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A human-centred approach to smart housing

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ABSTRACT

Smart buildings are complex systems, yet architecture, engineering, and construction (AEC) professionals often perform their work without considering the human factors of building occupants. Traditionally, the AEC industry has employed a linear design and delivery approach. As buildings become smarter, the AEC industry must adapt. To maximize human well-being and the operational performance of smart buildings, an iterative, human-centred approach must be employed. The omission of human factors in the design and delivery of smart building systems risks misalignment between occupant-user needs and the AEC industry's perception of occupant-user needs. This research proposes a human-centred approach to smart housing. The study employed a multi-phase, mixed-methods research design. Data were collected from 309 high performance housing units in the United States. Longitudinal energy use data, occupant surveys, and semi-structured interviews are the primary data inputs. Affinity diagramming was leveraged to categorize the qualitative data. The output of the affinity diagramming analysis and energy analysis led to the development of data-driven Personas that communicate smart housing user needs. While these data were gathered in the United States, researchers, practitioners, and policy-makers can leverage the human-centred approach presented in this paper toward the design of other human-centred buildings and infrastructure.

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Human-centred design; human factors; evidence-based design; design framework; indoor environmental quality; human behaviour

Introduction

Human–building relationships impact everyone in industrialized society. These human–building interactions (HBI) affect human well-being, building performance, and the environment. Today, we spend 87% of our time in buildings (Kleipsis et al., 2001). The impact of buildings on human well-being and environment is not trivial. For example, asthma rates continue to climb exponentially in industrialized countries (To et al., 2012). From the environmental perspective, buildings consume 20% of worldwide energy (40% of U.S. energy) annually. While humans are spending the majority of their lives within the built environment, national, and international policies are prioritizing environmental and social sustainability ahead of user well-being, comfort, and satisfaction (Altomonte et al., 2015). Even though the goal of delivering high performance housing (HPH) is in line with government and industry goals, a consequence of producing HPH and increasingly smart housing creates new, human-centred challenges for architecture, engineering, and construction (AEC) professionals.

We design and construct buildings for people. We place energy and technology into buildings for human use, comfort, and recreation. Unfortunately, technology often leads our decision-making process, excluding the human element from the design of our housing and broader infrastructure systems. Smart buildings provide an opportunity to design for the physical, physiological, and psychological needs of occupant-users. Human-centred design (HCD) places the human at the centre of the design problem space. Norman's (2013) seminal work, *The Design of Everyday Things* defines HCD as 'an approach that puts human needs, capabilities, and behavior first, then designs to accommodate those needs, capabilities, and ways of behaving' (p. 8). The AEC industry has yet to widely adopt HCD methods, often prioritizing cost-driven, technology-centred design. HCD could promote smart housing design for people.

To date, there has been limited work to employ HCD approaches toward the development of smart housing. Previous work has been domain specific and challenged by generalizing design knowledge from projects with a similar design process, method, and technique (Jeng, 2009). This research provides a adaptable, data-driven HCD housing framework. Specifically, this paper reports findings from a multi-phase, mixed-methods study. The

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study focuses on opportunities for AEC professionals to leverage HCD methods to focus smart housing design on occupant-users. As a result, our work aims to bridge the bodies of knowledge across human factors engineering and the AEC industry, resulting in human-centred, smart housing. To focus the work, the authors developed two objectives for the study: (1) identify the physical, physiological, and psychological needs of occupant-users for smart housing and (2) employ a HCD framework to develop data-driven smart housing personas.

Background

Smart housing

Literature investigating smart housing began to emerge in the early 1990s and has continued to trend upward. Several definitions of smart housing have been developed by previous researchers over the last 20 years. For example, Lutolf (1992) reported 'the smart home concept is the integration of different services within a home by using a common communication system. It assures an economic, secure, and comfortable operation of the home and includes a high degree of intelligent functionality'. Allen et al. (2001) suggested the inclusion of automation is what defined smart homes. The presence of a technology communication network within the home has also been used to define smart housing (Briere & Hurley, 2003). Alam et al. (2012) defined a smart home as 'an application of ubiquitous computing that is able to provide user context-aware automated or assistive services in the form of ambient intelligence, remote home control, or home automation'. Elariane and Dubé (2019) noted the four main components of a smart home are (1) smart meters, sensors, or monitoring, (2) automatic control system, (3) user interface, and (4) communication network to connect the devices with each other.

The role of communication and communication networks (e.g. internet) highlights a salient feature when defining smart housing. To understand the role of the internet use and human-centred smart housing research, the authors explored keyword relationship(s) in the literature. A search query was constructed using the Boolean operators AND, OR, and NOT. Thomson Reuters' Web of Science database was employed for the analysis. We used search terms 'human factors' OR 'human centered design' AND 'smart housing' OR 'smart city' OR 'smart transportation' OR 'smart building'. Using these search terms, our research team downloaded publication date information as tab-delimited text files. To understand the temporal relationships between the literature and internet use across the developed world, our team charted the number of publications per year, per search term (see Figure 1).

Results from the literature analysis suggest that as internet use climbed from 50% to 75% of world population (between 2005 and 2014), scientific literature in smart-housing, building, city, and transportation increased. Particularly interesting is the exponential growth of smart city research emerging in 2012, while the balance of smart infrastructure trended more slowly. Smart cities are comprised of smart housing (and other smart infrastructure), yet smart housing research has not advanced as quickly as technology and internet use. It is important to note, smart housing is not just dependent on world-wide internet use. Understanding broader housing trends is a critical next step.

Housing industry trends

There are important workforce, regulatory, and demographic trends in the housing industry that will impact smart housing. Since 2008, the residential design and construction industry has significantly decreased in number of establishments and number of employees (U.S. BLS, 2019). Fewer establishments, are producing more housing. At the same time, energy code requirements have become more stringent as governments respond to climate change (Amann, 2014). Demographic shifts will also impact the housing industry. The growth in senior population will result in increased demand for senior housing (e.g. ≥65 years old). By 2025, an expected 256 million people will be 65 and over. Between 2025 and 2050, senior populations are expected to double to approximately 1.6 billion (He et al., 2016). The growth in senior housing coupled with advancements in smart housing will challenge the status quo of home design. Meyer et al. (2014) noted that the housing industry has inadequate technology for occupants with diminished hearing and eyesight. As practitioners develop smart housing for seniors, they must consider that (1) smartphone use is on the rise with seniors (Anderson & Perrin, 2017) and (2) seniors experience perceptual, motor, and cognitive limitations that may impact the usability and use of apps and interfaces (Czaja et al., 2019). How will AEC professionals adapt to housing of the 21st century? The literature suggests continued growth in internet-enabled, smart technologies in our homes, but how will we consider human needs in smart housing?

Human factors and ergonomics

Human factors and ergonomics (HF/E) is defined as 'the scientific discipline concerned with the understanding of

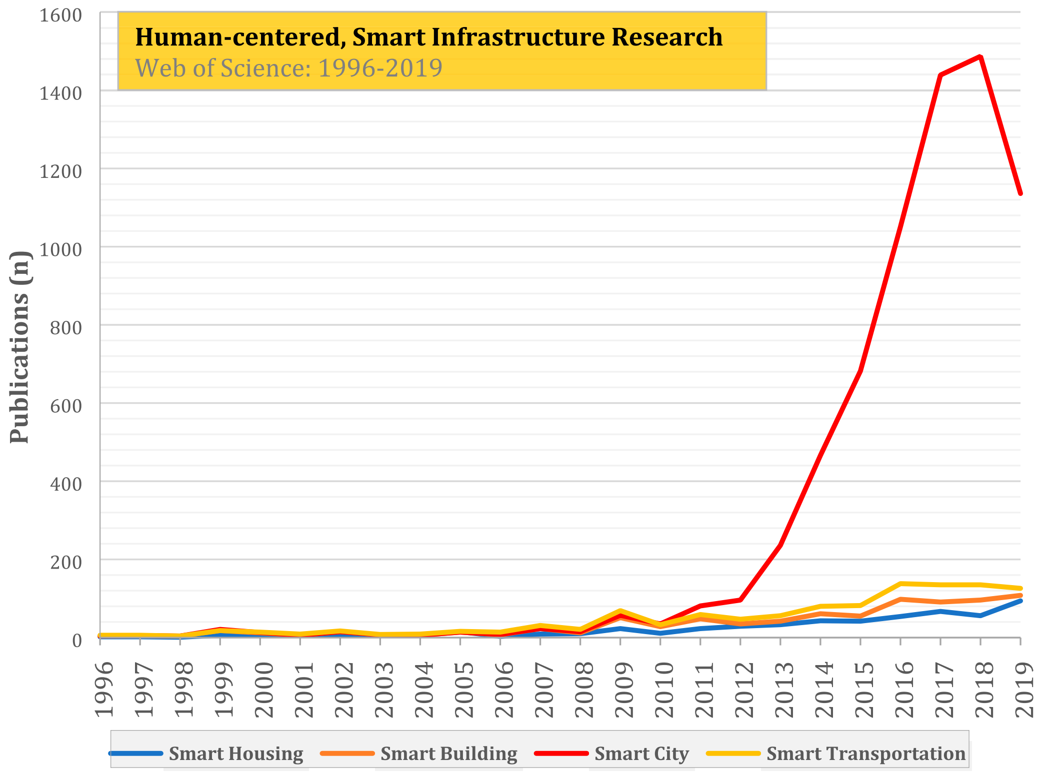


Figure 1. Human-centred, smart infrastructure literature and internet use relationship. Internet users source: Internet Telecommunications Union (2019).

interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance' (International Ergonomics Association, 2018). The HF/E discipline was born out of crisis. Second World War led to rapid technological and system developments that tested the physical, physiological, and psychological limits of humans. Since its inception as a discipline, HF/E has been employed to improve human-system relationships across many sectors and systems including agriculture, aerospace, aviation, chemical, healthcare, information technology and software, manufacturing, military, mining, nuclear and power utilities, occupational safety and health, and transportation. As technologies have advanced in other industries, HF/E has played a significant role in understanding, testing, and improving human-technology relationships. Specialization now includes biomechanics, selection and training, perception, cognition, psycho-social, safety to name a few.

Figure 2 maps the major HF/E advancements relative to housing between 1940 and 2020. As a discipline, HF/E has informed our understanding of humans' needs in the built environment and is well positioned to support advancements in smart housing.

Indoor environmental quality

While humans have designed, built, and occupied buildings for thousands of years, the literature reflecting HF/E research in buildings has largely focused on thermal comfort and more recently indoor environmental quality

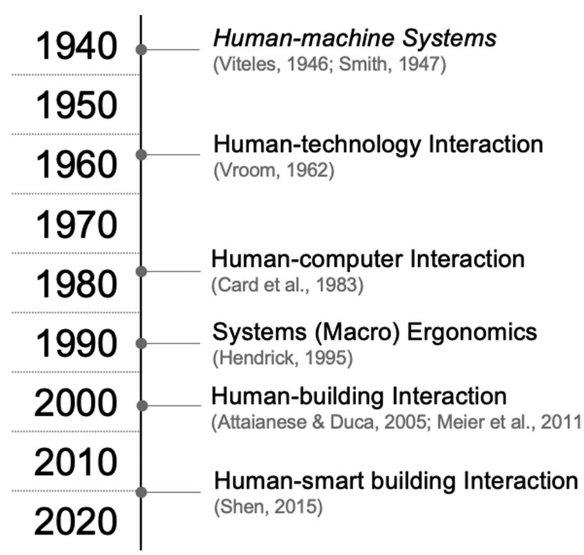


Figure 2. HF/E advancements 1940–2020.

(IEQ). For example, Belding et al. (1945) developed the 'thermal dummy' to evaluate clothing and thermal comfort relationships. Fast forward to the late 1960s and Povl Ol Fanger's (1972) seminal work on thermal comfort. Fanger developed the *Predicted Mean Vote* (PMV) model. The PMV combined the heat balance equation of human skin with a Likert-scale survey for participants. Results were correlated to air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing level. The PMV model was the foundation for the first human-centred standard in the built environment; *ASHRAE 55 – 1966 – Thermal Environmental Conditions for Human Occupancy*.

Moving beyond thermal comfort, IEQ is characterized by providing occupants with an acceptable indoor environment (ASHRAE, 2011). Four primary parameters of IEQ are: (1) thermal comfort, (2) indoor air quality, (3) acoustic comfort, and (4) visual comfort (Arif et al., 2016; Astolfi & Pellerey, 2008; Humphreys, 2005; Lai et al., 2009). The four primary parameters of IEQ are sensed and perceived by human physical, physiological, and psychological capabilities. IEQ research has largely developed from test chamber studies (Berglund & Cain, 1989; Fanger, 1972) to in-situ field studies of occupational-users in commercial buildings (Boyce et al., 2006; Day et al., 2020). Increasingly, researchers are evaluating IEQ outcomes in residential buildings (Agee et al., 2019; Lai et al., 2009; Vakalis et al., 2019). Current IEQ research often studies discrete parameters, and it is challenging to measure the interaction of IEQ parameters and other HBI. As smart housing advances, our ability to understand and augment HBI should aim to improve human well-being.

Human–building interaction

Humans interact with the built environment. How do we understand, unpack, and improve these HBI? First, it is important to define HBI. Shen (2015) defines HBI as 'the study of the interface between the occupants and the building's physical space and objects within it … HBI employs the design thinking process to guide the innovation process and produce effective solutions' (p. 2). HBI is where traditional AEC design meet HCD. Shin (2010) unpacked HBI at a macro-level, considering social, environmental factors as indicators of HBI. Increasingly, the literature is trending to micro-level HBI (e.g. specific occupant task and their resulting systems interactions). For example, Meier et al. (2011) evaluated the usability of thermostats. Jazizadeh et al. (2014) and Langevin et al. (2015) developed HBI-based models to improve thermal comfort outcomes in office buildings. Recognizing the challenges that emerge from the built environment becoming increasingly interactive, Alavi et al. (2016) suggested the Human–Computer Interaction (HCI) community would need to intervene in the AEC industry to improve HBI outcomes. Now that we have explored smart housing, HF/E, IEQ, and HBI literature, our next step is to consider how we will design smart housing for occupant-users.

Human-centred design

How do we design for the physical, physiological, and psychological needs of occupant-users in smart housing? Norman (2013) notes good design requires understanding of psychology and technology, specifically understanding the roles of humans and machines. Bijker (1995) reported the importance of considering human-centred systems. Shin (2010) argued that improving our understanding of human-infrastructure relationships requires contextual analysis. Holtzblatt et al. (2005) suggested that contextual analysis should be employed to examine the processes of technology development, for improved understanding of user needs. How do we motivate the AEC industry to focus on human-centred issues? Traditionally, the AEC industry has employed a linear design and delivery approach. As buildings become smarter and more connected, the AEC industry must adapt. As smart housing become more ubiquitous, the AEC industry will continue to integrate smart technologies that enable several modalities of interaction (e.g. visual, voice, haptic). This change in HBI, will require designers to consider and integrate such domains as Human Information Processing (HIP), Usability of interfaces, and Function Allocation (e.g. assigning human and machine roles) into their work to reduce the risk of misalignment of occupant-user needs. Beyond, additional design domains, the AEC industry will also need to focus on design processes. To maximize human well-being and the operational performance of smart buildings, an iterative, human-centred approach must be employed (see Figure 3).

Beyond iterative approaches to design, Norman's (1988) seminal work on HCD outlines four objectives that can be leveraged in smart housing design:

(1) the user's needs are met;
(2) the product is understandable and usable;
(3) the product performs the desired tasks, and;
(4) the experience of using the product is both positive and enjoyable.

The authors recognize that the AEC industry is bound by established standards and codes that would need to be integrated and inform a HCD approach. Toward this

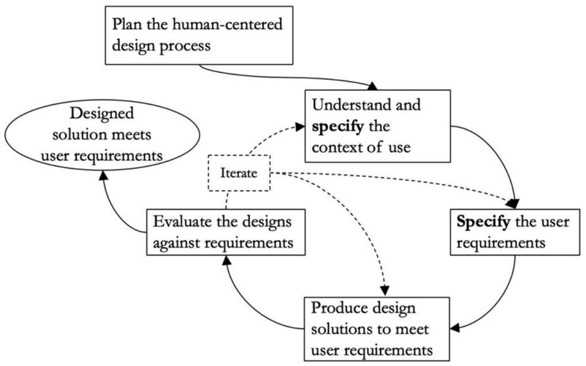


Figure 3. Iterative design approach. Adapted from ISO 9241-210, Ergonomics of human-system interaction.

understanding, our team organized relevant standards to HCD in smart housing in Table 1.

Alleviating current concerns by moving the industry toward HCD will require teams to reevaluate previous design methods. The authors contend that in order to help move the industry toward HCD smart housing, we must make the transition (1) easy, (2) help teams better reach their organizational and project goals, and (3) reduce their risk of poor performing projects. HCD is fundamentally aimed at making life easier for humans. As a design philosophy it is well positioned to help the AEC industry with the transition.

What specific HCD method(s) could be employed by the AEC industry to develop smart housing? Siddall et al. (2011) and Haines and Mitchell (2014) developed and utilized personas to characterize important users in the built environment. For this work, the authors develop personas for two occupant users who will live in smart housing. A persona is a communication tool for designers to create shared mental models. For example, a fictional user is given a name and picture. User behaviours and attitudes are often drafted using data from interviews and surveys; hence, energy and behavioural analysis developed in phase one and phase two of this work served as the inputs for the persona development.

Table 1. Relevant standards for a human-centred approach to smart housing.

Standard
ISO 9241-210 Ergonomics of human-system interaction; Part 210: Human-centred design for interactive systems
ISO 7730 Ergonomics of the thermal environment
ISO 16484-5:2003 Building automation and control systems
ISO 21542 Building construction – Accessibility and usability of the built environment
ANSI/ASHRAE 55 Thermal Environmental Conditions for Human Occupancy
ANSI/ASHRAE 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
ANSI/ASHRAE 90.2 Energy Efficient Design of Low Rise Buildings

Data

Over the last 6 years, the research team has been undertaking a longitudinal study of simulated and measured outcomes in high performance multifamily housing in the United States. Our interdisciplinary team collected data, in accordance with Virginia Tech's Institutional Review Board policy on Human Subjects research, using mixed methods, anonymized, and stored in the Energy Efficient Construction (EEC) database. The EEC database consists of quantitative and qualitative data from approximately 20 high performance multifamily projects, including two zero energy projects and include, but are not limited to: (1) *building technology*: enclosure, systems, appliances, diagnostic testing results; (2) *longitudinal energy use data*: unit-level energy simulations, measured energy use data with circuit-level, unit-level, and development-level resolutions at 1-hour, 1-month, and annual (3 years total) intervals; (3) *occupant feedback:* collected from questionnaires and semi-structured interviews; and (4) *development characteristics*: climate and weather data, direct and indirect costs, tax records, contract documents (e.g. construction plans and specifications), and pro formas. The EEC dataset is managed and maintained in a private, encrypted, Google Drive with a data dictionary developed to enable a clear understanding of variables, data type, and data sources. The authors have uploaded the dataset utilized in this study to the Center for Open Science's Open Science Framework (Agee et al., 2020).

Previous work by the research team mapped correlates of human-technology interaction and their impact on apartment-level energy use (Zhao et al., 2017). The work found 42% of energy use was attributed to energy efficient technologies. The remaining 58% of energy use was attributed to human-building interaction. Simply put, a technology-only approach has limits to efficacy. Therefore, focusing on a human-centred approach is critical to realizing innovative investments in housing of the future. To consider user-needs of smart housing, the research team isolated data from the EEC database. The data included (1) energy use data, (2) behavioural surveys, and (3) semi-structured interviews. Table 2 provides an over of the study's variables, description, value, and literature that has employed similar values for analysis.

Methodology

The focus of the data collection and analysis had two primary aims. First, to unpack human-technology interactions in our existing longitudinal data set of HPH developments. Second, to develop an adaptable, HCD

Table 2. Summary of variables for survey data analysis.

Variable	Description	Value	Literature
EC_{meas}	Measured energy use	*Continuous*, kWh/month	Lee et al. (1995), Parker et al. (2012), Thomas and Duffy (2013), Zhao et al. (2017)
$Tstat_{sum}$	User thermostat setting in summer	*Ordinal*: <68°F (20C); 68–72°F (22°C), 72–75°F (24°C); >75°F	Fischer (2008), Parker (2003), Peng et al. (2012)
$Tstat_{win}$	User thermostat setting in winter	*Ordinal:* <68°F (20° C); 68–72°F (22°C), 72–75°F (24°C); >75°F	Fischer (2008), Parker (2003), Peng et al. (2012)
Win_{use}	Season when opening windows	*Categorical:* Spring; Summer; Fall; Winter	Day et al. (2020), Zain et al. (2007)
Fan_{use}	Use of fans for comfort	*Categorical*: Yes; No	Feriadi et al. (2003), Parker (2003)
Hum_{pref}	User humidity preference	*Ordinal*: Low, Medium, High	Bennet and O'Brien (2017), Ouyang and Hokao (2009)
L_{shower}	Length of showers	*Ordinal*: Low, Medium, Long	Abrahamse et al. (2007), Hoak et al. (2008)
DW	Frequency of dishwasher use	*Ordinal:* None; Sometimes; Often	Ek and Söderholm (2010), Parker (2003)
C_{sum}	Comfort in summer	*Ordinal*: Low; Medium; High	Day et al. (2020), Ouyang and Hokao (2009), Vakalis et al. (2019)
C_{win}	Comfort in winter	*Ordinal*: Low; Medium; High	Day et al. (2020), Ouyang and Hokao (2009), Vakalis et al. (2019)

framework that could be leveraged by AEC practitioners motivated to develop smart housing solutions anchored in data-driven human needs. We utilized a multi-phase, mixed-methods study design (Creswell & Creswell, 2017). Commonly used AEC data collection methods are combined with human-centred methods resulting in a human-centred approach to smart housing. Figure 4 maps the three methodological phases (e.g. energy analysis, behavioural analysis, and persona development), project tasks, and research objectives. The mixing of methods occurs in phase three during the persona development.

Phase 1: energy analysis

An online benchmarking software (e.g. WegoWise) collected apartment-level electricity data on a monthly basis from May 2013 to April 2018. The sample included 309 sub-metered residential units across 20 developments in the state of Virginia. The apartments range from 1 to 4 bedroom apartments. Our research team supplemented EEC data with architectural data including conditioned floor areas (e.g. m^2), window-wall ratios, and unit locations (e.g. end unit, interior unit), and unit technologies, including heating, ventilation, and cooling equipment, from construction documents provided by participating developers. We also verified the designs through site visits. Energy use data were normalized by site energy use intensity (EUI). EUI normalization allowed the research team to establish annual kBtu/m^2 for each unit in the sample. We used R software for descriptive statistics and energy analysis specifically focused on variability between senior and non-senior energy use. A mean EUI was established for both senior and non-senior samples and used as an input in the persona development described in phase three of this methodology.

Phase 2: semi-structured interviews

The research team conducted semi-structured interviews to explore user experience in energy efficient, affordable housing units. To develop the personas presented in this paper, we asked 6 senior and 3 head-of-family occupants about their experience with energy efficient housing technologies. The interview script was developed using the U.S. Department of Energy's Energy Literacy Guide (U.S. DOE, 2012) to connect in home behaviours to learning experiences. We recorded each interview with a field recorder and took notes by hand to inform the data analysis phases. Following the interview, we transcribed each audio recording using a professional online transcription service. Our team then cross checked the audio recordings with the transcriptions to correct missed statements.

Next, the authors uploaded the extracted statements in NVivo12 for analysis and codebook development. A grounded theory approach was used for interview analysis (Charmaz, 2006). Grounded theory is appropriate for this work because it supports iterative approaches to data analysis, conceptually similar to many HCD methods (Glaser & Strauss, 1967). The approach is particularly relevant to HCD issues since it investigates actions, processes, and interactions between people and artefacts to generate theories about these interactions in the field (Charmaz, 2006; Glaser & Strauss, 1967).

Following the data transcription and cleaning, the team used In Vivo coding to analyse the interview data. In Vivo Coding uses the participants statements verbatim to guide the coding process. Saldaña (2015) noted that In Vivo Coding was well positioned for grounded theory studies because the coding process is grounded in the participants' own language. The research team used analytic memoing while developing the list of In Vivo codes. The analytic memos were used to document the coding process and prepare the text for affinity diagramming in which emergent themes and central categories were developed.

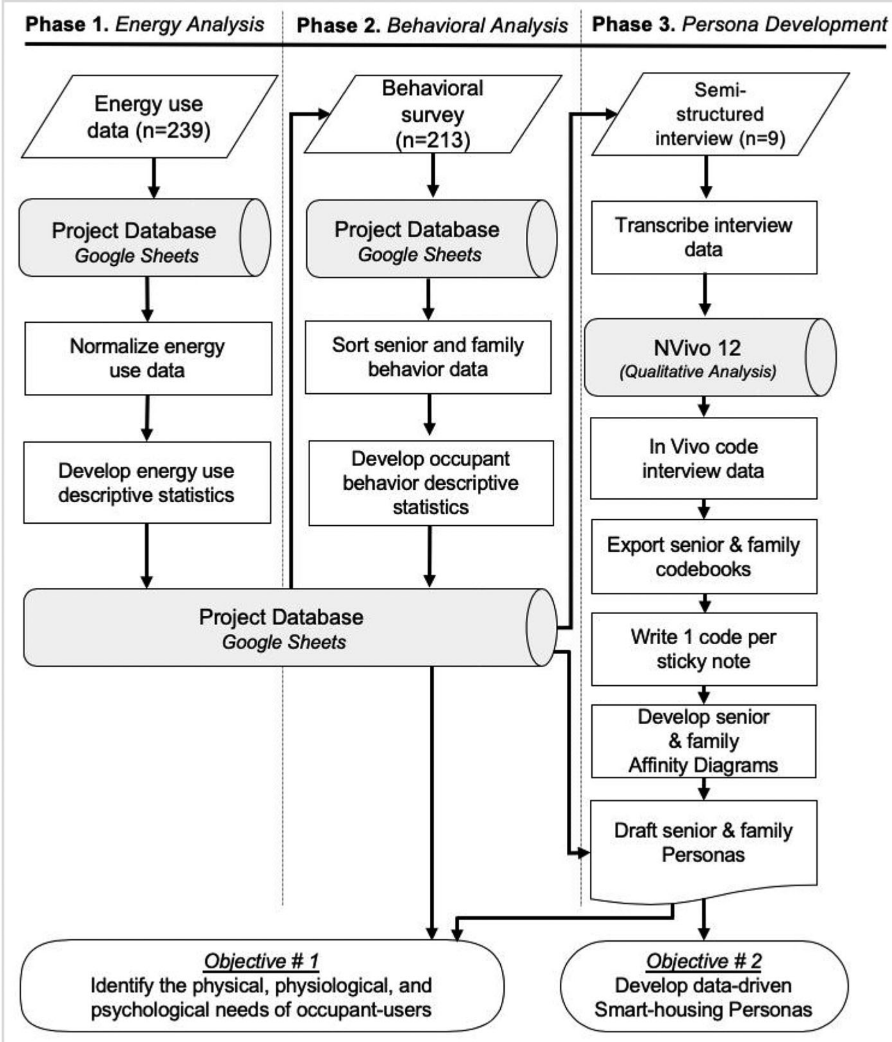


Figure 4. Flow chart for research objectives and methodology.

Phase 3: persona development

Affinity diagramming

Once the energy and behaviour analysis was complete, the team developed two personas; (1) a senior smart housing occupant-user and (2) a non-senior smart housing occupant-user. Phase one and phase two of this study analysed considerable quantitative and qualitative data. To synthesize data, we then developed two affinity diagrams. The Affinity Diagramming method was developed by Jiro Kawakita (1975). Affinity Diagramming is a common HCD method used to organize and map data using emergent themes. Hanington and Martin (2012) note Affinity Diagrams are a generative research approach commonly used in the design of human-centred products and systems. The method enables the researchers to unpack the complex behaviours and attitudes of participants. Once code books were developed for the senior and non-senior interviews, the researchers needed to synthesize codes into themes. The authors wrote each In Vivo code from the Phase two interviews on a sticky note. One at a time, the authors placed all sticky notes on the white board. Notes are clustered and result in the development of themes in the data (Beyer & Holtzblatt, 1999). Next, the authors outlined the primary objectives of the work in a persona draft, and then synthesized the (1) energy use and behaviour survey descriptive statistics and (2) the affinity diagramming themes were then utilized to outline each persona. The authors then looked for emergent themes in the data. Sticky notes with similar themes were rearranged next to each other. Once a theme emerged, the authors named each theme and then used these themes to draft personas of smart housing.

Personas

Personas were first developed as a tool to support the development of software (Cooper, 1999). A seminal

HCD method, personas generalize user needs and allow designers to focus on user behaviour and attitudes (Hannington & Martin, 2012). Personas help designers anchor their work in a fictional user's needs in the design of products and systems (Takai & Ishii, 2010). This approach reduces the risk of designers designing for themselves, technology, and/or first cost parameters.

The persona development in phase three of this study is where the mixing of methods occurs. For example, the authors mixed the energy and behaviour analysis findings from phase one and two of this work as data inputs for two smart housing personas. The authors referenced the descriptive statistics developed in phase one and the behavioural analysis developed in Phase two to describe the physical, physiological, and psychological needs of the two fictional users. Each persona was given a fictional name and picture. The corresponding author developed the first persona drafts. The co-authors reviewed and iterated the personas twice before finalizing a 'senior' and 'non-senior' persona.

Results

Phase 1: energy analysis

There are 34 missing values in the average electricity use per unit. For the rest, 205 instances, the minimum is 35.57 kBtu/m^2/year, while the maximum is 630.56 kBtu/m^2/year. The sample mean is 282.76 kBtu/m^2/year and the sample median is 266.30 kBtu/m^2/year. Figure 5 charts the scatter plot of the mean energy consumption of each sample unit.

Figure 6 compares senior units and non-senior units site EUI. On average, the senior units consume more energy than the non-senior units in the sample; senior mean = 298.50 kBtu/m^2/year, non-senior mean = 268.36 kBtu/m^2/year.

Phase 2: behavioural analysis

Among the 309 households who participated in the research, 239 households answered sufficient questions in the survey. 112 of these households are identified senior households (e.g. ≥65 years old) and the remaining 127 are non-senior (e.g. < 65 years old).

First, we will report survey responses related to comfort. Respondents were asked what thermostat settings were used in both summer and winter seasons (see Figure 7). Generally, seniors set their thermostats higher (e.g. warmer) during both summer and winter, compared to non-senior respondents. This could be due to physiological differences between the senior and non-senior respondents. The authors also considered that some senior participants may have grown up without air conditioning in their home, therefore they preferred warmer indoor environments.

Next, we evaluate responses about seasonal comfort when compared to previous housing (see Table 3). The majority of the sample felt more comfortable in both summer and winter months compared to previous

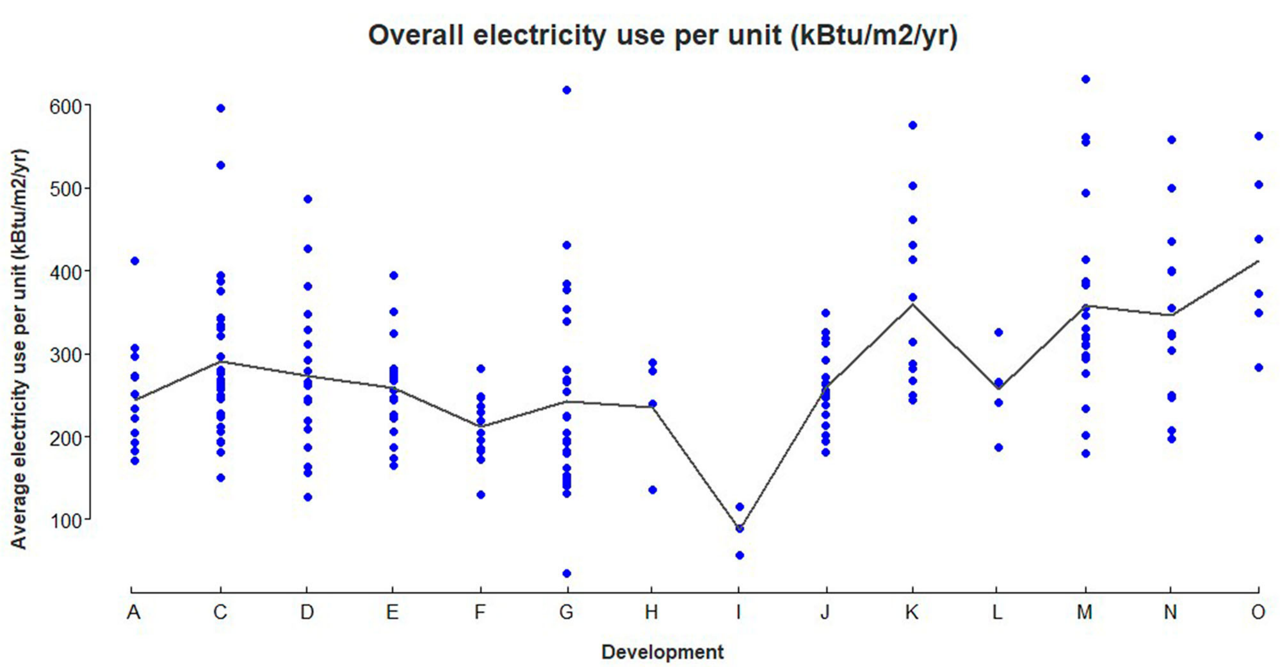


Figure 5. Scatter plot of site EUI.

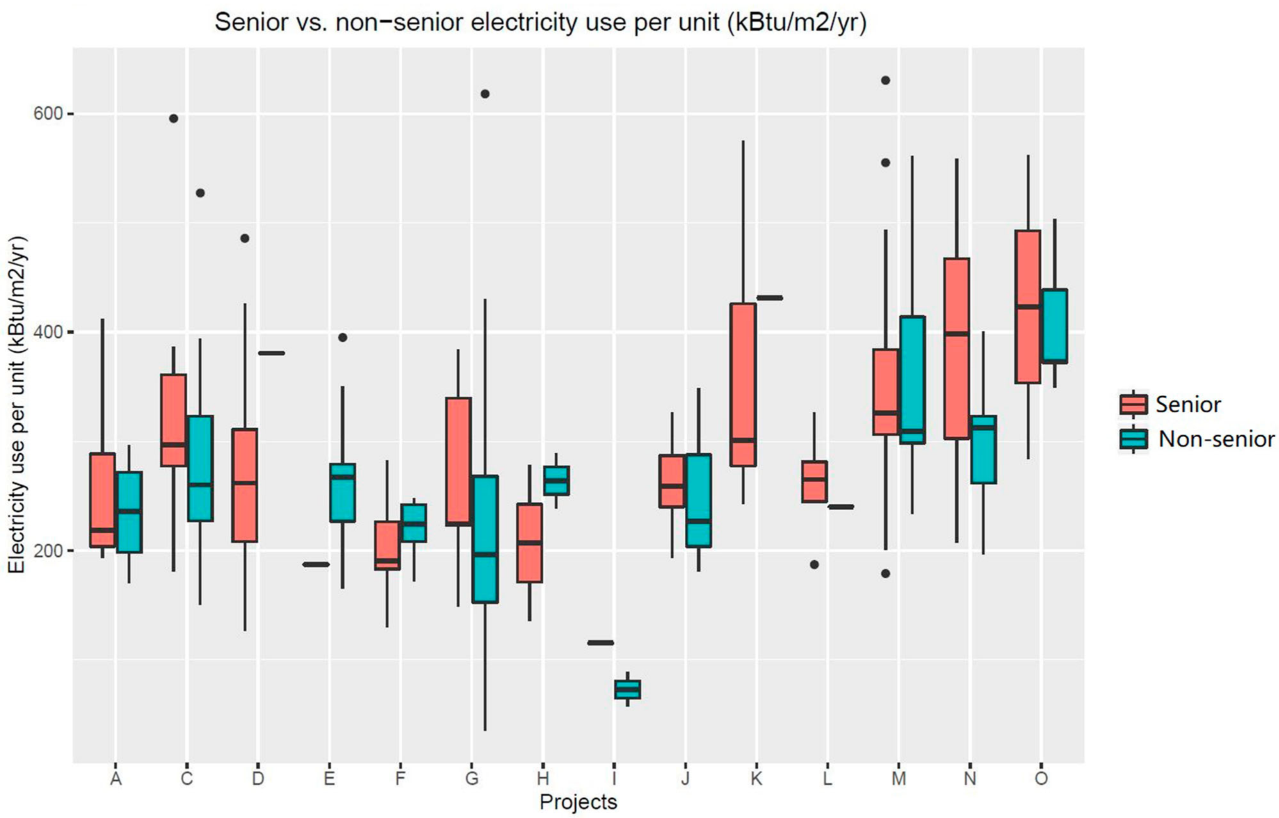


Figure 6. Senior and Non-senior site EUI.

housing. Only 3 participants reported being less comfortable during the summer, and 6 participants reported being less comfortable in the winter.

Comfort is highly subjective, based on individual perceptions of their indoor environment. Occupants can adapt their indoor environment by opening windows or utilizing a space heater. Table 4 reports adaptations used by respondents to improve their comfort. Specifically, participants were asked about their seasonal use of window opening, as well as space heater and fan use. Window and fan use is more common that space heater use in this sample. On average, 39% of non-senior participants report opening windows to improve comfort. On average, 33% of senior participants report opening windows to improve comfort. It is important to note, that the survey did not differentiate between ceiling fans and/or portable fans. Finally, space heaters are not provided by the management company for the sample units and may impact the reported use of this specific technology.

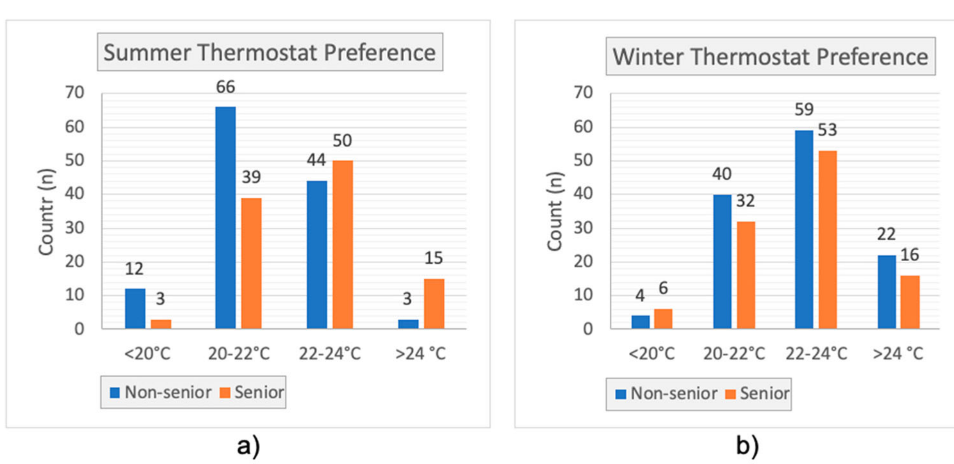


Figure 7. Senior and non-senior thermostat setting, summer (a) and winter (b).

Table 3. The comfort level of current unit to previous housing unit.

	Comfort level during summer months				Comfort level during winter months		
Sample	Much less comfortable	About the same	Much more comfortable	No response	Much less comfortable	About the same	Much more comfortable
Non-senior (*n* = 127)	2	44	78	3	5	45	77
Senior (*n* = 112)	1	36	71	4	1	35	76
Total (*n* = 239)	3	80	149	7	6	80	153

Table 5 reports shower and dishwasher use across the sample. Data suggest seniors take shorter showers and prefer handwashing dishes, while non-seniors take longer showers and use a combination of handwashing and their dishwasher to clean dishes. During phase three of this work (e.g. interview coding and affinity diagramming), the authors noted senior attitudes are more conservative with resources (e.g. money, energy, water) than non-senior participants. Some senior participants reported the impact of growing up with little resources, taught them to conserve.

Phase 3: persona development

Affinity diagramming

Following the In Vivo coding of the semi-structured interviews, the research team transferred 118 senior codes to orange sticky notes (1 code/sticky note) and 116 non-senior codes to orange sticky notes. The authors developed an affinity diagram from the senior participants first (see Figure 8(a)). Once the coded sticky notes were organized, six themes emerged: *Anti-technology, Challenges/in-convenient, Needs, Lifestyle, Human-building Interaction, Environmentally friendly Behaviour*.

Next, the authors developed an affinity diagram from the non-senior interviews (see Figure 8(b)). Once the coded sticky notes were organized, four primary themes emerged; *Comfort, Lifestyle, Technology*, and *Environmental Awareness*. The *Technology* theme resulted in three sub-themes: *Automation, Devices*, and *Behaviour*. The *Environmental* theme also resulted in three sub-themes: *Behaviour*, *Financial Considerations*, and *Social Impact*.

Table 4. Comfort adaptations.

	Open windows to improve comfort				Mechanical adaption to improve comfort	
Sample	Fall	Winter	Spring	Summer	Space heater	Fan
Non-senior (*n* = 127)	53	22	73	51	5	60
Senior (*n* = 112)	41	16	58	37	4	51
Total (*n* = 239)	94	38	131	88	9	111

Affinity diagramming produced salient differences between senior and non-senior attitudes toward human-housing relationships. For example, seniors spoke more about comfort, safety as a primary needs. Their behaviours were motivated to conserve resources. Non-seniors identified internet access and recreation opportunities for their kids as primary needs and highlighted their understanding of human impacts on the environment. While seniors practiced conservation, non-seniors identified more altruistic motives that drove their environmental beliefs. The interview codebooks and additional affinity diagramming data can be found in the available dataset used for this study (Agee et al., 2020).

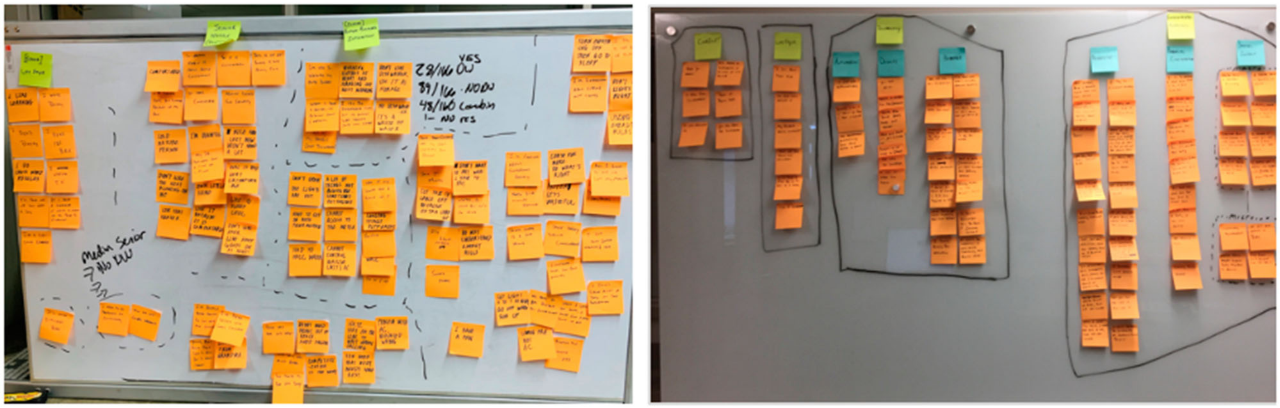
Personas

Once we completed the energy analysis, behavioural analysis, semi-structured interviews, and affinity diagramming, the authors synthesized the previous results to produce a senior persona (Figure 9) and non-senior persona (Figure 10).

The corresponding author developed the first persona drafts. The co-authors reviewed and iterated the personas twice before finalizing a ‘senior’ and ‘non-senior’ Persona. The iterative approach to the persona development helped to hone the behavioural and altitudinal nuances between the two fictional occupant-users.

Table 5. Shower use and dishwasher use.

	Shower use			Dishwasher			
Sample	Short	Medium	Long	Use	Handwash	Combo	No Response
Non-senior (*n* = 127)	39	62	26	27	61	39	0
Senior (*n* = 112)	46	60	6	15	68	28	1
Total (*n* = 239)	85	122	32	42	129	67	1



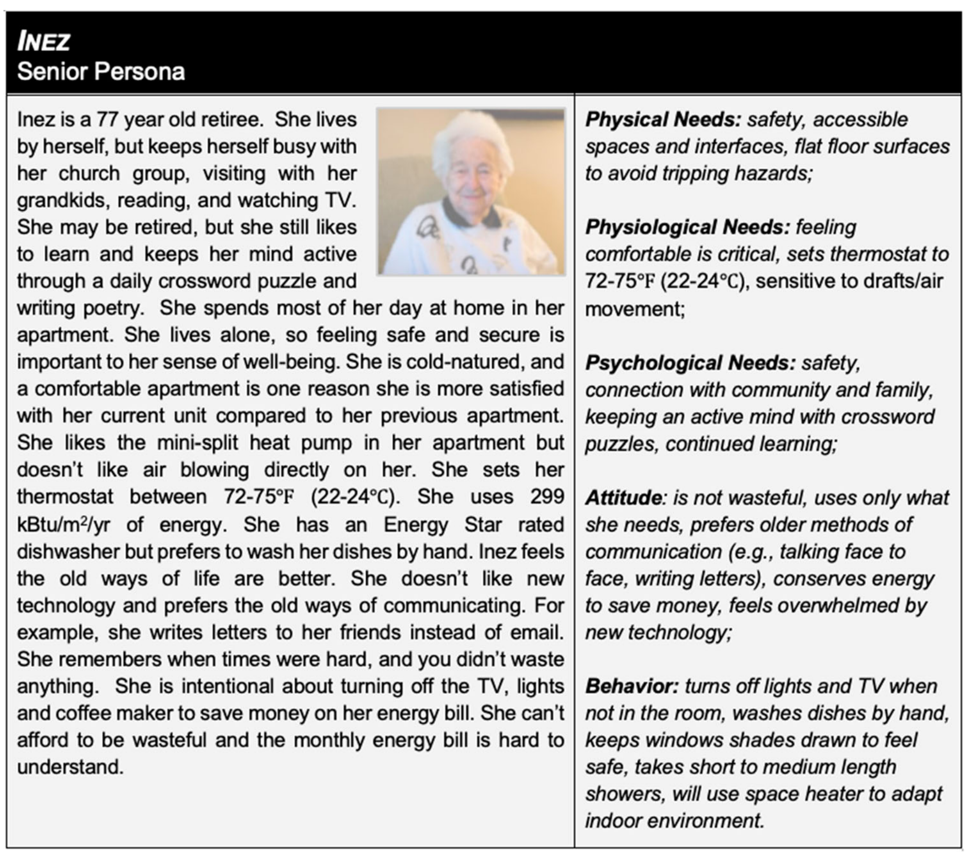
a) b)

Figure 8. (a) Senior affinity diagram and (b) non-senior affinity diagram.

Discussion

Data-driven personas help to anchor the design of a smart home in fictional user needs. This approach could be helpful when AEC teams are navigating smart home design(s) and disrupt our traditional approaches to decision-making. Instead of evaluating a design by first cost, energy efficiency, designer experiences, or aesthetics, a persona could help us ask 'what does Inez want or need in this design? How would Inez prefer to interact with this interface or system?" By focusing on the occupant-user, we quickly recognize how HCD challenges our tendency to design for ourselves, based on our perspective of the world.

It is important to note, HCD is not an 'end of the pipe' of design approach. HCD must be initiated in the schematic phase of the project, and updated (e.g. iterated)



INEZ
Senior Persona

Inez is a 77 year old retiree. She lives by herself, but keeps herself busy with her church group, visiting with her grandkids, reading, and watching TV. She may be retired, but she still likes to learn and keeps her mind active through a daily crossword puzzle and writing poetry. She spends most of her day at home in her apartment. She lives alone, so feeling safe and secure is important to her sense of well-being. She is cold-natured, and a comfortable apartment is one reason she is more satisfied with her current unit compared to her previous apartment. She likes the mini-split heat pump in her apartment but doesn't like air blowing directly on her. She sets her thermostat between 72-75°F (22-24°C). She uses 299 kBtu/m^2/yr of energy. She has an Energy Star rated dishwasher but prefers to wash her dishes by hand. Inez feels the old ways of life are better. She doesn't like new technology and prefers the old ways of communicating. For example, she writes letters to her friends instead of email. She remembers when times were hard, and you didn't waste anything. She is intentional about turning off the TV, lights and coffee maker to save money on her energy bill. She can't afford to be wasteful and the monthly energy bill is hard to understand.

Physical Needs: *safety, accessible spaces and interfaces, flat floor surfaces to avoid tripping hazards;*

Physiological Needs: *feeling comfortable is critical, sets thermostat to* 72-75°F (22-24°C), sensitive to drafts/air movement;

Psychological Needs: *safety, connection with community and family, keeping an active mind with crossword puzzles, continued learning;*

Attitude: *is not wasteful, uses only what she needs, prefers older methods of communication (e.g., talking face to face, writing letters), conserves energy to save money, feels overwhelmed by new technology;*

Behavior: *turns off lights and TV when not in the room, washes dishes by hand, keeps windows shades drawn to feel safe, takes short to medium length showers, will use space heater to adapt indoor environment.*

Figure 9. Inez, senior persona.

STACEY
Non-senior Persona

Stacey is a 35 year old fulltime mother of two and a librarian. She is happily married to Steve, a construction worker. She lives a busy life, balancing her professional and personal life. She is busy. Sometimes she feels too busy. Her life is about balance. Balancing time with her family, work, paying bills, and staying connected with her community. She recently had an energy retrofit completed on her home to save some money on her energy bill. She uses 236 kBtu/m^2/yr of energy. She and her kids both notice how much the new insulation contributed to making their home less noisy. Stacey is interested in solar panels to reduce her carbon footprint but can't afford solar panels. Instead, she has bought LED light bulbs and low flow water fixtures. She likes it a little cooler in the summertime, setting her thermostat between 68-72°F (20-22°C) and a little warmer in the winter between 72-75°F (22-24°C). Her family uses smart phones and tablets every day for work and recreation.

Physical Needs: *space for her children to play, somewhere quiet to rest after a busy workday;*

Physiological Needs: *sets thermostat to* 68-72°F (20-22°C) and a little warmer in the winter between 72-75°F (22-24°C);

Psychological Needs: *connection with community and family, time to rest from her busy schedule;*

Attitude*: environmentally aware, aims to reduce carbon footprint; enjoys using smart devices;*

Behavior: *uses LED lights and low-flow water fixtures, utilizes smart phone and tablet to stay connected. Uses a both her dishwasher and handwashing to clean dishes, takes medium to long showers, enjoys opening the windows to get some fresh air*

Figure 10. Stacey, non-senior persona.

throughout the design development, and construction document phases. At a minimum, the authors suggest iterations of the personas to align with established design milestones (e.g. schematic, design development, contract and construction documents) to ensure the opportunity for iteration and team participation in the process.

After the first design meeting, the team would collect and organize data based on the project requirements, system, or interface requirements. Ideally, the team has access to measured outputs and outcomes from previous projects. Example data could include, energy use data, occupant surveys, testimonials, and/or interviews. Increasingly, smart homes can be designed to measure and report data. If the team does not have access to past project data, publicly available datasets could be employed while the team establishes data collection protocols to measure outcomes for future projects. An example of a public dataset is the U.S. Department of Energy's Building Performance Database (BPD). BPD reports measured energy use for 685,000+ residential buildings. The sample spans multiple climate zones, housing types (e.g. attached, detached, single and multi-story) and technology characteristics. Government census data can also be used (e.g. income, age, family size, occupation, level of education) if specific demographic data for the future user is not available. Once the data is organized, descriptive statistics are developed on the quantitative dataset. Next, qualitative coding and analysis is developed and reviewed across the design team. The analysis should be iterative and draw participation across all members of the design team. Emergent themes in the data should be discussed and evaluated. The number of personas needed is dependent on many factors including, but not limited to housing type, financial model (e.g. for-sale versus for rent), data quality, and experience in the target market. The authors recommend 1–3 personas/per system or interface. Once the personas have been developed, they are read aloud at the beginning of each project team meeting to remind team members of their target users' needs, attitudes, and behaviours. When design alternatives are proposed, the personas inform decisions and reduce the risk of decisions being made based solely on first cost or designer worldview. The authors have found that this approach also helps to facilitate more inclusive design approaches and reduce dominant or more senior team members from driving design solutions. Following project completion, the team collects and analyses data to inform assumptions made in design and continually improve their HCD approach.

There are opportunities for HCD and smart housing integration beyond existing AEC workflows. We have an opportunity with smart housing to improve human well-being. Smart housing may become critical in the diagnosis and delivery of healthcare services and allow seniors to live independently longer. Researchers are already studying implications of increased smart-device use with seniors (Anderson & Perrin, 2017) and testing healthcare applications (Santana-Mancilla et al., 2020). Our research found important HBI differences between seniors and non-seniors. For example, seniors prefer higher thermostat set points to maintain thermal comfort, and prefer handwashing their dishes, and sometimes feel overwhelmed by technology. As we age, changes to our visual perception result in reduced visual sensitivity to contrast, colour, and motion (Salvendy, 2012). General design implications and suggestions include increasing the size, brightness, and contrast of symbols and letters to improve perception for older adults. The differences between senior and non-senior human factors are important for researchers, AEC professionals, and policy-makers to understand to better meet the needs of smart home consumers. Further, smart housing developed using HCD methods could enrich designs towards emergent areas of focus, such as social distancing.

Limitations

There are important limitations to this study. First, the authors acknowledge that the data inputs impact the analysis and outputs of the work. For example, the data collected and analysed in this study are from occupant-users in the United States. Context of the user's environmental, social, economic factors is important to consider and impact the results of the research. The goal of this work was not to develop two personas (e.g. senior and non-senior) that are generalizable to the population of all smart home occupant-users. Instead, the authors aimed to demonstrate how mixing traditional AEC methods with HCD methods and analysis could provide new opportunities to design smart housing for people.

Conclusions

In this research, the authors have demonstrated how HCD methods can be employed to design smart housing for human physical, physiological, and psychological needs. Commonly used AEC data collection methods (e.g. energy analysis, behavioural surveys, and occupant interviews) were combined with HCD methods (e.g. affinity diagramming and personas) to develop two data-driven personas of smart housing occupant-users. The personas developed in this study reported salient differences in the sample's user attitudes, behaviours, and human factors that impact HBI. For example, Inez (Senior persona) uses 299 kBtu/m^2/year, sets her thermostat setpoint between (22–24°C) to maintain comfort, takes shorter showers and intentionally limits her human-technology interactions (e.g. use of dishwasher, communication preferences, smart devices). Conversely, Stacey Adams (Non-senior persona) uses 236 kBtu/m^2/year, sets her thermostat to 22–24°C in the winter, 20–22°C in the summer. Stacey Adams was more environmentally aware and utilizes smart devices to stay connected.

As buildings become smarter, the AEC industry must adapt. To maximize human well-being and the operational performance of smart buildings, an iterative, human-centred approach must be employed. While this data was gathered in the United States, researchers, practitioners, and policy-makers can leverage the adaptable, HCD framework presented in this study to better align smart housing and infrastructure systems with user needs. This work also demonstrated how interdisciplinary teams can leverage HF/E and HCI expertise, mixed-methods, and iterative approaches to support the AEC industry's transition to human-centred, smart homes.

Future work could focus on applying HCD methods to test the usability of specific smart home interfaces. HCD will become critical as human-home systems shift task responsibilities between humans and machines (e.g. automation). We should not assume autonomous relationships are preferred by occupant-users, we should ask them. Think a loud tests could be used to gain critical insight into preferred automation levels of human-machine relationships (e.g. Function Allocation). Smart homes will increasingly collect data and send signals to occupant-users. We should explore preferred modalities of information (e.g. visual, auditory, haptic, and command versus status information) and recognize that occupant-user wants, and needs may be dynamic; necessitating adaptive systems in smart homes.

Disclosure statement

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