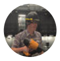
Human Factors of High Performance Multifamily Housing

Conference Paper · January 2019

6 authors, including:



Philip Agee
Virginia Polytechnic Institute and State University
17 PUBLICATIONS **95** CITATIONS

Dong Zhao
Michigan State University
71 PUBLICATIONS **850** CITATIONS

Frederick Paige
Virginia Polytechnic Institute and State University
11 PUBLICATIONS **11** CITATIONS

Andrew P Mccoy
Virginia Polytechnic Institute and State University
76 PUBLICATIONS **675** CITATIONS

Human Factors of High Performance Multifamily Housing

Philip Agee, M.Eng.
Student Member ASHRAE

Andrew McCoy, Ph.D.

Georg Reichard, Ph.D.
Member ASHRAE

Brian Kleiner, Ph.D.

Dong Zhao, Ph.D.

Fredrick Paige, Ph.D.

ABSTRACT

Buildings are complex systems, yet architecture, engineering, and construction (AEC) professionals often perform their work without considering the human factors that affect the operational performance of the building system. The AEC industry currently employs a linear design and delivery approach, lacking verified performance standards and real-time data feedback once a certificate of occupancy is issued. We rely on static monthly utility bills that lag and mask occupant behavior. We rely on lawsuits and anecdotal business development trends as our feedback mechanisms for the evaluation of a complex, system-based product. The omission of human factors in the design and delivery of high performance building systems creates risk for the AEC industry and has contributed to projects missing their performance targets. Neglecting an iterative, human-centered design and delivery approach inhibits our ability to close the industry's performance gap and relinquish its position as the top energy consuming sector. To close this gap, a multi-methods research design is employed to answer applied research questions that will serve as a vehicle to identify and jointly optimize human-building relationships. Specifically, this study reports findings from a multi-year study of the construction, and operations of 15 high performance multifamily housing projects in Virginia. Data include 1) originally simulated versus measured energy use data, 2) construction technologies and delivery methods, 3) commissioning procedures, and 4) occupant reported factors including thermostat set points, thermal comfort, appliance use, and user satisfaction with high performance housing. Preliminary findings suggest the use of Human Factors methods can improve our understanding of the construction, operations, and maintenance outcomes of high performance multifamily housing. Results from this work can be shared with AEC professionals to close the post-occupancy performance gap in high performance systems.

INTRODUCTION

Buildings provide a fundamental human need, serving as environmental separators. We construct buildings to provide shelter, keeping outside out, and inside in. Over time buildings have moved beyond their original scope of providing a basic human need. Today, we spend 90% of our lives in buildings (U.S. EPA, 2018; U.S. BLS, 2012). We eat, sleep, work, and recreate in buildings. Simply put, buildings impact humans, humans impact buildings, and buildings impact the environment. For example, buildings consume 20% of worldwide energy (40% of U.S. energy) annually. As we work to improve performance in the built environment, it is critical to improve buildings using a human-centered approach.

This study reports findings from a multi-year study that measured the energy performance and human factors of high performance multifamily housing (HPMFH) developments in Virginia. Over the last ten years, the Virginia Housing Development Authority (VHDA) has utilized green building rating system incentives as a policy vehicle in the Low-Income Housing Tax Credit (LIHTC) program to encourage energy efficiency (EE) in the affordable rental stock in Virginia (Climate Zone 4A). This research addresses key issues related to EE and affordable housing through the

Philip Agee, M.Eng. is a PhD candidate in the Dept. of Industrial & Systems Engineering, **Andrew McCoy, PhD** is a Professor in the Department of Building Construction, **Georg Reichard, PhD** is an Associate Professor in the Department of Building Construction, **Brian Kleiner, PhD** is a Professor in the Dept. of Industrial & Systems Engineering, **Fredrick Paige, PhD** is an Assistant Professfor in the Dept. of Civil & Environmental Engineer at Virginia Polytechnic Institute and State University, Blacksburg, VA. **Dong Zhao, PhD** is an Assitant Professor in the Dept. of Civil & Environmental Engineering at Michigan State University, East Lansing, MI.

measurement of actual, unit-level energy use in 237 apartments across 15 developments. Data are used to evaluate the effects of year to year operation, weather, and human factors on energy use. Data, analysis, and findings focus specifically on facilities constructed and certified to the EarthCraft Multifamily (ECMF) rating system in Virginia, one of the only datasets currently available that allows for this type of inquiry.

BACKGROUND

Multifamily Housing

According to the U.S. EIA (2016), 27% of the U.S. housing stock is comprised of multifamily housing; representing a unique opportunity to evaluate performance outcomes. The literature defines multifamily housing as a residential building with 5 or more housing units that share a common wall, floor or ceiling with another unit (Hendron and Engebrecht, 2010). Architecturally, multifamily design is constrained to simple massing solutions and unit layouts due to building codes, market demand, and economic realities (Larco, 2010). The architectural consistency of multifamily housing affords researchers with a level of sample homogeneity, enhanced reliability, and consistency when isolating statistical correlates of actual energy use, occupant comfort, and technology interaction effects. Further, the multifamily housing market is an interesting, but challenging problem space due to its segmented supply chain and common split financial incentives (McKibbin, 2013).

Multifamily Energy Use

For the past 50 years, heating and cooling has dominated energy consumption profiles in residential buildings, but the times are changing. Federally mandated building codes and industry-led technology innovations have caused occupant-driven loads, rather than enclosure-driven loads, to dominate residential building energy use profiles. The shift of energy end uses is amplified in multifamily housing. Unlike a typical detached single-family house with four or more walls, a foundation and attic enclosure systems exposed to ambient conditions; typical multifamily housing units have one or two exterior walls (if located on the corner of the building) exposed to ambient conditions. The limited enclosure area in multifamily housing translates to decreased energy used to for heating and cooling demand (Lstiburek, 2013; Lstiburek, 2016). Further, the combination of air sealing, duct sealing, the use of LED lighting, Energy Star appliances, efficient heating, cooling and water heating systems promoted in 3rd party energy efficiency programs further shift residential energy-end uses from heating and cooling dominant to occupant driven loads (e.g., water heating and miscellaneous electric loads). As these loads shift, understanding the relationship between the occupant and the broader housing unit as a system will become critical for AEC professionals interested in delivering HPMFH multifamily units (Agee et al., 2018a; Agee et al., 2018b; Parker et al, 2010; Brandemuehl and Field, 2011). As noted, humans are spending the majority of their lives within the built environment, but national and international policies are prioritizing environmental and social sustainability ahead of user well-being, comfort, and satisfaction (Altomonte et al., 2015). While the goal of delivering HPMFH housing is in line with federal and industry goals, a consequence of producing HPMFH creates new, human-centered challenges for AEC professionals.

Human Factors and Ergonomics

Human factors and ergonomics (HF/E) is defined as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, as the profession that applies theory, principle, data, and other methods to design in order to optimize human well-being and overall system performance" (International Ergonomics Association, 2018). The human factors discipline was born out of crisis. World War II led to rapid technological and system developments that tested the physical, physiological, and psycophysical limits of humans. Though the discipline of human factors was developed in the 1940s, researchers began exploring the relationship between human well-being (e.g., indoor environmental quality) and buildings in 19th century as a result of the industrial revolution. The earliest literature focused on improving the human factors of buildings, specifically thermal comfort, is attributed to Tredgold (1824). Belding et al. (1945) developed the "thermal dummy" to evaluate clothing and thermal comfort relationships for the National Research Council. Of course, Fanger's (1972) seminal work on thermal comfort provided the foundation for ASHRAE Standard 55: *Thermal Environmental Conditions for Human Occupancy.*

Human Factors and Ergonomics Methods. The construction industry traditionally approaches project design and delivery in a linear delivery approach. How often are users, such as occupants and/or maintenance staff included in the design process? The human factors discipline places the human at the center of research problems and design challenges. Designing and adapting construction systems for the benefit of humans performance and well being requires us to employ human-centered methods. Specific methods that the authors believe the construction industry could leverage include, but are not limited to; 1) *persona development* of users to reduce the risk of designers designing for their own needs and biases, 2) *function allocation*, characterizing human-machine interactions and assigning modalities of automation, 3) *thermal comfort surveys*, and 4) *semi-structured interviews* to gain critical insights to the usability of controls. Multiple methods can be used at the same time, as well as throughout the project to provide feedback to design teams in an interative manner. Iterative design and research methods focus on a quick design, implementation, evaluation, and analysis process (see Figure 1). The goal is to set system requirements, develop a protoype, gain user feedback, evaluate user feedback and then analysze the design changes to better suit the user needs.

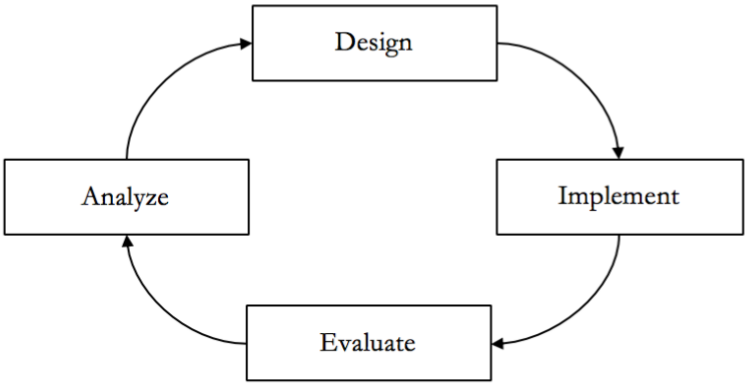


Figure 1 Human-centered design is an iterative process. Figure adapted from Hartson and Pyla, 2012.

Humans and buildings have been and will continue to be, inherently linked, so exploring the human factors of human-building relationships stands to benefit all in industrialized society. Beyond thermal comfort, other relevant HF/E research areas in the built environment include, but are not limited to; safety, work system design, indoor environmental quality (IEQ), usability of technologies/interfaces, and housing needs for senior and handicap populations.

ANALYSIS

The research team collected energy use, technology, and human factors data on 15, all electric HPMFH developments, representing 237 units. Estimated energy use data were collected from unit-level REM/Rate simulations. REM/Rate is a proprietary, asset rating, and static simulation tool used by AEC professionals, specifically HERS Raters, to rate building performance of a modeled home compared to a theoretical reference home that has the same conditioned floor area, massing, and enclosure surface areas. It is important to note REM/Rate is not the only energy simulation tool for residential buildings available to practitioners, but its market penetration, as well as the Department of Energy's (DOE) Zero Energy Ready Program adoption and application for simulating net-zero in the literature suggests its relevance (Christian et al., 2006; Thomas and Duffy, 2013). Observed energy use data were measured at monthly intervals over three years using an online utility benchmarking platform (e.g., WegoWise). Energy use data were weather normalized and analyzed in site energy use intensity (EUI). Technology data were collected from project contract documents and verified against REM/Rate simulations records. Table 1 provides a summary of 1) the sample characteristics, 2) estimated EUI, 3) observed EUI, and 4) energy use descriptive statistics.

Table 1. Sample energy use summary

Division	**Est. EUI** (kbtu/ft^2/yr)	**Obs. EUI** (kbtu/ft^2/yr)	**Diff. EUI**	***N***	**Std Err**	***t***	***p***	**Upper 95%**	**Lower 95%**
Overall	32.25	25.94	6.31	237	.78	8.11	<0.001**	7.84	-4.78
New	29.75	27.23	2.52	96	1.33	1.89	.031	5.17	-.13
Renovated	33.95	25.05	8.89	141	.88	10.10	<0.001**	10.63	7.15
Senior	34.28	28.42	5.86	89	1.16	5.05	<0.001*	8.16	3.55
Non-Senior	31.03	24.44	6.58	148	1.03	6.36	<0.001**	8.63	4.54

Note: Est = Estimated; Obs = Observed; Diff = Difference; N = sample size in apartments, Round-off errors may apply; ** = Significant at 99%.

The authors were surprised to find the simulated (estimated) performance was higher across the sample when compared to the observed energy use data. The team compared the simulation technology, occupancy, and climate assumptions in the simulations and found them to accurately reflect the contract documents. The simulations were generated by a single 3rd party HERS rating organization and could explain some of the consistency in the simulated versus measured results. A future anaylsis of the data will include other common residential simulation tools (e.g., BEopt and Ekotrope).

Finally, human factors were collected by a survey instrument at each of the 15 developments. It is important to note that all data collection and records management followed Virginia Tech's Institutional Review Board Protocol for Research Involving Human Subjects. Human factors varaibles collected and analyzed by the team included behavioral factors, satisfaction, summer temperature setting, winter temperature setting, humidity preferences, dishwasher usage, washer/dryer usage, quality of life, and education on building systems.

RESULTS

Energy Use

Now with three years of longitudinal energy use data, the team evaluated the sample performance between new construction, renovation, senior and non-senior projects. Over 3 years on average, all building types in the sample are statistically correlated with reduced energy usage. Of these building types, and similar to energy usage findings, new construction has the least significant correlation, suggesting areas for future work in design and construction. Overall, sampled units contain an energy use intensity 20% less than estimated. Sampled new construction units contain an energy use intensity 8.4% less than estimated. Sampled renovated units contain an energy use intensity 26.2% less than estimated. Sampled senior units contain an energy use intensity 17% less than estimated. Sampled non-senior units contain an energy use intensity 21.2% less than estimated. Figure 2 demonstrates the sample EUI performance, as well as a comparison of the Virginia and U.S. multifamily EUI averages.

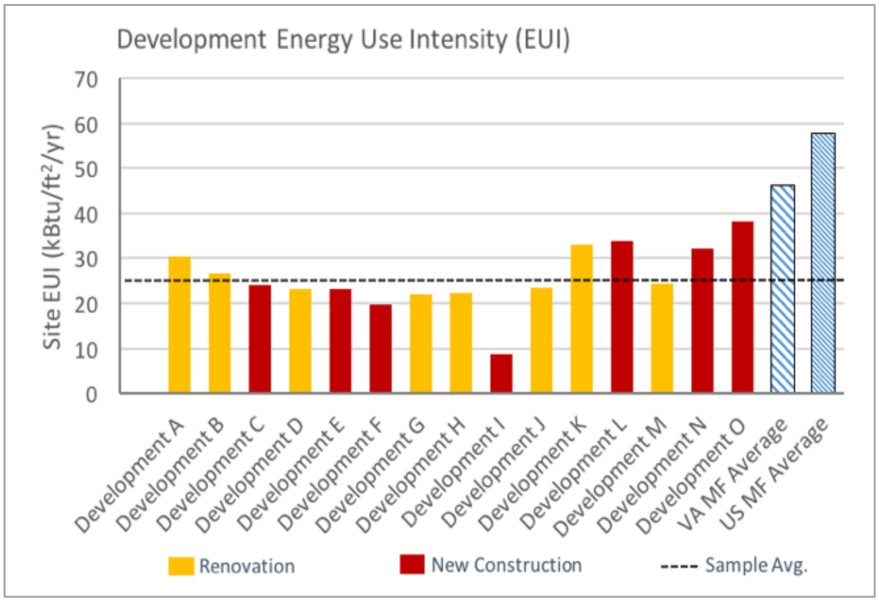
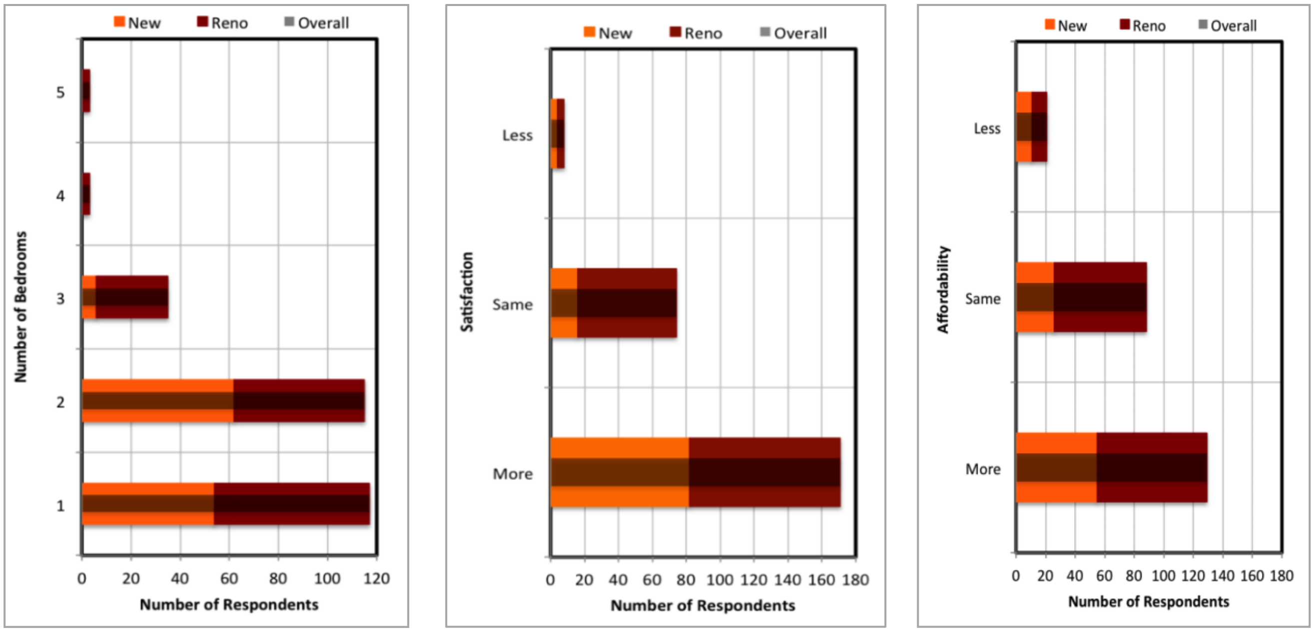


Figure 2 Site EUI performance of the sample from May 2013 to April 2016 by project type. Note, VA MF and US MF Averages were sourced from the U.S. EIA (2016).

User-centered Findings

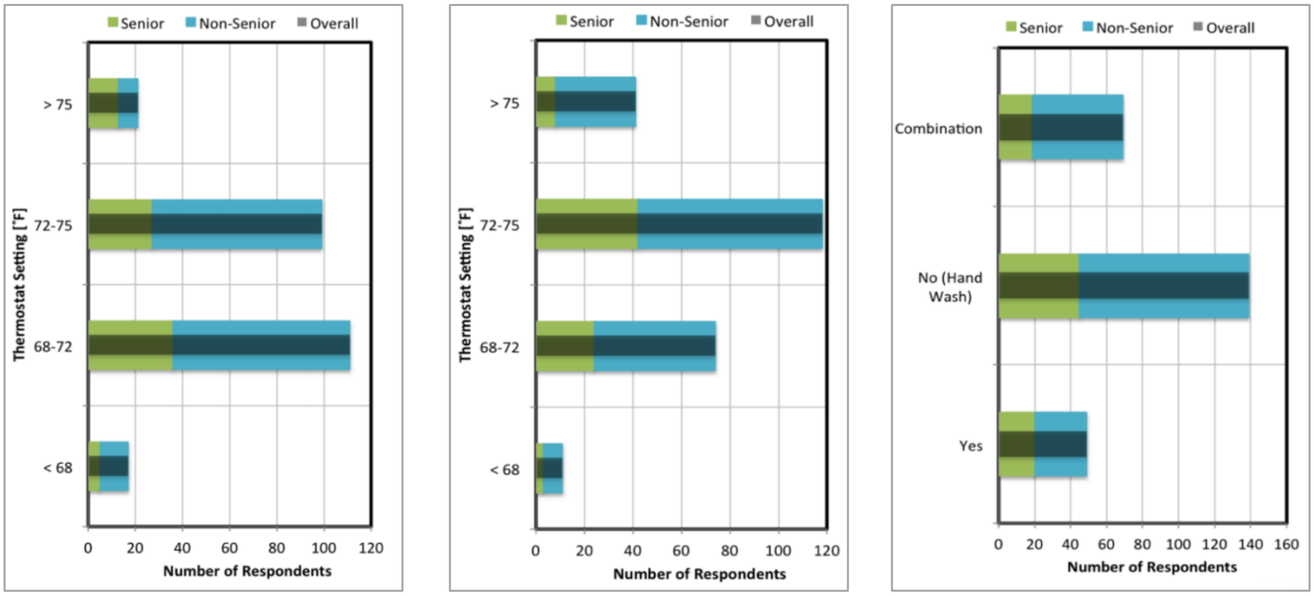
Next, we turn to the human factors of HPMFH. When asked to compare their current HPMFH unit to their previous housing unit, respondents overwhelmingly report greater satisfaction with their housing (see Figure 3a). Not all findings were consistent with the teams' expectations. For example, when asked "Do you use your dishwasher to wash dishes? *Answer bank: Yes, No, Combination of dishwasher and handwash*" the data showed residents in the sample overwhelmingly preffered to hand wash than use their Energy Star rated dishwasher (see Figure 4c). Some respondents stated they handwashed their dishes to save money on their electric bill, demonstrating a disconnect between user understanding of the appliance systems in their apartment.



a) b) c)

Figure 3 (a) bedrooms/apartment across the sample. (b) Occupant satisfaction in HPMHF compared to previous housing. (c) Occupant utility affordability compared to previous housing.

Respondents were also asked to share their preferred thermostat setpoints for both heating and cooling (see Figure 4). The reported thermostat preferences suggest the potential for misalignment between energy simulation protocols and energy code requirements.



a) b) c)

Figure 4 (a) Senior, non-senior, and overall sample summer thermostat set points. (b) Senior, non-senior, and overall sample winter thermostat set points. (c) Occupants in the sample prefer to hand wash their dishes, rather than use their Energy Star dishwashers.

CONCLUSION

This study reported findings from a multi-year study that measured the energy performance and human factors of HPMFH developments in Virginia. The researchers found:

1. The AEC industry could reduce risk, achieve performance goals, and improve user [occupant] experience by leveraging a human factors-based, iterative approach to their project delivery method(s). Specific methods that the industry could employ include, but are not limited to; a) persona development of users to reduce the risk of designers designing for their own needs and biases, b)function allocation, characterizing human-machine interactions and assigning modalities of automation, c) thermal comfort surveys, and d) semi-structured interviews to gain critical insights to the usability of controls.
2. Users such as occupants and maintenance staff of HPMFH housing are rich sources of data that should not be ignored. Their feedback should be collected, evaluated, and analyzed throughout the design, delivery, and operation of the a HPMFH project.
3. Human-centered, post-occupancy performance analysis is a critical component for any project team that aims to deliver HPMFH. User trust must be earned and data privacy standards must be practiced to maintain user trust.
4. HPMFH developments demonstrate sustained energy performance over 3 years post-occupancy; suggesting a benefit from 3rd party rating systems that provide verification, diagnostic testing, and basic commissioning of systems. In order to continue to make progress to reducing energy consumption in the built environment, design teams can maximize investments in technologies by keeping the user in the center of the design and problem space.

The authors continue to investigate the human factors of high performance housing. Current and future research include 1) evaluating how *Persona Development* (a common human-computer interaction method) can be leveraged by AEC designers to assist in the transition to human-centered buildings, 2) User experience and thermal comfort of zero energy housing, and 3) the role of fault detection systems in helping builder-developers prevent moisture related problems.

ACKNOWLEDGMENTS

The authors would like to thank their research partners, the Virginia Center for Housing Research at Virginia Tech, Housing Virginia, and Viridiant for their expertise and support.

REFERENCES

Agee, P., Reichard, G., & McCoy, A. (2018a). "Longitudinal Evidence of Inverter-Driven Heat Pump Performance in Low-Load Residential Buildings." Proc. ASHRAE 2018 Winter Conference. Chicago, IL, 20-24 January.

Agee, P., Reichard, G., McCoy, A., Kleiner, B., & Hamm, T. (2018b). "Closing the Post-Occupancy Performance Gap in Zero Energy Housing." Proc. 4th Residential Building Design & Construction Conference. State College, PA, February 28.

Altomonte, S., Rutherford, P., & Wilson, R. (2015). Human factors in the design of sustainable built environments. Intelligent Buildings International, 7(4), 224-241.

Belding, H. S., Darling, R. C., Griffin, D. R., Robinson, S., & Turrell, E. S. (1945). Evaluation of thermal insulation provided by clothing. In Clothing Test Methods (pp. 9-20). Washington Subcommittee on Clothing of the National Research Council.

Brandemuehl, M. and Field, K. (2011). Effects of Variations of Occupant Behavior on Residential Building net-zero Energy Performance. Proc. , Building Simulation 2011: 12th Conference of International building Performance Simulation Association, Sydney, 14-16 November. 2603-2610.

Brehmer, B. (1992). Dynamic decision making: human control of complex systems. Acta Psychologica, 81, 211-241.

Fanger, P. O. (1972). Thermal comfort: analysis and applications in environmental engineering. New York: McGraw-Hill.

Hartson, R., & Pyla, P. S. (2012). *The UX Book: Process and guidelines for ensuring a quality user experience*. Elsevier.

Hendron, R., Engebrecht, C. (2010). Building America research benchmark definition: Updated December 2009. 1-66.

International Ergonomics Association, 2018 . Retrieved February 2nd, 2018 from https://www.iea.cc/whats/index.html

Larco, N. (2010). "Suburbia Shifted: Overlooked Trends and Opportunities in Suburban Multifamily Housing." Journal of Architectural and Planning Research, Vol. 27, No. 1, pp. 69-87.

Lstiburek, J. (2013). "Unintended Consequences Suck." ASHRAE Journal. June 2013. 52-56.

Lstiburek, J. (2016). "Exhaust-Only Ventilation Does Not Work." ASHRAE Journal. August 2016. 68-73

McKibbin, A. 2013. Engaging as Partners: Introducing Utilities to the Energy Efficiency Needs of Multifamily Buildings and Their Owners. Washington, DC: American Council for an Energy-Efficient Economy

Mo, Y, Zhao, D., McCoy, A., Du, J., & Agee, P. (2017) "Latent Relationship between Construction Cost and Energy Efficiency in Multifamily Green Buildings." Proc. of International workshop of computing in civil engineering (IWCCE) ASCE.

Parker, D., Fairy, P., & R. Hendron. (2010). "National Renewable Energy Laboratory Updated Miscellaneous Electricity Loads and Appliance Energy Usage Profiles for Use in Home Energy Ratings, the Building America Benchmark Procedures and Related Calculations." Revised January 2011.

Sterman, J. (1989). Misperception of feedback in dynamic decision making. Organizational Behavior and Human Decision Processes, 43, 301-335.

Tredgold T.(1824).Principles of warming and ventilating public buildings. London: Dwelling Houses, Josiah Taylor; https://catalog.hathitrust.org/Record/012241658.

U.S. BLS. (2012). Databases, Tables and Calculators by Subject Retrieved from http://www.bls.gov/data/.

U.S. Energy Information Administration (EIA). (2016). Electricity Data. Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1.

U.S. Environmental Protection Agency (EPA). (2018). The Inside Story: The Guide to Indoor Air Retrieved from https://www.epa.gov/indoor-air-quality-iaq/inside-story-guide-indoor-air-quality#concerns

Zhao, D., McCoy, A. P., Agee, P., Mo, Y., Reichard, G., & Paige, F. (2018). Time effects of green buildings on energy use for low-income households: A longitudinal study in the United States. Sustainable cities and society, 40, 559-568.

Zhao, D., McCoy, A., Du, J., Agee, P. & Y. Lu. (2017). "Effects of Resident Behavior on Energy Consumption in Residential Buildings." J. Energy and Buildings. 134, 223–233.