shear numerical approach for the angle bracket joints was introduced by Pozza et al. (2018). They validated their numerical model with available experimental tests. Other studies (Ottenhaus et al. 2018; Tamagnone et al. 2018) have proposed simplified models to evaluate the performance of angle brackets and hold-downs to deal with in-plane lateral forces. This will allow the design of the CLT system to take into account the effect of angle brackets and hold-downs that work solely in shear and uplift. In another study (Brown et al. 2021), in order to evaluate the structural performance of commercial angle brackets, 29 joints were tested. The result of this study showed that the shear strength and stiffness of the castellated connections were 2.5 and 7 times bigger than the specimens using the commercial angle brackets.



Figure. 1. (a) Hold-down (b) angle bracket (Follesa et al. 2013)

The second category of joints are those used to prevent the relative sliding between contiguous walls or between a floor panel and the underlying wall, which are typically put together using self-tapping screws (Izzi et al. 2018). As shown in Figure 2, these joints include use of wooden profile or shear key/stepped edge configurations.



Figure. 2 Three different step joists (Follesa et al. 2013)

To understand the behavior of the joints some experimental tests have been performed by researchers. For instance, some researchers (Flatscher et al. 2015; Gavric et al. 2015) performed comprehensive experimental tests as part of the SOFIE and SERIES Projects, were respectively. The test results indicate the ductile behavior of the joints for shear resistance. However, this has not been observed in angle brackets, which can be due to either withdrawal of the nails from the floor panels or pull-through of the anchoring bolts, while these connectors have appropriate mechanical properties when loaded in lateral and axial loads. In contrast, the hold-downs showed to have high strength under tension, and the buckling of the metal flanges caused an inappropriate mechanical behavior under lateral loads. Moreover, some researchers (Fitzgerald et al. 2021; Hashemi et al. 2017) experimentally investigated employing Slip-friction connections (SFCs) to CLT rocking walls, which originally have been used in steel structures as dampers, to understand the damping and stiffness of this system. The results showed that although there was some damage in SFCs, the performance didn't change. In a research study, a rubber hold-down was proposed to create an energydissipating element, which was tested under quasi-static monotonic and cyclic loading (Asgari et al. 2021). Also, another study proposed increasing row spacing and end distance in the dowel layout to improve hold-down performance, a key element in CLT walls, and tested 47 hold-down joints monotonic and cyclic loading (Brown and Li 2021). Connections in timber construction, consisting of those built with CLT, play a significant role in providing stiffness, stability, ductility, and strength to the building. As a result, they require careful attention by designers.

DAMPERS IN CLT SYSTEMS

Aside from connection systems that function in assembly of a CLT building and providing resistance to sliding and uplift effects, more complex connection systems are emerging for CLT systems for performance under wind and earthquake loading conditions. For example, the use of dampers in CLT systems is becoming of interest, which can be due to two main reasons: improving the serviceability of the structure and improving seismic performance. In most design methods, deflection and vibration are important parameters, but the current design codes do not include criteria for CLT systems. Some researchers dynamically analyzed a seven-story CLT structure under seven earthquake records and obtained the optimum damping and stiffness values using optimization algorithms (Poh'sie et al. 2016). They concluded that the use of TMD could reduce the structural response of a CLT building by up to 40%. Hashemi et al. A new technology called resilient slip friction joint (RSFJ), which provides recentering and energy dissipation in a single passive system was employed by Hashemi et al. (2017). The numerical study on a five-story CLT building has shown that this passive control is able to remove residual deformations at connections. In another study, a friction damper in a CLT rocking wall system was studied (Hashemi and Quenneville 2020). Their experimental results revealed that this system can be used in earthquakeresistant low- to mid-rise CLT buildings. Thus, using dampers in CLT system have some advantages such as decreasing the seismic response of the structure and improving the serviceability of the structure.

TIMBER-BASED HYBRID STRUCTURAL SYSTEMS

Previous findings show that despite the advantages of mass timber systems, the use of such material/system for construction of high-rise buildings in a high seismic zone is not appropriate, mainly because of the low ductility associated with such systems. However, this weakness can be largely overcome by combining wood with a ductile material such as steel, leading to increasing the post-yield behavior of wooden structures. In fact, the advantage of hybrid structures is to use the benefits of each material to eliminate the weakness of the other material. Thus, this wood-steel hybrid system can also be used as a structural system in tall building construction. In recent years, some studies have been carried out on hybrid timber structures, one of which is called Finding the Forest Through the Trees (FFTT) system (Green and Karsh 2012), which includes steel beams and wooden columns (Bhat 2013). To increase the ductility in this hybrid system, steel elements were interconnected to resist gravity and lateral loads. This system has several advantages, including light weight, environmentallyfriendly, and high energy dissipation. For seismic resistance of buildings with up to 30 stories., four different options have been suggested (Hashemi and Quenneville 2020). Another study (Bhat 2013) evaluated the behavior of the FFTT system in more detail, which eventually led to suggestions for improving the performance of this hybrid

system. These recommendations were later confirmed by experimental tests. To improve structural performance, researchers have combined the CLT system with another structural system. For example, a recent study by Tesfamariam et al. (2019) suggested a new CLT-reinforced concrete (RC) hybrid system, which indicates a high capability against seismic lateral loads. That could increase the energy dissipation capacity of the hybrid system using metal dampers as connectors between the RC beam and CLT. Moreover, a type of hybrid CLT wall that includes laminated veneer timber as cross-layers was recently introduced (Wang ZQ, Luo D 2021), and the test results showed that the plastic damage of steel fasteners was the primary failure mode. They concluded that compared with conventional CLT shear walls, the hybrid CLT shear walls have greater lateral stiffness but less ultimate load strength. Some researchers (Khajehpour et al. 2021) suggested a dual structural system, which is a combination of steel moment frames with CLT shear walls, offering a strategy for economic and sustainable lateral load resisting system for mid-to high-rise structures. In summary, above research findings confirm that timber-based hybrid structural systems have some structural advantages such as increasing the energy dissipation and lateral stiffness.

CASE STUDIES (LOW-RISE AND MID-RISE)

Applications of the wooden system can be in low-rise, mid-rise, or high-rise buildings. A full-scale experimental test of low-rise CLT buildings subjected to lateral loading, where they tested two buildings under cyclic loading condition, was investigated by Yasumura et al. (2016). One building included 3.5-inch-thick, large CLT wall panels $(20 \times 9 \text{ ft})$, and the other one included 3.5-inch-thick, small CLT wall panels $(3 \times 9 \text{ ft})$. Their test results revealed that the ultimate strength of these buildings is 60–80% higher than the design load, demonstrating highly favorable structural performance. A study (Alinoori et al. 2020) presented the results of a series of experimental tests on CLT walls under compression, which can be used for the design of mid-rise structures. Their result showed that in comparison with the stud plate connecting system, the stud-to-stud connections provide better performance in terms of load-carrying capacity for the specimens under compression. This means that using stud-to-stud connection with no horizontal component in the load path can be an efficient strategy to enhance the bearing strength of the walls.

EXPERIMENTAL TESTS ON CLT

Recent experimental tests have helped examine the more accurate and realistic behavior of CLT systems. A shake table test, which was focused on a one-story full-scale wood shear wall system including a post-tensioned rocking CLT panel and conventional light-frame wood shear panels was conducted by Anandan et al. (2021). Another researcher (Mugabo et al. 2021) studied the behavior of diaphragms using a shake table for a full-scale two-story CLT system. They found that CLT diaphragms designed to remain elastic according to the basic philosophy of structural mechanics are able to achieve desirable seismic performance objectives. Moreover, the origins of

overstrength in some components of the diaphragm are required to be considered for a diaphragm design. An experimental study related to the flexural and compressive behavior of a new kind of sandwich CLT panel was performed by Santos et al. (2021). To improve thermal insulation and reduce weight, the inner layer is made of polyurethane rigid foam instead of timber. These studies show have helped to illustrate the role of full-scale shaking table tests to provide a better understanding of the role of diaphragms in the overall behavior of the CLT system.

NUMERICAL MODELS

Since an experimental study, especially full-scale testing, is usually cost prohibitive, the alternative is to study the structures numerically, even after doing some experimental tests. Software packages used for this purpose include OpenSees and ABAQUS software. For example, Figure 3 demonstrates the numerical model of a FFTT systems in OpenSEES. Since steel beams that connect the main timber components are supposed to yield before the timber members, the timber components are modeled as purely elastic, as long as the complete nonlinear behavior of the joints and the steel elements are accurately taken into account. To model timber shear walls, an elastic orthotropic material in the OpenSEES can be used. In order to take into account the stiffness modifiers for orthogonal directions, composite theory (K-Method (Fairhurst et al. 2014; Karacabeyli and Douglas 2013)) is employed. The elastic orthotropic material including orthogonal directions is assigned to TwoNodeLink element to represent the CLT walls. Another strategy for modeling a timber shear wall is to use a ShellMITC4 element (Dvorkin and Bathe 1984) including an elastic orthotropic material model to picture the elastic timber shear walls with orthotropic properties (Zhang et al. 2015).



Figure 3. Numerical model of FFTT systems adopted from (Zhang and Tannert 2018)

Nonlinear rotational springs are used at the junction of beams modeled with elastic elements to apply nonlinear behavior to the system (Bhat 2013; Zhang and Tannert 2018). This behavior is modeled using Pinching4 material. Figure 4(a) presents the behavior of the rotational springs. Moreover, in order to consider the P-delta effects on the shear walls, leaning columns with gravity loads are linked to the frame. The details of modeling of leaning columns can be found in Mirzai et al. (2018). Since joints would most likely be provided through rigid connections, they are assumed to be rigid. The hold-downs are simulated using *zeroLength* elements at both ends of the shear walls by assigning an elastic perfectly plastic material to capture the nonlinear properties of the

hold-downs. All the models are pinned in the middle of CLT shear walls. The holddown can also be modeled using the Holz–Stahl–Komposit (HSK) system, which was suggested by Bathon et al. (2014) Figure 4(b). In structures with 4 floors and higher, a connection of more than one CLT wall panel is required that increases the flexibility of the wall. To model the behavior of this connection, axial springs can be modeled so that they allow the wall to rock in plane (Popovski et al. 2010) as shown in Figure 4(c).



Figure 4. CLT walls to steel beam connection adopted from (Zhang et al. 2015) (b) Holddown (Bathon et al. 2014) (c) Connection of CLT walls (Fairhurst et al. 2014)

To simulate and evaluate behavior under loading conditions, finite element programs such as ABAOUS can be used in numerical analysis. For instance, in a study conducted at UBC (Ma 2013), a 2D model of the pin-supported CLT shear wall system equipped with low-yield steel dampers was modeled using the ABAQUS. The wall panels were simulated as 2D deformable shell elements. By entering the parameters of the orthotropic material, which include nine parameters, the correct behavioral model of a CLT material can be defined in ABAQUS. An experiment study (Gsell et al. 2007) provided an example for the second approach. They developed a fully automated procedure to get the elastic properties of full-scale CLT panels. They concluded that it was relatively accurate to assume the overall mechanical behavior of CLT panels to be orthotropic, homogeneous, and linear elastic. The pin connections at the base of the two wall panels were modeled as a pinned boundary condition. The translations of the X-, Y- and Z-directions were all constrained. The connections between the dampers and the CLT wall panels, which were assumed to be very strong and to perform linearly elastically, were modelled as tie constraints connecting the wall panels together. Figure 5 shows the numerical model of the CLT walls including the damper. The numerical and validation experimental studies thus confirmed assuming orthotropic, homogeneous, and linear elastic behavior for the material can provide enough accuracy to have an estimation of the behavior of the CLT structures.



Figure 5. Proposed shear wall system in ABAQUS Adopted from (Ma 2013)

SUMMARY AND CONCLUSION

A review of the research conducted on the behavior of CLT systems has been presented in this paper, which has gone over both experimental and numerical studies, which address the main characteristics of CLT buildings. Different types of CLT system connections, use of different dampers to reduce the structural response of CLT system, structural hybrid systems to eliminate the weaknesses of CLT system, and different numerical simulation techniques of this system on a micro and macro scale are the topics that have been discussed in this paper. The results available in the literature reveal that connections play an important role in providing stiffness, stability, ductility, and strength to the building. Moreover, to improve the seismic behavior of the CLT system dampers are beneficial. To compensate the weight disadvantage of steel and RC frames, and lack of ductility of timber frames, a hybrid system has proven to be a desirable solution. Several studies showed that using a timber-based hybrid structural system provides the opportunity to use a CLT system even in high-rise buildings. Fullscale shaking table tests have provided a better understanding of the role of diaphragms in the behavior of CLT systems under seismic loading conditions. Finally, the numerical studies validated by testing have shown the appropriateness of assuming orthotropic, homogeneous, and linear elastic behavior for the material when using finite element modeling and analysis programs such as OpenSEES and ABAQUS to reliably predict the behavior of the CLT systems.

REFERENCES

- Alinoori, F., Sharafi, P., Moshiri, F., and Samali, B. (2020). "Experimental investigation on load bearing capacity of full scaled light timber framed wall for mid-rise buildings." *Construction and Building Materials*, 231.
- Anandan, Y. K., Van De Lindt, J. W., Amini, M. O., Dao, T. N., and Aaleti, S. (2021). "Experimental Dynamic Testing of Full-Scale Light-Frame-CLT Wood Shear Wall System." *Journal of Architectural Engineering*, 27(1).
- Asgari, H., Tannert, T., Ebadi, M. M., Loss, C., and Popovski, M. (2021). "Hyperelastic hold-down solution for CLT shear walls." *Construction and Building Materials*, 289.
- Bathon, L., Bletz-Mühldorfer, O., Schmidt, J., and Diehl, F. (2014). "Fatigue design of adhesive connections using perforated steel plates." *WCTE 2014 World Conference on Timber Engineering, Proceedings*.
- Benedetti, F., Rosales, V., Opazo-Vega, A., Norambuena-Contreras, J., and Jara-Cisterna, A. (2019). "Experimental and numerical evaluation of hold-down connections on radiata pine Cross-Laminated-Timber shear walls: a case study in Chile." *European Journal of Wood and Wood Products*, 77(1), 79–92.
- Bhat, P. (2013). "Experimental Investigation of Connection for the FFTT, a Timber-Steel Hybrid System." THE UNIVERSITY OF BRITISH COLUMBIA.
- Brown, J. R., and Li, M. (2021). "Structural performance of dowelled cross-laminated timber hold-down connections with increased row spacing and end distance." *Construction and Building Materials*, 271.

- Brown, J. R., Li, M., and Sarti, F. (2021). "Structural performance of CLT shear connections with castellations and angle brackets." *Engineering Structures*, Elsevier Ltd, 240(March), 112346.
- D'Arenzo, G., Casagrande, D., Polastri, A., Fossetti, M., Fragiacomo, M., and Seim, W. (2021). "CLT Shear Walls Anchored with Shear-Tension Angle Brackets: Experimental Tests and Finite-Element Modeling." *Journal of Structural Engineering (United States)*, 147(7).
- Dvorkin, E. N., and Bathe, K.-J. (1984). "A continuum mechanics based four-node shell element for general nonlinear analysis." *Engineering Computations*, 1(1), 77–88.
- Fairhurst, M., Zhang, X., and Tannert, T. (2014). "Nonlinear dynamic analyses of novel timber-steel hybrid system." *WCTE 2014 World Conference on Timber Engineering, Proceedings*.
- Fitzgerald, D., Sinha, A., Miller, T. H., and Nairn, J. A. (2021). "Axial slip-friction connections for cross-laminated timber." *Engineering Structures*, 228.
- Flatscher, G., Bratulic, K., and Schickhofer, G. (2015). "Experimental tests on crosslaminated timber joints and walls." *Proceedings of the Institution of Civil Engineers -Structures and Buildings*, 168(11), 868–877.
- Follesa, M., Christovasilis, I. P., Vassallo, D., Fragiacomo, M., and Ceccotti, A. (2013). "Seismic design of multi-storey cross laminated timber buildings according to eurocode 8." *Ingegneria Sismica*, 30(4), 27–53.
- Gavric, I., Fragiacomo, M., and Ceccotti, A. (2015). "Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures." *Materials and Structures/Materiaux et Constructions*, 48(6), 1841–1857.
- Green, M., and Karsh, J. E. (2012). *Tall wood—THE CASE FOR Tall Wood BUILDINGS*. Vancouver, Canada.
- Gsell, D., Feltrin, G., Schubert, S., Steiger, R., and Motavalli, M. (2007). "Crosslaminated timber plates: Evaluation and verification of homogenized elastic properties." *Journal of Structural Engineering*, 133(1), 132–138.
- Hashemi, A., and Quenneville, P. (2020). "Large-scale testing of low damage rocking Cross Laminated Timber (CLT) wall panels with friction dampers." *Engineering Structures*, 206.
- Hashemi, A., Zarnani, P., Masoudnia, R., and Quenneville, P. (2017). "Seismic resistant rocking coupled walls with innovative Resilient Slip Friction (RSF) joints." *Journal of Constructional Steel Research*, 129, 215–226.
- Izzi, M., Casagrande, D., Bezzi, S., Pasca, D., Follesa, M., and Tomasi, R. (2018). "Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review." *Engineering Structures*, 170, 42–52.
- Karacabeyli, E., and Douglas, B. (2013). *CLT Handbook: cross-laminated timber*. Pointe-Claire, Québec, FPInnovations.
- Khajehpour, M., Pan, Y., and Tannert, T. (2021). "Seismic Analysis of Hybrid Steel Moment Frame CLT Shear Walls Structures." *Journal of Performance of Constructed Facilities*, 35(5).
- Liu, J., and Lam, F. (2018). "Experimental test of coupling effect on CLT angle bracket connections." *Engineering Structures*, 171, 862–873.
- Ma, S. (2013). "NUMERICAL STUDY OF PIN-SUPPORTED CROSS-

LAMINATED TIMBER (CLT) SHEAR WALL SYSTEM EQUIPPED WITH LOW-YIELD STEEL DAMPERS." THE UNIVERSITY OF BRITISH COLUMBIA.

Mirzai, N. M., Attarnejad, R., and Hu, J. W. (2018). "Enhancing the seismic performance of EBFs with vertical shear link using a new self-centering damper." *Ingegneria Sismica*, 35(4), 57–76.

Mugabo, I., Barbosa, A. R., Sinha, A., Higgins, C., Riggio, M., Pei, S., Van De Lindt, J. W., and Berman, J. W. (2021). "System Identification of UCSD-NHERI Shake-Table Test of Two-Story Structure with Cross-Laminated Timber Rocking Walls." *Journal of Structural Engineering (United States)*, 147(4).

Ottenhaus, L.-M., Li, M., and Smith, T. (2018). "Structural performance of largescale dowelled CLT connections under monotonic and cyclic loading." *Engineering Structures*, 176, 41–48.

Poh'sie, G. H., Chisari, C., Rinaldin, G., Amadio, C., and Fragiacomo, M. (2016). "Optimal design of tuned mass dampers for a multi-storey cross laminated timber building against seismic loads." *Earthquake Engineering and Structural Dynamics*, 45(12), 1977–1995.

Polastri, A., Giongo, I., and Piazza, M. (2017). "An innovative connection system for cross-laminated timber structures." *Structural Engineering International*, 27(4), 502–511.

Popovski, M., Schneider, J., and Schweinsteiger, M. (2010). "Lateral load resistance of cross-laminated wood panels." *11th World Conference on Timber Engineering 2010, WCTE 2010*, 3394–3403.

Pozza, L., Saetta, A., Savoia, M., and Talledo, D. (2018). "Angle bracket connections for CLT structures: Experimental characterization and numerical modelling." *Construction and Building Materials*, 191, 95–113.

Santos, P., Correia, J. R., Godinho, L., Dias, A. M. P. G., and Craveiro, H. (2021). "Experimental and numerical assessment of a cross-insulated timber panel solution." *Engineering Structures*, 235.

Tamagnone, G., Rinaldin, G., and Fragiacomo, M. (2018). "A novel method for nonlinear design of CLT wall systems." *Engineering Structures*, 167, 760–771.

Tesfamariam, S., Madheswaran, J., and Goda, K. (2019). "Displacement-Based Design of Hybrid RC-Timber Structure: Seismic Risk Assessment." *Journal of Structural Engineering (United States)*, 145(11).

Wang ZQ, Luo D, Z. W. (2021). ") Effect of hybrid structure on lateral load resistance of cross laminated timber wall." *Journal of Forestry Engineering*, 2(2), 145–151.

Yasumura, M., Kobayashi, K., Okabe, M., Miyake, T., and Matsumoto, K. (2016). "Full-Scale Tests and Numerical Analysis of Low-Rise CLT Structures under Lateral Loading." *Journal of Structural Engineering (United States)*, 142(4).

Zhang, X., Fairhurst, M., and Tannert, T. (2015). "Ductility Estimation for a Novel Timber – Steel Hybrid System." *ASCE Journal of Structural Engineering*, 142(4), 1–11.

Zhang, X., and Tannert, T. (2018). "Seismic reliability analysis of a timber steel hybrid system." *Engineering Structures*, Elsevier, 0–1.

Net-Zero Townhome Retrofi Design: Penn State's 2020-2021 Solar Decathlon Design Challenge Competition Entry H. L. Zimmerman¹

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ABSTRACT

Since 2014, members of the Pennsylvania Housing Research Center have collaborated with the Energy Efficient Housing Research Group at Penn State to support studen design teams to compete in the Department of Energy (DOE) Race to Zero and Solar Decathlon competitions. The annual Solar Decathlon design competition challenges interdisciplinary student teams of both undergraduate and graduate students to design an affordable and marketable net zero-ene gy ready home. At a minimum, these homes must meet the DOE Zero Energy Ready Home standard and incorporate sound building science principles. Each year, Penn State students have gone beyond the baseline competition requirements through their partnership with a Pennsylvania-based housing organization. These partnerships provide a real site, context, and practical design constraints for the students' submission and have opened opportunities for greater community impact and industry collaboration. The 2020-2021 student design team partnered with the State College Energy+ team, an organization composed of The Home Foundation (THF), the State College Community Land Trust (SCCLT), the Borough of State College, the Pennsylvania Housing Research Center (PHRC), and the Hamer Center, to develop a net-zero retrofit design for eight affo able housing townhouses located in downtown State College. The team translated and applied the Zero Energy Ready Home Standard, designed for new construction, to help retrofit existing housing stock. This design strategy greatly improves the performance of existing buildings and provides a sustainable solution to the lack of available land for new residential construction in the State College and Centre County area while providing affordable and adaptable units to suit a variety of tenants. This case study will describe the Penn State team's overall organizational approach, adaptation to a fully virtual format, and integrative design process, as well as the technical design of the housing systems presented at the 2021 Solar Decathlon design competition.

INTRODUCTION

For many years the Pennsylvania Housing Research Center and the Energy Efficien Housing Research Group at Penn State have supported student interest in sustainable design and competing in the Department of Energy's Solar Decathlon design challenges (referred to as SDDC) to design a net zero energy ready home. This year's interdisciplinary design team of 22 students tackled a completely virtual format to partner with the State College Energy+ team and design a retrofit strategy for eight townhouses located in downtown State College. The following case study will provide an overview of Penn State's involvement in energy efficient housing design, th team's integrated design process and approach to a fully virtual setup, and the technical design of the retrofit strategy for the 2021 competition submission.

ENERGY EFFICIENT HOUSING DESIGN AT PENN STATE

Solar Decathlon Build Challenge (2007-2009)

Students and faculty at Penn State have been participating in the Solar Decathlon competitions for almost fifteen years, beginning in 2007 with the Solar Decathlon Build Challenge. This competition asked students and faculty over two years to design and build a net zero energy ready home. The 2007 'MorningStar' home and 2009 'Natural Fusion' design catalyzed energy efficient design interest at Penn State These projects continue to serve as precedents for net zero design at Penn State today, with Solar Decathlon teams and sustainable design courses studying and touring the 'MorningStar' home to learn from its design.

Race to Zero Challenge (2014-2018)¹

The Race to Zero Challenge, also called the Challenge Home Competition in 2014 and 2015, was developed to compliment the Solar Decathlon Build Challenge by providing an alternative route to study and design net zero energy homes with a one year, paper-based competition. This shift greatly reduced the costs associated with the Solar Decathlon Build Challenge by not requiring students to construct their design and allowed for a greater focus on building science and market-ready homes.

This competition challenges students to design an affordable home for the median family income in their area and to comply with the DOE's Zero Energy Ready Home Standard. Additionally, students are encouraged to partner with an affordable housing industry partner in their area. Penn State has partnered with the State College Community Land Trust (SCCLT), the Centre County Housing and Land Trust (CCHLT), and S&A Homes in the past to help students explore various designs and expand beyond the scope of a single home to have a greater impact in the area.

Solar Decathlon Design Challenge (2019-Current)

During the 2018-2019 competition year the Race to Zero Competition was integrated with the Solar Decathlon Build Challenge to create The Solar Decathlon Competition where teams have the option of participating in the design challenge, a paper-based one-year competition, or the build challenge, a two-year project to design and build a net zero energy building.

Penn State has competed in the SDDC in the single-family suburban home division

since 2019 and has continued to connect with industry partners including Habitat for Humanity of Greater Centre County (HFHGCC) and the Centre County Housing and Land Trust (CCHLT) to design net zero energy ready homes and expand beyond the scope of a single home to design a flexible system.

For the 2020-2021 competition the Penn State team partnered with the Energy+ team, a local group composed of various organizations in State College to compete in a different division from past years. This year's team participated in the attached housing division with a group of eight townhomes available as rental units. Instead of new construction, the team tackled a retrofit of the existing units to meet net zero ene gy by adding new layers to the envelope, upgrading the MEP systems, reorganizing the layout of the units, adding solar panels, and adding community spaces.

DESIGN PROCESS

Educational Structure

Within the format of the SDDC competition, our team focuses heavily on the educational components to instruct students on Net-Zero Energy Ready design and the fundamentals of building science to train the next generation of engineers and designers in sustainable design. Each year teams begin by reviewing previous designs to acclimate new students to the elements of energy efficient design. Past team member continuing with the competition help to lead the project while acting as mentors to new team members. The project is heavily guided by student interests and exploration, providing students with a sense of ownership of the project.

The team operates as a student club in the fall semester under the guidance of a faculty supervisor, a flexible approach which allows freedom to explore the project and learn foundational building science for energy efficient buildings. In the spring, th team operates as a one-credit course, CE 411, to provide a more structured approach to the competition requirements. The course is also a requirement of the Residential Construction minor which draws additional team members to the project. While this strategy provides the flexibility and structure needed to meet the competition goals, it can be challenging to retain student engagement from the fall to the spring semester. Additionally, many students who join in the spring semester are unaware of the opportunity for engagement in the fall semester and would otherwise have joined the team earlier.

Team Structure

Our 2021 SDDC team was an interdisciplinary group of 22 undergraduate students from various architecture, architectural engineering, and civil engineering back-grounds. Seven students returned to the team from the 2020 design challenge to lead the group and guide the project, with 15 new students who had little to no experience with net zero energy design.

The design team focused heavily on integrated design and used the biweekly scheduled meetings to communicate the overall design with the full team and make many design decisions. To best organize the work, the team established five subteams, each led by one or two of the returning team members: Architecture and Landscape Architecture, Construction Management, Energy and Life Cycle Analysis, Envelope, and MEP (mechanical, electrical, and plumbing). New members Figure 1: Student Site Visit to Project Site were encouraged to join one or several



subteams related to their areas of interest. Each subteam met regularly to research and develop design strategies.

In the fall semester, the entire team met weekly to establish the baseline understanding of net zero energy design and begin to explore the project. Subteams were introduced in the spring, and meetings were held twice a week to help develop, refine, and finalize the design. The hour for the course meeting was used for team presentations or reviews with the project partner or faculty and industry advisors to receive feedback and guidance on current work. Saturday meetings were two hours and often used as an opportunity to meet in subteams to make sizable progress in the project.

Virtual Format

Due to the ongoing coronavirus pandemic all club meetings shifted to a virtual format, including the 2021 SDDC. Our team proved to be especially resilient, developing many strategies to communicate and stay organized in a virtual setup. Utilizing Zoom² and its breakout room function for weekly meetings helped to organize subteams and allow participants to move between groups for various discussions.

Many online websites were used to organize files, ask questions, and stay in touch. Google Docs³ allowed all the files to be in one locati n while Conceptboard⁴ acted as a virtual workspace to place images, text, and draw annotations to assist group discussions. In addition to emails and announcements, GroupMe⁵ was used as a messaging app to allow team members to quickly ask and answer questions related to the design or any deadlines coming up.

The virtual format provided a unique opportunity to engage our project partner in an online setting. Using PollEV⁶ we engaged each person from the Energy+ team individually to ensure everyone's opinions were heard and documented. The team was then able to reference the answers generated by PollEV to review and adapt the design. The team responded and adapted to the pandemic to stay engaged in the project and produce a refined, elegant project proposal



Figure 2: Virtual Meeting with Energy+ Team Members

2021 SD PROJECT⁷

Project Partner and Community Engagement

The 2021 design team worked with a large group of people known as the State College Energy+ team⁸ for this year's project. The Energy+ team is a group of mostly volunteers from many organizations including The Home Foundation (THF), the State College Community Land Trust (SCCLT), the Borough of State College, the Pennsylvania Housing Research Center (PHRC), and the Hamer Center. Building on the work done at the GreenBuild Project from the Race to Zero competition,⁹ the Energy+ team continued the idea of sustainable housing to retrofit existing buildings and provide healthy, affordable housing to low-income groups including young families, recent graduates, or graduate students.

Working with existing townhouse apartments proved to be both challenging and enlightening. Beginning with an existing structure and working closely with the Energy+ team members allowed our team to design a realistic solution while considering the budget for the project, local building codes, and potential hazards for rental units. While most of the Energy+ team is not well versed on building systems, many of them have very strong conceptual ideas on what makes a house a home and were able to help shape the design to create a welcoming, healthy, affordable environment in these homes. Virtual meetings allowed for frequent communication of goals and design ideas to guide the development of the project.

Design Goals

The team's goals with this project were to blend the expectations and requirements of the SDDC, the Energy+ team, and the student interests to create a design that satisfies all groups. To summarize the blending of priorities and expectations the team created three goals addressing the major categories of the project:

1. Performance- Utilize south-facing rooftop for solar PV and meet the ZERH requirements to achieve a net zero energy design using energy modeling.

2. Appearance: Aesthetic improvements to create a sense of diversity among the units; design is integrated into the landscape. Final design is aesthetically pleasing and creates a beautiful example of how net zero energy designs can work in the State College area.

3. Experience: Improved interior environment; use of high quality, low carbon materials; tenants feel that they are individuals within a community. Create a safe and welcoming space for students and professionals to live.

In addition to these three goals, the team chose to design a retrofit strategy which has the potential to be applied on multiple projects in the State College area. Most of the land zoned for housing in State College has already been developed, and there is very little space available for new construction. Rather than tear down existing buildings to be replaced with new construction, creating tons of construction waste and emissions, this design allows the existing buildings to remain and improves the tenant's lifestyle with a healthier living environment.



Figure 3: Existing Units at Old Boalsburg Road



Figure 4: Proposed Retrofit Desig

Architectural Design

Upon examining the eight units located at Old Boalsburg Road, the team determined the units lacked variety for different types of tenants. To correct this, three floor plans were developed to adapt the apartments to suit graduate students, young families, and

recent graduates. The western unit was divided into two studio apartments to maximize the flexibility of the now nine units, and other interior space was developed according to the needs of the potential tenants. Units designed for graduate students were developed with more equal distributions of bedroom space, while young families have a clearly defined master bedroom with a smaller workspace or child s room and direct access to the unit's basement for additional storage. Additionally, community spaces were added to promote a neighborhood environment. A picnic area and children's play area were developed to encourage use of the backyard. Additional solar panels were included in the design to form a solar canopy over parking and allow excess energy to be generated and used in the building or sold back to the grid for profit.

The elevations of the units will all be upgraded with the envelope retrofit to provide a visually appealing street view highlighting the modern, energy efficient design an providing a precedent of a net zero energy retrofit in the State College area

Building Envelope Design

As tenants will remain in the units during the retrofit process, the team designed a non-disruptive strategy which will allow all the units to be upgraded with minimal impositions on the tenants. Strategies for the roof, walls, and basement were developed to ensure a very tight air seal and high performing building envelope.

Roof: The attic space will be conditioned with control layers on the sloped roof of the attic. The existing fibe glass insulation will be removed, and a chainsaw retrofit will eliminate the existing eaves and roof. The new wall build-up will layer OSB with taped seams, mineral wool insulation, and ZIP-sheathing under the roof shingles, on top of the existing structure. New cellulose insulation will be installed in the attic, and the chainsaw retrofit will ensure continuous control layers at the corner where the wall meets the roof. The final roof will have an R-value of R-49.



Figure 5: Exterior Retrofi

Wall: The wall retrofit will be executed from the outside of the units, minimally di rupting the tenants. The existing vinyl siding will be removed and the OSB checked for any water damage that would need to be repaired. Small holes will be cut in the top of the existing OSB to fill the wall cavity with cellulose insulation. A new layer of OSB with taped seams will be added, and a new frame of 6" trusses attached to the outside will hold another 5.5" of cellulose insulation which will be wrapped in ZIP-sheathing and the finish materials. Both cavities full of insulation will provide an R-value of R-36 for the walls. Basement: Due to code height restrictions the basement will not be conditioned. Control layers for the envelope will run along the first-floor joists and will all be installe as there are no existing control layers in the floor of the apartments. The basement will be air-sealed using spray foam insulation and verified with a blower door test. Any gaps will be sealed, and dense-pack cellulose will be installed to achieve an R-value of R-20.

Building Systems Design

The current units do not have any cooling control and only supply heat in the winter. Being in climate zone 5A, State College is a heating-dominated climate, however, has many warm days where cooling is needed for tenant comfort. The team selected a solution which would meet the needs of the tenants without oversizing the systems for the small spaces while designing for resiliency in the event of extreme weather. Space Heating and Cooling: The team selected four outdoor multi-zone heat pumps to provide heating and cooling to the nine apartments. Each mechanical unit provides a 36,000 BTU/hr. capacity with two ductless mini splits to two apartments. Each two-story apartment for the graduate students and families contains a 9,000 BTU/hr. and a 6,000 BTU/hr. head while the two studio apartments contain one 9,000 BTU/hr. unit each.

Ventilation: The current units have no mechanical ventilation systems as they were not common at the time of construction. To serve the extreme airtightness of the retro-fitted units, estimated to be 0.6 ACH50, an Energy Recovery Ventilator was selected for each apartment to provide both sensible and latent heat recovery.

Energy Analysis

Energy modeling was consistently used during the development of design decisions to encourage dramatic reduction of the energy consumption of the units. Units were evaluated based on their location and adjacencies, and the models were developed to reflect the drastic improvements proposed with the retrofit The initial energy model of the existing units resulted in a HERS score of 175 for an end unit and 174 for an internal unit. Noticeable impacts came from increased insulation and air sealing, new right-sized mechanical systems, and efficient appliances After summarizing the retrofit design decisions, the Retromorphisis home without photovoltaics achieved a HERS score of 45 for an end unit and 46 for an internal unit.

The building has an ideal layout for photovoltaics with a large south-facing roof. The team designed an array at a 35° tilt angle to generate enough energy to offset the a - nual energy consumption of the units after reducing the energy consumption with the retrofit. With the proposed photovoltaic layout of 5.25 kW per unit the HERS score was -5 for the end units and -7 for internal units with an overall net-positive design.

A large consideration of this project was the embodied energy generated through material use and waste. The existing building was maintained to reduce construction waste, and new materials, such as the cellulose insulation, were selected for their low embodied energy. A life cycle analysis was conducted to compare this retrofit to sim - lar projects, and the team's design consumed 26% less primary energy than a standard retrofit



Figure 6: Energy Reduction Strategies and Impacts

Financial Feasibility

State College, PA has a unique housing market due to the large influence that Penn State University has on the area, with only 17% of State College residents owning their own home. The other 83% are renting their homes temporarily, typically on a 12-month lease. Rental unit prices are most directly associated with proximity to downtown and campus, as well as the aesthetic appeal of the building interior.

These units have been developed towards more stable renters and provide an affor - able option in the State College area. With the proposed retrofit, the building perfo - mance and aesthetic will be radically transformed, and now offer an ADA studio for \$1350 per month, a studio with a private balcony for \$1550 per month, two graduate units for \$1800 per month, two affordable units for \$ 100 per month, and three family units at \$1800 per month. A new leasing structuring should also offer more stability to the owner, as the family and affordable units are now incentivized to have long term leases.

CONCLUSION

Building on the history of Penn State's involvement with the Solar Decathlon, the 2020-2021 design team partnered with the State College Energy+ team to tackle a retrofit of eight townhouses. The team was successful in retaining students from previous years and recruiting new students even during a pandemic. Students and faculty

excelled in adapting to the virtual format and having to meet virtually allowed students to explore new software and means of communicating.

Unfortunately, the Penn State team was not invited to compete as part of the attached housing division for the 2021 SDDC, however the group presented at the competition as an exhibition team. For additional community engagement, the team presented their final work to the Ene gy+ team as a final summary and to Penn State s own President Barron.

The final design will serve as an example in the State College community of what can be done to achieve a net zero energy retrofit and will hopefully serve to be a catalyst for many groups to begin retrofitting existing housing stock in State College instead of demolishing and building new construction houses. Affordable housing fills a much-needed void in the State College community as the price of rent continues to rise due to the large amount of student renters from the University. The retrofit of these units will allow the Energy+ Team to grow their portfolio of energy efficien housing and provide them with a model for future retrofits as they continue to reshape the State College area. The tenants will be provided with a much healthier and enjoyable living environment to truly thrive in their living space, and the design for these units will hopefully encourage many others to pursue energy efficient or net-zer design as the existing housing stock is being renovated.

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END NOTES

- 1."Race to Zero/Solar Decathlon," Energy Efficient Housing Research Group, Sites at Penn State, 2022, https://sites.psu.edu/ eehr/projects/race-to-zerosolar-decathlon/.
- 2."How the World Connects," Zoom, Zoom Video Communications, 2022, zoom.us.
- 3."Google Docs," Google, 2022, docs.google.com.
- 4."An Infinite Canvas for your hole Team," Conceptboard, Conceptboard, 2021, conceptboard.com.
- 5."The Best Way to Chat with Everyone You Know," GroupMe, Skype, 2022, groupme.com.
- 6. "Powering Hybrid Work and Inclusive Conversations," Poll Everywhere, 2022, polleverywhere.com.
- 7.Penn State Solar Decathlon Design Team, "Retromorphisis," March 2021.

^{8. &}quot;Energy+," State College Community Land Trust, Centre County United Way, 2022, http://www.scclandtrust.org/energy-initia-tive.html.

^{9. &}quot;GreenBuild Construction Blog," Energy Efficient Housing Research Group, Sites at Penn State, September 2018, https://sites. psu.edu/eehr/greenbuild-construction-blog-2/.

Review of Different Types and Performances of Tornado Shelters for Residential Buildings

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Abstract

Over the past 30 years, U.S. communities have sustained significant economic losses from hurricanes and tornadoes. While not as extensive in terms of spread of affected areas, the mid-west U.S. deals with tornadoes that are much more destructive than hurricanes. As an example, on November 17, 2013, a total of 106 tornadoes touched down across seven states in the mid-west, two of them having estimated peak wind speed in the range of 166 to 200mph, which resulted in significant damage and destruction to 2400 homes. Unlike hurricanes that are expected to almost annually affect southern and eastern coastal regions of the U.S., tornado return period is expected to be 1000 years for any given square mile. With such low probability to experience an actual devastating tornado, residential buildings are not currently required to be designed against tornado effects. Instead, the preferred solution to save lives in the event of tornado outbreak is to use shelters, which can be made for individual homes or for community or neighborhood in tornado prone areas. The Federal Emergency Management Agency (FEMA) has published a series of documents providing guidelines for such shelter construction and their basic design requirements. The main objective of this paper is to provide a review of the main types of aboveground and belowground shelters that can be made of different materials, e.g., concrete, steel, masonry, and timber, and that can be constructed outside the home or inside such as in thegarage. The attributes of various options are compared, including any information available on the cost. The paper also reviews the performance of various types of tornado shelters in past destructive tornadoevents.

Introduction

Tornadoes cause severe damage to structural and infrastructural systems, and each year only in the United States, tornadoes result in 70 deaths on average and about 400 million dollars in damage (National Geographic 2019). Based on Insurance Information Institute (2022), in 2021 alone 94 people died due to tornadoes, and the worst cost in one year due to tornadoes was in 2020 for \$9.6 billion. The total cost of 10 costliest tornado damage over the past 21 years has been \$53 billion. While efforts toward promotion of design of buildings in general and homes in particular against tornado effects is continuing (e.g., Prevatt et al. 2012), at this time it is still important to build storm shelters for residential buildings to protect human lives. The aim of the study reported here is to describe different types of tornado shelters that are available in the market and compare them based on the material, cost and performance of tornado shelters during a tornado.

Tornadoes and hurricanes are examples of events in which extreme wind conditions occur. A tornado is a violently rotating column of air with wind speeds that are significantly higher than the design wind speeds that we use while designing a standard building. Three different types of tornado effects produce damage during a tornado: 1) Forces due to tornado wind pressure, 2) Forces due to a drop in atmospheric pressure, and 3) Impact forces produced due to tornado generated debris. These three different types of forces exert pressure on structures that are generally much higher than the design strengths the structure is designed for, and thus result in excessive structural damage. The tornado outbreak of March 3, 2019 in the Southeastern United States is an example of such damage, where over the course of 6 hours, a total of 41

tornadoes touched down across portions of Alabama, Georgia, Florida, and South Carolina. The strongest of these was an EF4 tornado that devastated rural communities from Beauregard, Alabama through Smiths station, Alabama to Talbotton, Georgia, killing 23 people and injuring at least 1000thers. Because it is very expensive to construct homes that can withstand the tornado forces, the preference to build storm shelters that can save human lives and reduce injuries and fatalities during such extreme wind events.

Types of Tornado Shelters and Their Classification

Tornado shelters can be differentiated based on a number of different factors such as the number of people occupying the shelter, the intended users, and the location of the shelter. As a main category, storm shelters can be differentiated based on the number of people the shelter is designed for, leading to the main two types of residential safe room and community safe room. According to FEMA (P-361, 2015), a residential safe room can serve a maximum of 16 people. Residential safe rooms are generally occupied by people who are familiar with one other (i.e., people of a family or neighbors), thus a smaller space is allocated to each person in the shelter, i.e., 3 ft² per person. A safe room that is not classified as residential safe room is considered to be community safe room, which is generally built by a community to safeguard a large number of people during a tornado. As people in a community safe room do not know one another, a larger space per person is allocated for the safe room, i.e., 5 ft² per person. While constructing a community safe room, at least one wheelchair space should be provided for every 200 people that the shelter is designed for.

As another important classification, based on their intended use, tornado shelters can be considered in two categories: single-use safe room and multi-use safe room. Single-use tornado shelters are intended for use only in the event of a tornado; hence, they usually have a simplified design. The advantage of a single-use tornado shelter is that they are not cluttered with furnishings that take up the floor space, which may be requiredduring a tornado. Due to their simplified design, such shelters are readily accepted by the local building official or fire marshal. On the other hand, when a safe room is used on a daily basis along with providingshelter during a tornado, it is known as a multi-use tornado shelter. For example, a multi-use tornado shelter at a school may also function as a classroom, a lunchroom, or an assembly room. The ability to use a safe room for more than one purpose is often very appealing to homeowners. Multi-use safe rooms may offer agood return on investment as they are used regularly. However, it is important to verify that the daily use of the safe room does not interfere with the timely use of the safe room during a tornado. Whether a safe room is single- or multi-use can affect the cost of building components, finishes, furnishings, and other occupancy-driven design parameters. Single-use safe rooms generally have a simple design (i.e., short walls, short roof span, minimal interior partitions and finishes) and thus have a lower cost per square foot as compared to multi-use safe rooms that generally have higher walls and longspan roof assembly. The operation and maintenance plans for a safe room vary as a function of whether or not the safe room is single-use or multi-use space. For a multi-use safe room, it is necessary to demonstrate that the normal daily usage of the space will not interfere with the timely operation of the safe room, while for a single-use saferoom, one needs to demonstrate that the safe room will not be misused or neglected (e.g., using the safe room as a storage space will decrease the usable floor space and occupant capacity) and will be available for use in a timely manner during an extreme-wind event.

There are different types of tornado shelters available in the market based on the location of the shelter. Some shelters are installed inside a house on a concrete slab, while others are installed in the backyard. The location of the tornado shelter depends on factors like geographic location, ground water level and material of the shelter. The types of tornado shelters based on their locations are: 1) Stand-alone above-ground shelter, 2) Internal above-ground shelter, 3) Underground storm shelter in the backyard, and 4) Underground stormshelter in the house. Stand-alone above-ground shelters are designed as separate structures that can protectpeople during a tornado. A stand-alone shelter needs to have a solid steel reinforced concrete base. Internal above-ground safe rooms can be added in the house during the construction phase or an already existing area of the house can be reinforced to withstand the forces

experienced by the structure during a tornado. These safe rooms need to be bolted to a thick concrete slab in the house. Hence, before constructing an internal above-ground safe room, it is important to verify that the concrete is thick enough to support the weight and the forces induced by the shelter. Adding a shelter while constructing a new house may be the cheapest option in most cases, as it increases the total construction cost only by about 1% to 2% (FEMA P-320, 2014). In areas of high ground water level and in areas where ground water level increases significantly, it is recommended to construct an internal above-ground shelter.

To save living space, storm shelters can also be constructed underground. However, an underground storm shelter can only be constructed in regions where the ground water level is low, and the level of ground water does not increase during storm surge. An advantage of an underground shelter is that the shelter can be considered being shielded by soil cover and thus is not required to be tested for missile impact if there is more than 12 inches of soil cover protecting the horizontal surfaces (i.e., roof) and more than 36 inches of soil cover protecting the vertical surfaces (i.e., walls) (FEMA P-320, 2014). One of the major disadvantages of an underground shelter in the backyard is that there is the likelihood of occupants being hit by missile generated by tornado while trying to access the shelter. Underground tornado shelters are also susceptible to stresses and strains if soil freezes in the winter time. Underground tornado shelter within the house is a better option. However, the major disadvantage of an underground shelter within the house is that there is a possibility that the door of the shelter gets blocked by tornado debris. On the other hand, from previous tornado events it has been observed that in most cases, neighbors help each other by removing the debris blocking the shelter door. According to Homeadvisor (2020), the cost of a tornado shelter typical range varies from \$2,638 to \$11,441.

Tornado shelters made up of different materials are available in the market. This section discusses the different types of materials used to build tornado shelters and also discusses the advantages/disadvantages of these materials. Materials used for constructing tornado shelters include the following: 1) Reinforced Concrete (Reinforced concrete wall or Insulated Concrete Form (ICF)), 2) Steel sheathing, 3) Concrete masonry unit (CMU), 4) Carbon fiber reinforced hybrid polymeric matrix composite, 5) Plastic (Polyethylene), and6) Cross laminated timber (CLT).

Reinforced Concrete -- Test results from several tests conducted by Texas Tech University (TTU) suggestthat a 6-inch thick reinforced concrete wall is needed to stop a 15-pound wood 2 X4 wood stud (test missile) at 100 mph.

Insulated Concrete Form (ICF) -- ICFs are cast-in place concrete walls that are sandwiched between two layers of insulation material. ICFs are available in two forms: as individual panels with plastic connectors in each panel into which concrete is poured and as pre-formed interlocking panels into which concrete is poured. According to FEMA (FEMA P-361), the thickness of reinforced concrete walls with ICFs should have a uniform cross section of at least 4 inches. There should not be any discontinuities in walls made of ICFs as that can allow missiles to penetrate the shelter. While constructing a tornado shelter made out of ICFs, it should be ensured that the concrete is properly vibrated to eliminate any voids in the panels and ensure proper consolidation of mortar.

Steel sheathing -- Several tests were conducted at TTU (FEMA P-361) to find out the thickness and configuration of steel sheet that can provide protection against missile impact. From the tests, it was found out that 12-gauge or heavier steel sheets always pass the missile impact tests. The tests also showed that the configuration of the steel sheet also matters. When the steel sheet is properly configured, the steel sheathing stops the missile by deflecting and spreading the impact load to other wall assembly components. When the steel sheet is improperly configurated, the wall assembly can be perforated and fail the

deflection limitations set by FEMA. If the permanent deformation of the steel sheet exceeds 3 inches, then the configuration is deemed unacceptable by FEMA.

Concrete Masonry Unit (CMU) -- A Concrete Masonry Unit (CMU) block is a standard sized rectangular block used in building construction. CMU blocks can be ungrouted, partially grouted and fully grouted. Grouting increases the strength of the structure. Thus, fully grouted and reinforced CMU walls are used for construction of tornadoshelters. Several tests were performed at Texas Tech University (TTU) to find the configuration of CMU that can provide protectionagainst missile impact in a tornado. Based on these tests, FEMA suggests two configurations of CMU units that can be used for tornado shelters: 1) 6-inch CMU walls that are fully grouted with ASTM C476 grout and reinforced with #4 rebar at 36 inches on center and 2) Fully grouted 8-inch CMU walls reinforced with #5 bars at 48 inches on center.

Carbon fiber reinforced hybrid polymeric matrix composite-- A tornado shelter using Carbon fiber reinforced Hybrid matrix composite (CHMC), or 'Carbon Flex' has been developed recently (Hingyu Zhou et al. 2014). The system is composed of two plies of 19.1 mm (3/4 inch.) thick C grade plywood and a layer of recently developed Carbon-fiber reinforced Hybrid polymeric Matrix Composite (CHMC). Carbon Flex is a carbon fiber-based composite manufactured via a new patented hybrid-polymer matrix system involving amino-based polymeric compounds to provide necessary damping and high strength sustainability of the carbon fibrous component under high impact loading. As CHMC has superior deformation and energy dissipation capabilities, it is used in a tornado shelter to sustain the impact loads by tornado borne debris. To enhance the shear resistance of the composite wall system, the two plies with thickness ³/₄" are oriented at [0 °/90°] and the two 4" wide Carbon flex strips are oriented at $[\pm 45°]$. CHMC panels passed the impact load test as per the design criteria mentioned in FEMA (P-320, 2014). The advantage of using CHMC is that an existing non-tornado resistant wood structure can be upgraded to provide protection from tornado using Carbon Flex, due to lightweight, relatively inexpensive and manageable features of the composite.

Cross Laminated Timber (CLT) -- Cross Laminated Timber (CLT) is an engineered wood product that is gaining popularity as an alternative to concrete and steel in construction of residential and commercial buildings. CLT panels are formed by stacking layers of wood in orthogonal directions and gluing them together using a hydraulic press. The orthogonal structure of CLT panels allows the panel to be able to resist in-plane and out-of-plane loading. Thus, CLT panels can be used as walls, floors, and roofs. One of the advantages of using CLT is that it is environmentally friendly. Timber acts as a carbon sink if harvested properly through conversion of CO₂ to biomass and in the process of bio- sequestration via photosynthesis. Another advantage of using CLT is that we can incorporate the use of lower grade wood in the CLT panel. As it is possible to identify the lamellae visually and mechanically, we can use the lower classes of wood in the central layers of the panel where the tension and compression forces are less. The disadvantage of using a CLT panel is that in general CLT panels do not provide satisfactory noise reduction. Tornado shelters made up of CLT panels were tested at the Forest Product laboratory. Different configuration of CLT panels were tested for wind loading and impact resistance as per the guidelines provided by ICC/NSSA-500. Results from the tests indicate that CLT tornado shelters made up of four ply walls can safely withstandthe most severe impact test included in the ICC/NSSA -500 standard. It is important to note that all the panels that were used in the study were prefabricated and full size (the entire 8 X8 panel had no joints or splices).

Tornado shelters made from plastic (Granger ISS Tornado Shelter) - The Granger ISS tornado shelter is a tornado shelter made up of plastic pieces/parts by using the rotational molding process. This process of production produces parts that are durable and resilient and thus can last for thousands of years. The shelter is a double wall polyethylene design that is filled with foam to provide additional strength and rigidity.

Along with providing strength and rigidity to the shelter, the foam also acts as an insulator, thus keeping the temperature of the shelter constant and eliminating moisture and condensation issues.

Comparing Tornado Shelters Made of Different Materials and Prices

Tornado shelters made from concrete are heavy when compared to other materials like steel, CLT and Fiberglass. As concrete tornado shelters are heavy, they may not need as much additional anchorage as the lighter ones do. Underground concrete tornado shelters are feasible and do not have any major concerns, while underground steel tornado shelters need to be coated with coal tar epoxy or galvanized to prevent corrosion of steel. During installation of an underground steel tornado shelter, extreme care must be exercised to verify that no leaks are present in the storm shelter. The advantage of using an aboveground steel tornado shelter over an aboveground concrete tornado shelteris that the steel tornado shelter can be taken apart (or removed from anchors) and reassembled (or re- erected/re-anchored) if you are moving to a new home. Of all the materials used for manufacturing tornadoshelters in the market, CLT shelter is the only one that is ecofriendly. Another advantage of using CLT tornado shelter is that it weighs less when compared to steel and concrete tornado shelters making them easy to handle. At the end, the type of tornado shelter to install depends on the occupants' preference. If the occupants planto relocate to a new place, then they may decide to purchase a steel or CLT aboveground tornado shelter as these can be taken apart and reassembled in a new place. While if the occupants want the tornado shelter to be at the same place throughout its lifetime, then they can buy an underground tornado shelter or an aboveground shelter made up of concrete.

According to Homeadvisor.com (2020), depending on the type and size, the cost of a tornado shelter varies from \$2,638 to \$11,441 with an average cost of \$6,982. Furthermore, the price of a shelter that can accommodate 4 to 6 people starts around \$3,000, while the price of one that can accommodate 12 or more people can run up to \$30,000. On the other hand, the price of an aboveground tornado shelter varies from \$3,000 to \$15,000, which is less when compared to the value of an underground tornado shelter, which could be between \$4,000 to \$30,000.

Performance of Residential tornado shelters during the Oklahoma tornado (May 20, 2013)

On May 20, 2013, an EF5 tornado moved through the city limits and in the southwest portion of Moore killing 24 people and injuring 377 people. The width of the tornado path touching the ground was about 2.1 km and it travelled 27 km through Moore. The goal of the assessment team was to collect information on tornado damage to residential wood frame construction in the region. During the assessment, the team was able to investigate 75 different types of tornado shelters that were subjected to complex loading profile in an actual tornado. Of the 75 tornado shelters that were investigated by the assessment team, only seven were aboveground shelters, while the rest were of underground type. Of the 68 underground residential shelters, majority were made up of prefabricated concrete or garage slab tornado shelter. While investigating the storm shelters pictures were taken of storm damage, structural component failure, and debris failure, and later, the digital cameras were synchronized with GPS devices to obtain the location of all the images. In this study, a wall is considered to be perforated if the projectile is able to enter the interior of the shelter, while a penetration is defined as damage to the exterior surface of the shelter without any perforation.

Figure 1(a) shows a prefabricated concrete shelter that was the common type observed in the area. Figure 1(b) is an example of a sliding door garage floor shelter. The disadvantage of the tornado shelter in Figure 1(b) is that car may have to be moved so that occupants are able to enter the safe room. According to investigation, a majority of the garage slab shelters performed very well, but in some instances, the shelters were blocked by large objects and debris. Figure 1(c) illustrates an example of a shelter that was blocked by debris after the garage and house collapsed. It is also important to note that in most cases the neighbors would help the people who were stuck in the shelter within 30 minutes of the event. Another issue with

underground shelters was that in some cases the shelters were filled with water caused by heavy rains or severed water lines. Fig 1(d) is an example of a shelter that was flooded with water.



Figure 1. (a) Prefabricated concrete shelter. (b) Garage slab shelter. (c) Debris blocked entry after the attached garage failed. (d) Flooded shelter from severed water lines (Standohar-Alfano et.al, 2014).

In case of aboveground tornado shelters, most of them performed very well with just cosmetic damage on the exterior portions of the shelter due to debris impact. Figures 2(a) and 2(b) are the two examples of concrete/CMU safe rooms that were observed by the investigation team who reported both shelters performed well during the tornado.

A few other aboveground tornado shelter types were observed by the investigation team as shown in Figure 3, where two types of interior aboveground steel shelters and one type of exterior steel were seen. Figure 3(a) shows a shelter found in western Moore in an area of EF3 damage where no major damage was observed in this tornado shelter, except for a few scratches on the exterior of the shelter due to debris impact. Even though some portion of the roof assembly fell on the shelter, no major damage was observed on the shelter. Figure 3(b) is the second steel aboveground tornado shelter observed in an area of EF4 damage, where again there were some scratches and buffing impact due to tornado debris, but no major damage or perforation was observed on the shelter. Figure 3(c) is a cylindrical tornado shelter capped with a dome observed in an EF0 damage area where no damage was observed on this cylindrical tornado shelter either. A completely different aboveground type was also seen as illustrated in Figure 3(d), which shows a homemade concrete dome refuge made without any design guide. This concrete dome refuge, which was located in an area of EF4 damage, was 3ft tall and 2ft wide with a door of 3/16 inch steel and made up of 7inch thick concrete exterior. The dome performed very well in the tornado.

A safe room made up of insulated concrete form (ICF) was also investigated by the team. This safe room was constructed in 2001 using ICF concrete waffled grid walls. The roof of the safe room was made up of 2X8 inch wooden top plate with metal studs. J-bolts were used to anchor the roof to the ICF walls. During

the tornado, there was a complete removal of the attached garage and the roof. Based on the damage experienced by the neighboring homes, the home was estimated to be in a region of EF4 damage.



Figure 2. FEMA designed concrete/CMU safe room (a) Near the intersection of SW 149th street (b) Centrally located among the rooms remaining and the general location is indicated by the black circle (Standohar-Alfano et.al, 2014).

The exterior ICF walls of the home included 1.5 inch of foam on the interior and exterior side of the concrete wall. The total thickness of the wall including the foam and the concrete core was 9.25 inch. No. 4 rebar was used as horizontal and vertical reinforcement in every other cell of the exterior walls. The centers of the cells were spaced at 12 inches. The ICF safe room was also used as a storage closet. The safe room measured 8 X 8.67 feet with 8ft tall walls. As it can be seen from Figure 4, one of the safe room walls acted as an exterior wall of the home. Two square metal poles perforated the exterior wall of the safe room, where one of the projectiles is shown in Figure 5(a). The pole that entered the safe room extended approximately 2 ft into the room. Figures 5(b-d) show the detailed images of the projectile that entered the room. The projectile entered the room from the part of the wall where there was no reinforcement. Determining the exact size of the reinforcement was not deemed important by the investigation team.



Figure 3. Aboveground residential shelters (a and b) Steel shelters bolted to the ground slab; (c) Cylindrical steel exterior storm shelter; (d) Homemade concrete dome refuge (Standohar-Alfano et.al, 2014).



Figure 4 (left). Floor plan of the ICF home where failure of an aboveground safe room occurred; an exterior image of the safe room and tornado motion is shown (Standohar-Alfano et.al, 2014).
Figure 5 (right). (a) One of the square metal poles that perforated the exterior wall of the safe room; (b) Dimension of the pole that perforated the safe room; (c) the end that punctured the wall; (d) theother end used for thickness measurement (Standohar-Alfano et.al, 2014).



Figure 6. Poor concrete pour indicated by (a) Large area of poorly consolidated concrete below missile perforation; (b) Large void in the concrete in the thinned area of the waffled grid and in the vicinity of the plastic clip (Standohar-Alfano et.al, 2014).

Issues with workmanship and construction quality was an explanation hypothesized by the investigation team. As shown in Figure 6 large holes and voids were observed at the location of perforation in the concrete. The location and configuration of the plastic cross-ties led to concrete flow issues, resulting in 1 inch thick concrete at the location of the perforation of the wall. Thus, extreme care must be taken while pouring concrete to ensure that all areas of the safe room walls are properly filled. From the investigation, it was concluded that the majority of the safe rooms performed well during the tornado and had no perforations except for one ICF safe room.

Conclusions

This paper has provided a brief review of different types of tornado shelters commonly available in the market and CLT as a new type with potential for use in the near future. From the literature review, it can be concluded that both aboveground and belowground tornado shelters are available in the market, but both types of tornado shelters have their own limitations. Aboveground tornado shelters can only be installed in areas that have a strong concrete base to transfer the loads to the ground. While belowground tornado shelters should only be installed in areas of low ground water level. From the review, it can be concluded that the ideal material for the tornado shelter depends on the use of the shelter. If there is a need for a shelter thatcould be relocated in its lifetime, then a steel tornado shelter, it is better to use concrete than steel, as steel shelters may experience corrosion over time. After reviewing the investigation of residential tornado shelters performed well during the tornado except for tornado shelters made of ICF panels. While the failure of the ICF panels was attributed to poor workmanship, concrete shelters in general provide safe shelters. Thus, it can be concluded that if proper code methods are followed while building a tornado shelter, then the shelter will be able to protect human lives during a tornado.

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References

- American Society of Civil Engineers (2016). "Minimum Design Loads and Associated Criteria for Buildings or other Structures." ASCE/SEI 7-16.
- Federal Emergency Management Agency (2014). "Taking shelter from the storm." FEMA P-320, 13-30.
- Federal Emergency Management Agency (2015), "Safe rooms for tornadoes and hurricanes." FEMA P-361, B01-B32.
- Hingyu Zhou, Kittinan Dhiradhamvit, Thomas L Attard, (2014). "Tornado-borne debris impact performance of an innovative storm safe room system protected by a carbon fiber reinforced hybrid polymeric-matrix composite", Journal of Engineering structures 59.
- HomeAdvisor (2020). "How Much Does a Storm Shelter Cost?" https://www.homeadvisor.com/cost/safety-and-security/build-a-storm-shelter/.
- Insurance Information Institute (III), (2022). "Facts + Statistics: Tornadoes and Thunderstorms," <u>https://www.iii.org/fact-statistic/facts-statistics-tornadoes-and-thunderstorms</u>.
- International Code Council (ICC) (2008) "ICC/NSSA standard for the design and construction of storm shelters", American National Standard. 7-17.
- National Geographic, (2019), "Tornado Facts and Information," https://www.nationalgeographic.com/environment/article/tornadoes#:~:text=Every%20year%20in% 20the%20United,the%20water%20from%20a%20riverbed.
- Prevatt, D. O., van de Lindt, J. W., Back, E. W., Graettinger, A. J., Pei, S., Coulbourne, W., Gupta, R., James, D., and Agdas D., (2012), "Making the Case for Improved Structural Design: Tornado Outbreaks of 2011," ASCE Journal of Leadership and Management in Engineering, Vol. 12, No. 4, pp. 254-270.
- Robert H Falk et al (2019). "Development of a Ready-to-Assemble Tornado Shelter from Cross-Laminated Timber (CLT)." US Department of Agriculture, Forest Service, Forest Products Laboratory.
- Standohar-Alfano et al. (2014). "Performance of Residential Shelters during the May 20,2013, Tornado in Moore." American Society of Civil Engineers.
- The Engineered Wood Association (2018)," Standard for Performance-Rated Cross Laminated Timber", ANSI/APA PRG 320-2018.

Case Study Finite Element Modeling and Analysis of a CLT Tornado Shelter

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Abstract

Although tornadoes are among the most devastating natural hazards in the United States, currently, building codes do not require homes to be designed against tornadoes. Instead, the more economical solution seems to be building tornado shelters inside or outside homes (e.g., the cost of a tornado shelter can be estimated \$3,000 to \$12,000). The materials used for construction of such shelters vary depending on whether the shelter is to be built aboveground or buried underground and the size of the shelter, which depends on the number of people expected to use the shelter. While conventional materials include masonry, concrete, and steel, due to the interest in more sustainable materials, a cross-laminated timber (CLT) shelter hasbeen designed and tested at the USDA Forest Service Forest Products Laboratory. The main objective of this paper is to use the designed and tested shelter as a case study to develop a detailed finite element modeling (FEM) approach and validate it based on the available test results. The paper initially describes the design of the shelter and its details, including design criteria, tornado loading, specification of the elements and components used, and the testing setups and the results of simulated wind loading and missile impact tests. The paper then presents the details of the modeling including CLT panels, connectors and fasteners using SAP 2000 structural analysis software. Details of the materials and component properties, e.g., stiffness of fasteners and connectors, and CLT panels effective shear and bending stiffness, as determined using analytical methods are presented. The outcome of the FEM validation will help in similar designs, including parametric variation of such designs.

Introduction

Tornadoes cause severe damage to structural and infrastructural systems, and each year only in theUnited States, tornadoes result in 70 deaths on average and about 400 million dollars in damage (National Geographic 2019). Based on Insurance Information Institute (2022), the total cost of 10 costliest tornado damage over the past 21 years has been \$53 billion. While efforts are underway to develop tornado resistant home designs and provide standards towards this objective (e.g., Prevatt et al. 2012) and thus reduce such enormous damage scale, nonetheless, currently storm shelters are the main choice for protection of lives. In particular, for existing vulnerable homes, building tornado shelters seems a logical way toward reducing casualties. Therefore, it is important to build storm shelters for residential buildings to protect the occupants. The tornado return period is expected to be 1000 years for any given square mile (FEMA P-361, 2015). As the probability of experiencing a tornado is very low, residential buildings are not currently designed against tornado effects. It is much cheaper to build a standalone tornado shelter (e.g., the cost of a tornado shelter can be estimated \$3,000 to \$12,000)rather than reinforcing/stiffening the whole house to resist tornado effects, i.e., loads and debris impact. There are different types of tornado shelters currently available in the market. Tornado shelters can be built underground or aboveground. While some shelters are only designed for use as a shelter, others can be used for other purposes as well. Tornado shelters made up of different materials like concrete, steel, concrete masonry unit (CMU), cross-laminated timber (CLT) and plastic are available in the market. The goal of this study is to contribute toward a numerical modeling approach to evaluate CLT type tornado shelters.
Accordingly, a case study of a tested shelter is used to develop a detailed finite element modeling (FEM) approach to be validated based on the available test results.

Standards for Tornado and Hurricane Resistant Shelters

Introduction to FEMA and ICC Documents - In May 2002 the International Code Council (ICC) and the National Storm Shelter Association (NSSA) initiated a joint project to write a standard for the design and construction of storm shelters. Currently, there are two standards (FEMA and ICC) that are used for the design and construction of tornado shelters. FEMA P-361 was the first standard released in July 2000, which set forth comprehensive design and construction criteria for tornado and hurricane shelters. Since then, two new editions of FEMA- P361 have been published to incorporate the changes in codes (IBC, IRC, ASCE 7 and ICC 500) and the lessons learned through post-disaster investigations. The second edition of FEMA P-361(2008) that was published in 2008, updated and expanded the recommendations by referencing much of ICC 500 (2002). The third edition of FEMA P-361 (2015) was published in March 2015.

Development of FEMA Safe Room Guidance - When natural catastrophic events like tornado,hurricane, or earthquake take place, the Federal Emergency Management Agency (FEMA) usually deploys a technical team of experts to document the performance of structures during such events. The objective of such teams is to observe and assess the performance of structures and evaluate the design and construction practices in the affected regions. Based on the evaluation results, the teams then make recommendations to improve the performance of buildings in future disasters. In 1998, using the results of research conducted by the National Wind Institute (NWI) of the Texas Tech University, FEMA published "Taking shelter from the storm: Building a Safe Room for Your Home or Small Business (FEMA P-320 (2014)", which included constructions plans for small in-residence safe rooms.

Design Criteria of FEMA P-361 - The purpose of ICC 500 (2008) is to establish minimum requirements for the design, construction and installation of storm shelters, while FEMA P-361(2015) is more conservative, and its main purpose is to provide near absolute protection.

Design Wind Speed - ICC 500 recommends the design wind speed for tornado shelters should be in accordance with Figure 304.2(1) of ICC 500, while since FEMA P-320 (2014) is more conservative, it recommends the design wind speed of the shelters should be 250mph, regardlessof the location.

Development of ICC 500 - In 2003, ICC in partnership with the National Storm Shelter Association (NSSA) and FEMA formed a national committee to develop a standard to codify thedesign and construction requirements of tornado and hurricane storm shelters. The main purpose of ICC 500 (2008) is "to establish minimum requirements to safeguard the public health, safety, and general welfare relative to design, construction, and installation of storm shelters constructed for protection from high winds associated with tornadoes and hurricanes" [ICC 500 Section 101.1]. The scope of ICC 500 includes the design, construction, installation, and inspection of storm shelters. The storm shelters included in ICC 500 may be (separate) detached buildings or rooms and areas within buildings. Shelters designed and constructed using ICC 500 shall be designed as either hurricane shelters, tornado shelters, or combined hurricane and tornado shelters.

ICC 500 Design Criteria

ICC 500 (2008) proposes design criteria for different types of loads: 1) Rain Load, 2) Roof Live Load, 3) Hydrostatic load, 4) Wind Load, and 5) Atmospheric Pressure Change. The rain load to be applied on the storm shelters should be in accordance with ASCE 7. However, for hurricane shelters, rainfall rate should be determined by adding a rate of 3 inches of rainfall per hour to the rainfall rate obtained from ASCE 7.

The roof live load for the tornado shelters shall be based on the minimum live loads specified in ASCE 7. However, for a tornado shelter, the roof live load should not be less than 100 pounds per square foot.

Buoyancy and hydrostatic loads should be considered when designing underground portions of the storm shelter. While designing underground portions of the storm shelter, it should be assumed that the ground water level is at the surface of the ground, unless adequate drainage is available. Design wind loads for the storm shelters should be determined using Method 2, from section 6 of ASCE 7 (2016) with a few exceptions: The design wind speed for the tornado shelters should be obtained from the wind speed maps. The wind directionality factor (K_d) and the importance factor (I) should be taken as 1.0. Exposure Category C shall be used to determine wind pressure on tornado shelters. The topographic factor (K_{zt}) for tornado shelters should not exceed 1.0. Section 6.2 of ASCE 7 should be used to determine the enclosure classification of the tornado shelter. Anadditional internal pressure due to atmospheric pressure change should be considered for tornado shelters that are classified as enclosed buildings. Pressure coefficient (GC_{pi}) shall be taken as ± 0.18 when 1 square foot of venting area is provided per 1000 cubic foot of interior shelter volume. Moreover, for tornado shelters classified as partially enclosed, an internal pressure coefficient of ± 0.55 shall be used.

Design Criteria for Wind Borne Debris

All tornado shelters should be designed to resist the impact of windborne debris during a tornado. A 15pound sawn lumber 2 by 4 is directed at the shelter to test the shelter for protection against debris impact during a tornado. Walls, doors and other surfaces of the shelter that are inclined 30 degrees or more from the horizontal are considered as vertical surfaces, and surfaces inclined lessthan 30 degrees are treated as horizontal surfaces. For the portions of the tornado shelter that are covered with soil, if the horizontal surface of the shelter is protected with less than 12 inches of soil cover and the vertical surface of the shelter is protected with less than 36 inches of soil cover, then these surfaces are needed to be tested for resistance to missile perforation.

Missile Impact Testing - Specimens of tornado shelter should be impact tested with a test missile of 15pound sawn lumber 2 by 4. The wood density, including moisture content should be such that the required 15 ± 0.25 -pound weight is met with a length of 13.5 feet ± 6 inches. Any common softwood lumber species as defined by DOC PS 20 can be used as a test missile. The lumber used as a test missile must be free of splits, checks, wane, or other defects and must be grade stamped No. 2 or better. The device used for measuring missile speed must be capable of measuring the velocity to within ± 1 foot per second. The angle of impact of the test missile mustbe within 5 degrees normal to the primary plane of the test specimen.

Pass/Fail Criteria for Missile Impact Tests - Perforation, dislodgement and disengagement, spall and permanent deformations are the four criteria that are used to identify if the storm shelter can provide protection during a tornado.

Perforation - If the missile impact tested samples have perforation in the interior surface by the design missile, then the component is considered to have failed the test.

Dislodgement and Disengagement - The load bearing fasteners used for holding the storm shelters in place must not get dislodged or disengaged, as it would endanger the safety of the occupants. During testing, a rigid frame with #70 unbleached kraft paper is installed within 5 inches of the interior surface of the shelter component; if the dislodgement fails to perforate the kraft paper, then the dislodgement is considered as harmless.

Spall - During testing, excessive spall should not be released from the specimen. Spall in a specimen is considered to be excessive when it leads to perforation in a #70 unbleached kraft paper that is secured to a rigid frame 5 inches away from the specimen.

Permanent Deformation - Permanent deformation of the test specimen is determined by measuring the distance from a straight edge held between two undeformed points on the specimen. The maximum permanent deformation must be measured to the nearest 1/8 inch and must not exceed 3 inches.

Wind Loading on a Shelter during a Tornado

Based on the design criteria provided by ICC 500 (2008) and FEMA (P-361, 2015), the wind pressure on a tornado shelter during an EF5 tornado with wind speed of 250 mph is calculated using equation (26.10.2) in ASCE 7-16. The wind pressure on the tornado shelter during an EF5 tornado per FEMA (P-361, 2015) guidelines is shown in Table 1. The negative sign means that the pressure acting on the surface is suction. The positive sign indicates an inward pressure on the surface of the wall.

Surface	Pressure (psf)
Windward wall	167.28
Leeward wall	-132.6
Side wall	-155.72
Roof	-225.08

Table1. Wind force on the shelter

Using CLT Panels for Constructing Tornado Shelter

CLT is an engineered wood product that is gaining popularity as an alternative to concrete and steel in construction of residential and commercial buildings. CLT panels are formed by stacking layers of wood in orthogonal directions and gluing them together using a hydraulic press. The orthogonal structure of CLT panels allows the panel to be able to resist in-plane and out-of-plane loading, which makes CLT panels suitable to be used as walls, floors, and roofs.

One of the advantages of using CLT is that it is environmentally friendly, as timber acts as a carbon sink through conversion of CO_2 to biomass and in the process of bio- sequestration via photosynthesis. Another advantage of using CLT is that we can incorporate the use of lower grade wood in the CLT panel. Furthermore, because it is possible to identify the lamellae visually and mechanically, we can use the lower classes of wood in the middle laminations of the panel wherethe tension and compression forces are less.

Tornado shelters made up of CLT were tested at the Forest Product laboratory (2019). Different configurations of CLT panels were tested for wind loading and impact resistance as per the guidelines provided by ICC/NSSA -500 (2008). Results from the tests indicate that CLT tornado shelters made up of four ply walls can safely withstand the most severe impact test included in theICC/NSSA -500 standard. The aim of the study reported here is to build a SAP 2000 model of a CLT shelter described in Falk et al. (2019), subject the model to wind loads at tornado level, and compare the results with lab test results reported in Falk et al. (2019) to validate the model.

Layout of the Lab Tested Tornado Shelter

The tornado shelter tested in Falk et al. (2019) was made up of five 8ft X 8ft CLT panels with 5.5-inch thickness. The CLT panels were made up of V1 grade CLT with four laminations oriented orthogonally. Angle bracket connectors made up of 14-gauge steel angles with 4 in. x 4 in. legs were used to connect perpendicular walls of the tornado shelter. These 4 in. x 4 in. angle brackets were attached at each inside

corner of the shelter with 3/8-by 3-inch lag bolts predrilled 8-inch oncenter. Hold-downs made up of 13 inch long, 2 inch wide and ¼ inch thick A36 steel bar bent in L-shape were used to connect the walls of the shelter to the concrete floor slab. Each hold-down was attached to the tornado shelter using five 3/8 by 3-inch long lag bolts, and each hold-down had a ¾-in diameter through hole on the shorter leg for anchoring to the foundation.

Defining CLT Material Properties in SAP 2000

Shear Analogy method (Kruzinger, 1995) is used to define the properties of CLT panel in SAP 2000. This method that is applicable for solid panels with cross layers where the load is perpendicular to the panel takes into account the shear deformations of the cross layers in the CLT panels when force is applied perpendicular to the panel. The method is not limited to the number of layers within the panel. According to Blass and Fellmoster (2004), the shear analogy method is the most precise design method for CLT panels. This finding was confirmed by tests performed at FPInnovations. It is used with the help of a plane frame analysis program, to consider different moduli of elasticity and shear moduli of single layers for nearly any system configuration (e.g., number of layers, span-to-depth ratio). Based on the literature review, it was determined that shear analogy method is appropriate to model a CLT panel in SAP 2000. Hence, shear analogy method as described in Bless and Fellmoster (2004) is used to create a model of CLT panel in SAP 2000 in this study.

The tornado shelter tested in Falk et al. (2019) is made up of CLT panels with dimension 8ft X 8ft and 5.5 inches thick. The CLT panel used for tornado shelter in Falk et al. (2019) was made up of four laminations with total thickness equal to 5.5 inches. With respect to FEM, as the thickness of the CLT panel is 5.5 inches, thin shell element was used to model the CLT panel. Given that the material properties of CLT change with direction, orthotropic shell element was used to define the CLT panel. Link elements were used to define the stiffness of bolts connecting the panels together (wall to wall and wall to roof). As discussed earlier, the effective bending and shear stiffness of 4- ply CLT panel was calculated using the Shear Analogy method and assigned to thin orthotropic shell element in SAP 2000. Using the Shear Analogy method, the bending stiffness in the major strength direction (EI_{major}) is 103 X 10⁶ lb-in²/ft, while the bending stiffness in the major direction (GA_{major}) is 80 X 10⁴ lb/ft, while in the minor direction (GA_{minor}) is 89 X 10⁴ lb/ft.

Defining Stiffness of Connections in the Tornado Shelter

Vertical and horizontal truss elements with 2- nodes (6 Degree of Freedoms) are used to define thestiffness of the angle brackets and the hold-down connections, which connect the wall panels to each other and to the concrete floor. The horizontal stiffness of the connections is computed based on the slip modulus at serviceability limit state of each fastener. The equation for slip modulus is obtained from Table 7.1 of the 2004 edition of Eurocode 5. The metal plate to concrete connection is assumed to be rigid for the wall to concrete slab connection. Figure 1 shows the configuration of the steel angle bracket and the bolts, while Figure 2 shows the deformed shape of the configuration when force is transferred from the CLT panel to the steel angle bracket. Figures 1 and 2 are plan view of the tornado shelter where two orthogonal CLT panels connect.



Figure 1. Configuration of the steel angle bracket (plan view)



Figure 2. Deformed shape of the angle bracket (plan view)

From the deformed shape of the angle bracket, it can be concluded that we need to determine the shear and axial stiffness of the bolts, and stiffness of the angle bracket to calculate the effective stiffness of the configuration. The axial stiffness of the bolt is calculated using AISC, (2016). The shear stiffness of the bolt is calculated using the equation for slip modulus in Table 7.1 of Eurocode 5, (2004). A model of the angle bracket was analyzed in SAP 2000 to calculate the stiffness of the angle bracket. Finally, the effective stiffness of the system shown in Figure 2 is calculated by considering the stiffness of the angle bracket and the axial stiffness of bolt 2 in series and this assembly is parallel to the shear stiffness of bolt 1. The stiffness configuration is shown in Figure 3. The axial and shear stiffness of the bolts is calculated using the following equations:

 $K_{axial} = (EA)/L = 1.06 X 10^6 lb/in.$

 $K_{\text{shear}} = K_{\text{slip}} = 2\rho_{\text{m}}^{1.5} d/23 = 54887 \text{ lb/in.}$ (Table 7.1, Eurocode 5, 2004).

As mentioned before, a model of the angle bracket was analyzed in SAP 2000. A 1000 lb force was applied on the model, and the resulting deflection of the angle bracket was found to be 0.49 in. Thus, the stiffness of angle bracket was noted to be 2047 lb/in. The effective stiffness of the configuration was then calculated by using the formula for springs in parallel and springs in series. Based on the stiffness configuration, the effective stiffness of the angle bracket connection is K =56930 lb/in. Similar procedure was used to calculate the effective stiffness of the angle bracket when forces were applied in different directions.

The effective stiffness of the hold-down connections used to connect the CLT walls to the concrete floor was calculated using the same procedure. The configuration of the hold-down connection is shown in Figure 6. As shown in the figure, five bolts are attached to the CLT panel and one bolt is attached to the concrete floor because of two reasons: (1) the uplift force on the shelter during a tornado is higher than the shear force, and (2) the flexural stiffness of the bolt is much smaller than the axial stiffness of the bolt. The effective stiffness of the hold-down connection was calculated to be 59234 lb/in. The effective stiffness of the angle bracket and the hold-down connections were then assigned to the truss elements in SAP 2000. The final configuration of the tornado shelter model is shown in Figure 5.



Figure 3: SAP 2000 model of the tornado Shelter.







Figure 5: Final configuration of the tornado shelter

Comparing Deflection of SAP2000 Model with Lab Tested Tornado Shelter

Based on Falk et al. (2019) report, lateral wind pressure tests were performed on the walls of the tornado shelter. In the test, the full-size tornado shelter was secured to the floor of the lab and placed adjacent to a strong concrete wall. To simulate a uniformly applied load on the tornado shelter, an airbag was sandwiched between the shelter and the concrete wall. With the help of a regulator pressurized air was delivered to the airbag. Air pressure in the airbag was incrementally increased, and over approximately 2 minutes the pressure was increased to a maximum of 2.3 X design wind pressure. While increasing the air pressure in the airbag, deflection measuring gauges were used to measure the displacement of the shelter

at two upper corners of the shelter (oppositeside from the airbag) designated as SP1 and SP2. MTS 793 software acquired the load and deflection data at a rate of 1Hz. A graph of displacement as a function of wind pressure was obtained from the software. The lab test setup to apply lateral force on the shelter is shown in Figure 7, while the direction of the load applied on the shelter is shown in Figure 8.





Figure 6(a). Configuration of the hold-down connection (front view), X(b) Deformed shape of the hold-down connection (front view).



Figure 7: Lab test setup to apply lateral force on the shelter

Figure 9 shows the deflection of the SAP 2000 model compared to the deflections obtained from the experimental results. From the graph, it can be concluded that up to a pressure of 250 lb/ft², the deflection of the SAP 2000 model is in close agreement with the deflection of the shelter based on experimental results. As the airbag pressure increases above 250 lb/ft², the deflection obtained from experimental results is much higher than the deflection of the SAP 2000 model. This is because the experimental mockup undergoes inelastic deformation under excessively high pressure, while the SAP 2000 model is developed only for linear elastic deformation. Since the maximum pressure that is experienced by a wall during an EF5 tornado is 167 lb/ft², there is no need to consider inelastic deformation while designing for deflection due to wind pressure in a tornado. As the deflection of the SAP 2000 model is in close agreement with the deflection of a CLT tornado shelter during a tornado. Given that excessive deformation can be related to potential impact on the safety of the occupants, the modeling can provide an approach to check for such conditions, e.g., if deflection exceeds 3 in., in this case study. Details of this study can be found in Yadav (2022).



Figure 8. Uniformly distributed load applied on wall of CLT tornado shelter.



Figure 9. Graph comparing the shelter wall deflection in SAP 2000 with experimental results.

Conclusions

The risks to human life and property damage posed by tornadoes are great. In the study reported here, a CLT tornado shelter model was built in SAP 2000 and verified with lab tested results. Design criteria specified in FEMA P-361 (2015) and ICC 500 (2008) were used to calculate the maximum wind pressure acting on the shelter during an EF5 tornado. Based on the design criteria in FEMA P-361 (2015), the maximum pressure acting on a shelter during an EF5 tornado is 167 lb/ft² and the maximum deflection in an 8ft X 8ft tornado shelter should be less than 3 inches. Orthotropic shell elements were used to model the CLT panels in SAP 2000 and truss elements were used to model the connections. The stiffness of the steel angle and hold-down connections were assigned to the truss elements. Similar to the lab tested shelter, a uniformly distributed load was applied to one wall of the shelter and deflection was measured at the opposite two corners. A graph of displacement as a function of wind pressure was obtained from the SAP 2000 analysis and compared with the graph from the lab test to evaluate the potential failure due to flexure. From the comparison it was concluded that the deflection of the SAP 2000 model is in close agreement with the deflection of lab tested shelter up to a uniformly distributed load of 250 lb/ft². As the pressure increases beyond 250 lb/ft², the deflection of the lab tested model is higher than the deflection of the SAP 2000 model, and this is because the SAP 2000 model does not account for inelastic deformations in the connection. According to FEMA P-361 (2015), the maximum pressure experienced by a shelter during an EF5 tornado is 167 lb/ft². Thus, it can be concluded that the SAP 2000 modelling procedure discussed in this paper is capable of reasonably predict the flexural deflection of the shelter walls when

uniformly distributed loads are applied on the shelter. The validation of the FEM will help us built similar models in SAP 2000 for variations of the CLT shelter study presented here.

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References

- American Society of Civil Engineers. (2016). "Minimum Design Loads and Associated Criteria for Buildings or other Structures." ASCE/SEI 7-16.
- Blass H.J., and Fellmoster, P. (2004). "Design of solid wood panels with cross layers" In Proceedings of the 8th World Conference on Timber Engineering, June 2004.
- European Committee for standardization (CEN). (2004). "Eurocode 5: Design of timber structures" Part1-1: General Common rules and rules for buildings. EN 1995-1-1.
- Falk, R.H.; Bridwell, J.J.; Williamson, T.; Black, T. (2019). "Development of a Ready-to-Assemble Tornado Shelter from Cross-Laminated Timber (CLT)" Research paper FPL-GTR-266, WI:US Department of Agriculture, Forest Service, Forest Products Laboratory.
- Federal Emergency Management Agency. (2014). "Taking shelter from the storm." FEMAP-320, 13-30.
- Federal Emergency Management Agency. (2015). "Safe rooms for tornadoes and hurricanes." FEMA P-361, B01-B32.
- Zhou, H., Dhiradhamvit, K., Attard, T. L. (2014). "Tornado-borne debris impact performance of an innovative storm safe room system protected by a carbon fiber reinforced hybrid polymeric-matrix composite", Journal of Engineering structures 59.
- Insurance Information Institute (III). (2022). "Facts + Statistics: Tornadoes and Thunderstorms," <u>https://www.iii.org/fact-statistic/facts-statistics-tornadoes-and-thunderstorms</u>.
- International Code Council (ICC). (2008). "ICC/NSSA standard for the design and construction of storm shelters", American National Standard. 7-17.
- Kruzinger H. (1995). "Mechanically jointed beams and columns.", Timber Engineering.
- National Geographic. (2019). "Tornado Facts and Information," <u>https://www.nationalgeographic.com/environment/article/tornadoes#:~:text=Every%20year%20in%2</u> <u>0the%20United,the%20water%20from%20a%20riverbed</u>.
- Prevatt, D. O., van de Lindt, J. W., Back, E. W., Graettinger, A. J., Pei, S., Coulbourne, W., Gupta, R., James, D., and Agdas D. (2012). "Making the Case for Improved Structural Design: Tornado Outbreaks of 2011," ASCE Journal of Leadership and Management in Engineering, Vol. 12, No. 4, pp. 254-270.
- The Engineered Wood Association. (2018). "Standard for Performance-Rated Cross Laminated Timber", ANSI/APA PRG 320-2018.
- Yadav, R. (2022). "Evaluation of the Performance of CLT Tornado Shelters," Master of Science Thesis, Penn State University, University Park.

State of the Art Review of Building Enclosure Use of Cross-Laminated Timber

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Abstract

CLT panels are a relatively new building material that have been known prominently for their environmental benefits and their strength. However, it is seen that the panels also perform well as a building enclosure system. This gives the panels more use than just the structural elements and can provide other benefits to the structure from an occupant comfort and structure protections standpoint. When looking at CLT panels from this perspective, it is important to see the limitations of the panels and what needs to be overcome in design to ensure a structure will not have any issues in the future. This paper looks at the properties of the panels including air leakage, vapor transport, heat transfer, and sound insulation. Furthermore, the benefits and limitations of CLT panels for such functions are discussed and some recommendations are given from the U.S. CLT Handbook and other sources to see some of the solutions for these issues. Finally, the analysis of an apartment building, Forte Living, in Australia is presented to illustrate how it is designed to overcome the limitations.

Introduction

Early laminated timber began with glulam beams in the late 19th and early 20th centuries (APA 2017). Glulam beams are made by laminating wood boards in a parallel direction to create a large beam that can allow much longer spans than dimensional lumber (APA 2018). In the late 20th century, Europe started to use a new technology known as cross-laminated timber (CLT) (Karacabeyli et al. 2013). CLT is made by changing the orientation of adjacent layers, so the grains are crossed between layers (Younis and Dodoo 2022). This material, when used as a slab or wall panel, is seen to be as strong as concrete or masonry counterparts, but with much less weight (Karacabeyli et al. 2013; Hassan et al. 2019). This property is one of the reasons this product has been gaining popularity in current construction practices (Schenk et al. 2022).

In addition to its strength and light weight, CLT is also of great interest due to the benefits it can provide to the environment. Trees store carbon in the wood and release oxygen back into the atmosphere, a continuous process for trees as they grow. This process allows wood products to have a negative carbon impact on the environment. Therefore, engineered wood products, like CLT, have a large favorable carbon

impact on the environment due to the volume of wood used in the product (Karacabeyli et al. 2013).

Most published documents in the literature have focused on the structural aspects of CLT (Kurzinski et al. 2022), like its use as wall panels and floor/roofs, as well as lateral load resisting elements within a building. There has been very little emphasis on the use of CLT for non-structural aspects such as building enclosure systems and their properties such as resistance to air leakage, vapor transport, heat transfer, and sound transmission (Kukk et al. 2021). While there are many advantages to using the panels in these applications, there are also some disadvantages, e.g., air leakage (Martin et al. 2019). There are some challenges to CLT use in building science that will be discussed in later sections.

Air Leakage

Structures need to be airtight and will likely need an air barrier to meet the requirements of the International Building Code. Air carries heat and moisture with it, which can cause discomfort to the inhabitants and may cause damage to the structure. CLT panels are seen to be airtight, depending on the thickness. One source of air leakage is the connections between panels, which requires special attention to ensure that they are constructed to be airtight. Computer Numeric Control (CNC) machines have allowed for tight tolerances when the panels are being manufactured, allowing for a decrease in the gaps between panels (Evans 2013). Nonetheless, there can still be human errors that can cause air leakages. Additional air leakage can be caused by gaps between boards or cracks that can form in the board from shrinkage in the boards (Continuing Education Center 2020) (Martin et al. 2019, Kukk et al. 2021). Shrinkage in the wood could occur when moisture in the wood will leave the board. where the excess moisture is from the transportation, storage, and construction of the panels, and other factors (Continuing Education Center 2020). One way to reduce the effect of shrinkage is to edge glue adjacent boards, since this will allow the boards to remain attached and reduce any gaps that will cause the air leakage (Skogstad et al. 2011). Other approaches include applying a sealing compound to the joints or using interior drywall to create an air barrier. The sealing compound is similar to the edge gluing except, depending on the material, it could crack over time and need to be replaced over time. Drywall should not be a primary approach, as it is difficult to have a continuous barrier in the interior (Karacabeyli et al. 2013).

With CLT panels, other measures should be added so if there is a failure, such measures will give additional protection to the structure. The CLT Handbook (Karacabeyli et al. 2013) states that a continuous air barrier should be included, as the wood can create gaps in the panel due to shrinkage after a couple of years and are not reliable. Another measure mentioned is to use drywall on the interior, which will be somewhat airtight. It is not known if the panels are going to remain reliable throughout their life, but it is best to have another layer of air barrier. Accordingly, an air barrier should be applied around the structure to best protect the structure to ensure the comfort of the occupants and prevent any heat loss due to air leakage. The

CLT Handbook (Karacabeyli et al. 2013) states that a water resistive barrier can serve as an air barrier.

Vapor Transport

CLT panels can act as a vapor barrier when thick enough. According to the Swedish CLT Handbook (Swedish Wood 2019), panels that have more than 5 layers or are thicker than 2.75 inches can act as a vapor retarder. However, as mentioned before, the joints would need to be designed to be airtight to keep the moisture from passing through. The issue with making the panel thick is that the thicker panel adds a lot of unnecessary weight to the building. In addition, leaving the panels unprotected will cause the panels to be susceptible to the long-term effects of moisture (Strang et al. 2021). When exposed to moisture, wood will have its properties changed if it is below the fiber saturation point, which is found to be on average 28-30% (Karacabeyli et al. 2013). When manufactured, panels must be at a moisture content of $12\%\pm3\%$ (APA 2019). Some changes could be dimensional, as the wood swells and shrinks to changes in the moisture, and changes to the strength and thermal properties of the wood (Karacabeyli et al. 2013).

The U.S. CLT Handbook (Karacabeyli et al. 2013) recommends that the panels have a water resistive barrier (WRB) to reduce the amount of liquid water that can be absorbed by the CLT. This barrier is recommended to be vapor-permeable membrane, or a medium to high permeance membrane, is recommended to allow the panels to dry from any moisture. When the panels are constructed, they are required to be at 12%±3% to make sure there are no complications with the adhesives bonding to the laminations (APA 2019). After the manufacturing, the panels moisture content can change in the construction and transportation phases since the storage of the panels is not perfect and will cause the moisture to enter the panel. A vapor permeable membrane would allow the excess moisture to pass through and allow the panel to dry. This is a more efficient method of drying the panel than an inward vapor drive due to the thickness of the panel (Karacabeyli et al. 2013). If an impermeable membrane is used, the moisture would remain in the panel and cause rot and microbial growth within the wood (Swedish Wood 2019).

Another method to make sure the panels dry properly is to add an airspace to the wall section (Karacabeyli et al. 2013). The additional ventilation will help the panels dry and prevent too much moisture from accumulating in the panel. Providing this cavity, along with a water resistive barrier, reduces the amount of liquid water that will be in contact with the panel since the water will follow the drainage plane along the wall. The vapor permeance of the WRB would allow the panels to dry if there is too much moisture in the panels, decreasing the chance that rot and microbial growth would occur. The WRB is typically seen to be placed on the exterior side of the CLT panel, as this will protect the wood from the outdoor environment (Karacabeyli et al. 2013).

As an example, an Australian building called Forte Living uses a metal façade, a metal coating, and hardwood timber to provide a rain screen to the building. There is

also a cavity between the rain screen and panels to allow the panels to dry (Wood Solutions 2020). In general, this structure uses the same recommendations as the Handbook states. The designers made sure that the panel is capable of drying, even after the panel is installed.

Heat Transfer

Related to heat transfer, a CLT panel has two different properties: its high thermal resistance and its ability to act as a thermal mass (Matrinez et al. 2018). Starting with the thermal resistance, the thermal conductivity of wood is much lower than steel or concrete. North American softwood species typically have a thermal resistance of about R-1.2 per inch (Continuing Education Center 2020, Karacabeyli et al. 2019). For a 10-inch CLT panel, the R-value is approximately 12, which would require additional insulation to meet the minimum insulation requirements, which fall between R-15 and R-31 (Continuing Education Center 2020). For walls, exterior insulation is recommended, as this will protect any critical points on the panel, like joints, from the extreme temperatures. In addition, a vapor-permeable insulation should be used on the exterior to decrease the risk of condensation inside the assembly. Keeping the insulation on the exterior will allow the CLT panel to remain at the indoor temperature and minimizing any thermal or moisture fluctuations that the outdoors can cause (Continuing Education Center 2020). Figure 1 shows an example of a wall using exterior insulation. Interior insulation can also be added to improve the energy performance of the wall. The CLT wall assembly does not have too many thermal bridges compared to other construction materials. Thermal bridges usually occur from any cladding attachments (Continuing Education Center 2020). Figure 1 has a nail attaching the cladding that causes a very small thermal bridge effect, when compared to other materials like steel or wood studs that are associated with large thermal bridges. Other cross sections of walls with a CLT panel, there is an airspace between the exterior insulation and the panel to allow any moisture that makes it through the insulation to drain down the panel instead of being absorbed by the panel.



Figure 1: Exterior wall detail (Photo Credit: FPInnovations; used with permission)

When considering the thermal mass property, CLT panels have a high heat capacity and a low density (Swedish Wood 2019). This means that the panel will absorb some heat in the daylight hours and release it at night. This helps with energy performance since the panel is releasing some heat, lowering the amount of energy needed to generate heat. The thermal mass or storage property of the panels is beneficial in mixed climate areas since the slabs will help with energy savings in the colder months by generating its heat. This property, however, varies depending on a couple of factors, such as the thickness of the panel and the species of the wood.

Sound Insulation

Cross-laminated timber panels provide some sound insulation in a structure (Lin et al. 2021). However, it does not meet the minimum requirements of the International Building Code, which has requirements for limiting sound transmission and impact transmission in both a laboratory-controlled setting and the panel installed in the field. Laboratory tests determine the Sound Transmission Class (STC), which follows ASTM E90 and E413, and Impact Insulation Class (IIC), which follows ASTM E492 and E989, in a controlled environment (Karacabeyli et al. 2013). Field tests determine the same values, except in an actual building where flanking transmission is present. Flanking transmission is a sound path that is not the direct path, such as through a door or window (Karacabeyli et al. 2013). Field tests follow different ASTM standards from before depending on which rank is being determined (Karacabeyli et al. 2013). These values are a unitless rank of how the assembly performs and allows for a comparison of how different materials perform, where the higher the value, the better the insulation. Looking at the sound transmission in a controlled environment from the U.S. CLT Handbook, a CLT panel's sound insulation depends on the thickness of the panel, where the walls can have a sound transmission class of 32-34 for a 3.74-4.53-inch panel (Karacabeyli et al. 2013). Floors were seen to have a sound transmission of 39 for a 5.31- and 5.75-inch-thick slab (Karacabeyli et al. 2013). The

impact transmission for the same two floors was seen to be 23 and 24, respectively. These do not meet the standard for the IBC, which requires a minimum of 50 for STC and IIC and a minimum of 45 for these values tested in the field (ICC 2020). Therefore, there needs to be more materials added to the floors and walls to reduce the sound transmission.

To solve flanking transmission, the best method is to make wall panels unconnected. Flanking transmission occurs in multiple ways, like sound traveling through electrical outlets or traveling through wall and floor junctions (Karacabeyli et al. 2013). One way to decrease flanking transmission is to make structural elements discontinuous. This could be done by using a floating floor or making the elements discontinuous and putting a seal between the elements. Other methods include being very careful with the design and construction of the structure by paying attention to the electrical outlets or checking and sealing any cracks in the panels. All these methods help to reduce the flanking transmission and, as a result, will increase the rating of the sound insulation.

To reduce the sound transmission through a wall or floor, more material, such as insulation or gypsum board, or spaces, such as an airspace would be needed. According to the CLT Handbook (Karacabeyli et al. 2013), there are wall sections that include a CLT panel at the center and studs and gypsum on either side of the panel to increase the thickness. There are various other configurations and details for walls, such as using thick CLT panels and gypsum board to increase the sound insulation. Figure 2 shows an example of an interior wall with a CLT panel. The materials used can be seen and shows that these materials help to decrease the sound transmission, since the field STC of 47 is greater than the required 45 (Karacabeyli et al. 2019, ICC 2020). For floors, the same sections are used and may include mineral wool in between two slabs. There may also be a suspended ceiling, which will decrease the sound significantly due to existence of a large airspace above. Figure 3 shows a floor section that includes a suspended ceiling that is filled with insulation. This is seen to greatly increase the sound insulation, as both the field STC and IIC are 53 and are greater than the required 45 (Karacabeyli et al. 2019, ICC 2020). These methods are utilized to decrease the sound and impact transmission through the floors and walls.



- 1. 15.9-mm thick Type X gypsum board
- Type RC-1 (one leg) 25-gauge resilient channels at 600 mm O.C.⁽¹⁾
- 3. 78-mm thick CLT
- 25-mm thick air gap filled with rock fibre insulation (Roxul-AFB[®])
- 5. 78-mm thick CLT
- Type RC-1 (one leg) 25-gauge resilient channels at 600 mm O.C.⁽¹⁾
- 7. 15.9-mm thick Type X gypsum board

Figure 2: Wall with a field STC of 47 (Photo Credit: FPInnovations; used with permission)



- 1. 10-mm thick laminated flooring
- 3.5-mm thick rubber membrane (InsonoFloor)
- 3. 175-mm thick CLT
- 100-mm high sound isolation clips (RSIC-1ADM[®] Multi-Clip)
- 5. Metal hat channels
- 6. Rock fibre insulation (Roxul-AFB®)
- 7. 15.9-mm thick Type X gypsum board
- 8. 12.7-mm thick Type X gypsum board

Figure 3: Floor with a suspended ceiling with field STC and IIC of 53 (Photo Credit: FPInnovations; used with permission)

Forte Living uses some of the techniques mentioned before. The walls use plasterboard to help insulate the sound between apartments, similar to what the CLT Handbook recommends (Wood Solutions 2020). Figure 4 shows a wall section that seems to be similar to what is used. This wall gives a field STC of 54 (Karacabeyli et al. 2019). The floors use a concrete screed, plasterboard, a suspended ceiling, and insulation in the suspended ceiling to reduce airborne sound transmission and impact transmission (Wood Solutions 2020). This technique is similar to some of the solutions given from the CLT Handbook (Karacabeyli et al. 2013). The difference is the use of a concrete screed to reduce the transmission. This layer is probably used to reduce the impact transmission since concrete already has the desirable property of reducing the sound of an impact.



- 1. 15.9-mm thick Type X gypsum board
- 2. 38-mm x 64-mm wood studs at 400 mm O.C.
- 3. 64-mm thick rock fibre insulation (Roxul-AFB®) in wall cavity
- 4. 12.7-mm thick air gap
- 5. 3-ply 105-mm thick CLT
- 6. 12.7-mm thick air gap
- 7. 38-mm x 64-mm wood studs at 400 mm O.C.
- 8. 64-mm thick rock fibre insulation (Roxul AFB®) in wall cavity
- 9. 15.9-mm thick Type X gypsum board

Figure 4: Wall section detail similar to Forte Living walls (Photo Credit: FPInnovations; used with permission)

Conclusion

Designers are beginning to evaluate and consider the use of CLT panels as a building enclosure system. For such use, it is necessary to establish that once installed, CLT panels can provide the functions expected from a building enclosure system, e.g., air barrier, vapor retarder, thermal and sound insulation, and impact resistance, to name a few. Issues with these systems arise when the panel develops cracks from changes in moisture. Therefore, CLT panels require other materials to help perform these functions reliably and to meet the minimum requirements set by the International Building Code. When comparing CLT's building enclosure properties to other structural materials, such as concrete or steel, CLT performs just as well as concrete and does not provide as much of a thermal bridge as steel. CLT's properties to act as a vapor barrier, thermal mass, and remain airtight make it comparable to concrete, where the major difference is weight between the two materials. With these properties, CLT's use in buildings could expand beyond a structural aspect and include building science.

References

- APA -- The Engineered Wood Association, (2018). "Glulam in Residential Buildings - Construction Guide," Form No. X450, <u>www.apawood.org</u>.
- APA The Engineered Wood Association, (2019). "ANSI/APA PRG 320-2019 Standard for Performance-Rated Cross-Laminated Timber." APA – The Engineered Wood Association.
- Continuing Education Center, (2020). "Embracing the Timber Age," VaproShield. <u>https://continuingeducation.bnpmedia.com/courses/vaproshield/embracing-the-timber-age/</u>, Visited Site on 8/21/2021.
- Evans, L., (2013). "Cross Laminated Timber: Taking Wood to the Next Level," ReThink Wood. <u>https://www.awc.org/pdf/education/mat/ReThinkMag-MAT240A-CLT-131022.pdf</u>, Visited Site on 8/19/2021.
- Hassan, O. A. B., Oberg, F., and Gezelius, E., (2019). "Cross-laminated timber flooring and concrete slab flooring: A comparative study of structural design, economic and environmental consequences," Journal of Building Engineering, Vol. 26, November 2019, 100881.
- (ICC) International Code Council, (2020). "2021 International Building Code (IBC): ICC Digital Codes." <u>codes.iccsafe.org/content/IBC2021P1</u>, Visited site on 8/18/2021.
- Karacabeyli, E. and Douglas, B., (2013). "CLT Handbook Cross-Laminated Timber, U.S. Edition," FPInnovations and Binational Softwood Lumber Council.
- Karacabeyli, E. and Gagnon, S. (2019). "Canadian CLT Handbook 2019 Edition," FPInnovations. <u>https://web.fpinnovations.ca/wp-content/uploads/clt-handbook-complete-version-en-low.pdf</u>, Visited Site on 9/8/2021.
- Kukk, V., Bella, A., Kers, J., and Kalamees, T., (2021). "Airtightness of Cross-Laminated Timber Envelopes: Influence of Moisture Content, Indoor Humidity, Orientation, and Assembly," Journal of Building Engineering, Vol. 44, December 2021, 102610.

- Kurzinski, A., Crovella, P., and Kremer, P., (2022). "Overview of Cross-Laminated Timber (CLT) and Timber Structure Standards Across the World," Mass Timber Construction Journal, Vol. 5, pp. 1-13.
- Lin, J.-Y., Yang, C.-T., and Tsay, Y.-S., (2021). "A Study on the Sound Insulation Performance of Cross-Laminated Timber," MDPI Materials, Vo;. 14, No. 15, 4144, doi: <u>10.3390/ma14154144</u>.
- Martin, U., Blanchet, P., and Potvin, A., (2019). "Modeling the Impact of Assembly Tolerance Regarding Air Leaks on the Energy Efficiency and Durability of a Cross-Laminated Timber Structure," BioResources, Vol. 14, No. 1, pp. 518-536.
- Matinez, J. E., Alonso-Martinez, M., Rabanal, F., P., A., and Diaz, J. J. d. C., (2018). "Study of the Influence of Heat Transfer of a CLT Beam through FEM," Journal of Physics Conference Series, 1107, 032003, 6p., doi :10.1088/1742-6596/1107/3/032003.
- Schenk, M., Hubner, C., and Cabrero, J. M., (2022). "Cross-Laminated Timber: A Survey on Design Methods and Concepts in Practice," MDPI CivilEng 2022, Vo;. 3, No. 3, 610-629, <u>10.3390/civileng3030036</u>.
- Skogstad, H. B., Gullberkken, L., and Nore, K., (2011). "Air Leakages through Cross Laminated Timber (CLT) Constructions," <u>https://www.treteknisk.no/resources/filer/publications/Air_leakages_in_cross_laminated_timber_constructions_28022011_docx_xy7tg.pdf</u>, Visited site on 8/20/2021.
- Strang, M., Leardini, P., Brambilla, A., and Gasparri, E., (2021). "Mass Timber Envelopes in Passivehaus Buildings: Designing for Moisture Safety in Hot and Humid Australian Climates," MDPI Buildings, Vol. 11, No. 10, 478, <u>https://doi.org/10.3390/buildings11100478</u>.
- Swedish Wood. (2019). "The CLT Handbook." Wood Solutions (2020). "Forte Living." <u>http://www.woodsolutions.com.au/inspiration-case-study/forteliving</u>, Visited site on 8/18/2021. Younis, A. and Dodoo, A., (2022). "Crosslaminated timber for building construction: A life-cycle-assessment overview,: Journal of Building Engineering, Vol. 52, July 15, 2022, 104482.



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