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Ten questions concerning human-building interaction research for improving the quality of life

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ABSTRACT

This paper seeks to address ten questions that explore the burgeoning field of Human-Building Interaction (HBI), an interdisciplinary field that represents the next frontier in convergent research and innovation to enable the dynamic interplay of human and building interactional intelligence. The field of HBI builds on several existing efforts in historically separate research fields/communities and aims to understand how buildings affect human outcomes and experiences, as well as how humans interact with, adapt to, and affect the built environment and its systems, to support buildings that can learn, enable adaptation, and evolve at different scales to improve the quality-of-life of its users while optimizing resource usage and service availability. Questions were developed by a diverse group of researchers with backgrounds in design, engineering, computer science, social science, and health science. Answers to these questions draw conclusions from what has been achieved to date as reported in the available literature and establish a foundation for future HBI research. This paper aims to encourage interdisciplinary collaborations in HBI research to change the way people interact with and perceive technology

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within the context of buildings and inform the design, construction, and operation of next-generation, intelligent built environments. In doing so, HBI research can realize a myriad of benefits for human users, including improved productivity, health, cognition, convenience, and comfort, all of which are essential to societal well-being.

1. Introduction

The built environments we inhabit have traditionally been considered static containers for human activities. One confirmation of this is an article entitled “Smart Buildings: Facts, Myths and Implications” published in 1986 by The American Institute of Architects, in its *Architecture* magazine for Technology and Practice, which states, “the fact is, a totally integrated building does not exist today” [1]. This is still the case for most existing buildings [2]. However, recent progress in the field of Information Technology (IT) enables a new generation of smart technology to be applied to buildings [3]. Improved sensing, communication, interfaces, and controls, powered by Artificial Intelligence (AI), allow new forms of mutual interactions between buildings and the people who inhabit them, enabling and supporting novel ways of human building interactions. The field of Human-Building Interaction (HBI) explores this interplay between buildings and humans and informs the way buildings are conceived, designed, constructed, occupied and managed to improve the life and experience of the people who inhabit them [4–10].

HBI has been considered an evolution of Human-Computer Interaction (HCI) that incorporates physical spaces into the interactions among humans and computers [4,8,11]. However, this approach risks oversimplifying the field; people not only interact with but also ‘inhabit’ buildings that have both physical properties and digital systems that can sense, reason, and respond to occupancy-related information [12]. Users of HBI are immersed in the physical environment they are interacting with, causing these interactions to have an impact on a broad array of user experiences that go beyond the time-limited interaction with the technology, such as implications for physical and mental health. Furthermore, at any given time, there are usually multiple occupants within the environment, and one user’s interactions with the building might impact other users. To that end, compared to HCI, where users interact with a system directly through well-defined modalities, HBI is complex, can change over time, and are influenced by various factors outside the specific human-technology interface.

Researchers with backgrounds in building sciences, building technologies, architectural engineering, mechanical engineering, and architecture have been studying the topics of HBI for decades. Notably, Annex 66, “Definition and Simulation of Occupant Behavior in Buildings,” perhaps was the first international research collaboration to focus on the human behavior in the built environment as an initiative of the International Energy Agency’s “Energy in Buildings and Communities Programme” between 2013 and 2018. Several topics were explored by this group such as occupant movement and presence modeling, occupant action modeling, integration of occupant behavior models with building energy simulations, as well as broad application of these occupant behavior models in building design and operations, which demonstrated the importance of occupant behavior modeling in the building science and technology field [13]. Immediately followed by the work of Annex 66, in 2018, a group of international researchers started Annex 79, “Occupant-Centric Building Design and Operation” to focus on “unanswered questions” about occupant comfort and behavior, applications, and knowledge transfer to practitioners. A wider range of researchers with backgrounds in psychology, physiology, and other related fields are included in Annex 79, and the scope of Annex 79 covers a wide range of topics of HBI, such as the impact of environmental exposure to human behavior, building interfaces and human behavior, occupant modeling strategies and tools, occupant data collection, and applying occupant behavior models in building design process, occupant-centric building controls, and integration of occupant-centric control strategies in building automation systems [14].

As building technologies increase and the scope of research within HBI expands to incorporate new disciplines and broader interdisciplinary group efforts like those noted above, it is important to consider the range of possibilities for HBI to improve quality of life. This paper seeks to provide information to the broader community of scholars, practitioners, and other stakeholders who may not be aware of the potential of or methods for engaging in HBI research. Our goal is to emphasize the direction and research movements in this area, and the opportunities that HBI brings, rather than attempting to define a narrower research field. We provide this information in the form of ten questions (Fig. 1). First, we provide a comprehensive and systematic definition of HBI (Q1), and then describe the key stakeholders (Q2), shared goals (Q3), and benefits of HBI (Q4). We then describe the types of human engagement (Q5) and the broad range of building components that are incorporated into HBI including all types of buildings (e.g., residential, commercial, educational, industrial), their operational systems (e.g., HVAC, lighting, envelope, information), and their immediate surroundings (e.g., entrances, rooftops, urban or rural context) (Q6). We discuss how buildings and their occupants influence each other towards individual and shared objectives (Q7), and describe enabling technological advancements (Q8) and how HBI research can be scaled to support networks of buildings, communities, cities, and more (Q9). We close by discussing the opportunities and challenges that must be considered in HBI research (Q10). These ten questions and their answers were developed by a diverse group of international researchers with backgrounds in various disciplines including architecture, various fields of engineering, computer science, behavioral science, health science and cognitive science.

2. Ten questions and answers

2.1. Q1: What is human-building interaction?

Multiple definitions and examples exist on how individual professional fields contribute to the understanding and advancement of interactions among humans and buildings. For instance, architects and engineers undertake the role of designing buildings and their systems, including choices about programmed and/or functional dimensions, aesthetics, product materials, systems engineering, and life safety (as required by code). Until recently, however, these processes have lacked a broader role in understanding, predicting, and shaping how people will act and react to a physical environment once construction is completed [15]. Previously, the social and health sciences have observed the impact of physical environments on human behavior, performance, and health [16,17]. More recently, a new understanding of the possible convergence across disciplines has emerged (e.g., efforts by Annex 79), which can potentially inform the development of human-centered environments [4,8,11]. Some early contributions have come from HCI, which has supported examination of human-computing interfaces within built environment for regulating energy consumption and thermal comfort [11].

Considering these contemporary trends, various scholars have sought to define the emerging field of HBI and articulated a vision for future HBI research [4–10]. HBI has been defined as *“the study of the interface between the occupants and the building’s physical space and the objects within it”* [18]. Traditionally, the focus of HBI has been on system interactions and interconnections with the aim of lowering the building-occupant energy use while also improving thermal comfort. However, the primary objective for HBI has expanded, as noted in a more recent definition, *"It is to study and understand humans (building occupants) and predict why they need or want to interact with the built environment and the computer technologies in it"* [19]. This expanded scope provides greater propensity for achieving outcomes that address broader societal goals such as mental health, worker performance, equity, and inclusion [20].

While we acknowledge the contributions of several domains to define a scope for HBI, we must consider interdisciplinary approaches that fully integrate aspects across humans, buildings, and technological features in consideration of collective human experiences and broader societal goals. To this end, we define HBI as an *interdisciplinary field that aims to understand how buildings affect human outcomes and experiences, as well as how humans design, interact with, adapt to, and affect the built environment and its systems*. The mission of HBI research is to support buildings that can learn, adapt, evolve, and enable occupant adaptation to improve the quality-of-life of its users while optimizing resource usage and service availability at multiple scales, from a single building to the broader city.

As HBI evolves and technologies improve, strategic and coherent goals can be established to explore increasingly complex components of the interactions between humans and buildings. Initially, understanding and documenting the ways users respond to intelligent buildings and the resulting impacts on human engagement and well-being will support the design of technologies to improve interactions. As buildings become smarter and more 'aware,' the dynamic interplay between embodied human and building intelligences will become an increasingly needed area of focus for HBI.

2.2. Q2: Who are the stakeholders for HBI research?

HBI research requires strong engagement and collaboration across numerous stakeholder groups. Acknowledging and incorporating diverse stakeholders' experiences, roles, and backgrounds is critical to ensure HBI research that promotes effective solutions for the built environments in which we live, work, and play. Previous studies categorized the stakeholders of these projects in several ways [21–26], often identifying stakeholders involved in conventional building research, including the client or the owner, architects, designers, and engineers, building operators, contractors, and other consultants. There is a need to rethink and expand consideration of key stakeholders for HBI research, and develop frameworks for stakeholder engagement plans within HBI research to maximize outcomes [27]. We propose a taxonomy that organizes this expanded list of HBI stakeholders into four groups which consist of occupants, researchers, contributors, and authorities.

Occupants: As buildings' end-users, occupants affect building performance while simultaneously being affected by its design and indoor environmental conditions [28]. A building's occupants and their needs are dynamic and often conflicting but are primarily driven by the activities taking place within the building. For example, the type of occupants and needs in an office building will be different from those of a residential building, manufacturing plant, shopping mall or religious structure. Many buildings include mixed-use spaces and must accommodate a wide range of individual differences among diverse occupants (e.g., culture, age, physical abilities). It is critical to examine, understand, and incorporate perspectives of a building's occupants in the design process and to dynamically adapt buildings to accommodate dynamic systems. This can be done using traditional research methods (e.g., participatory action research, focus groups) or deploying novel sensing technologies that provide data streams to learn how people

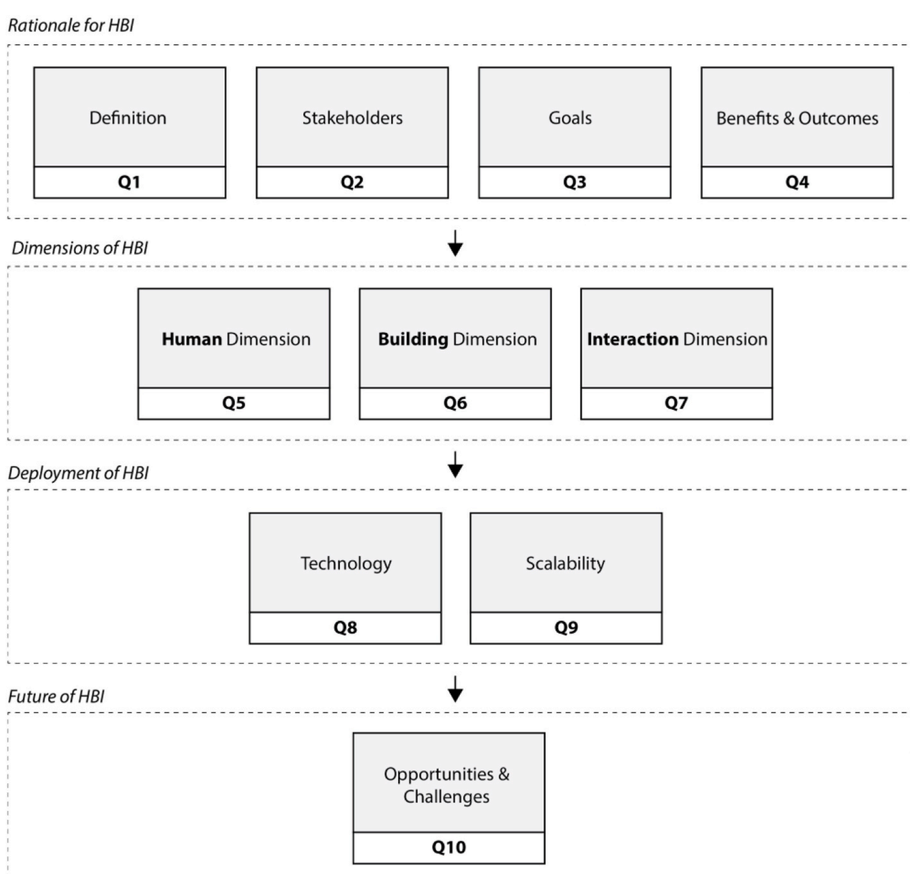

Fig. 1. Focus and organization of ten questions.

interact with buildings and among themselves [29].

Researchers: HBI research requires active engagement of scholars beyond those from conventional building and engineering sciences to include additional areas of engineering, computer and information scientists, psychological and social scientists, and occupational and health scientists, among others. With an increasing focus on the integration of technologies and emergence of smart buildings, engineering, computer, and information scientists are needed. HBI connects and combines research in HCI with research on built environments [8] and research on occupants and occupant behavior (e.g., such as Annex 79 [30]). HBI fosters interactions with non-digital elements of the building through digital means [7], requires engineering of sensors, and leverages data-driven methods that capitalize on combinations of multi-modal data made in sensing, data mining, and actuation techniques [8]. The interactions between occupants and buildings necessitate expertise in multiple human aspects as part of HBI research, including psychological, physical, and physiological responses to environmental stimuli [31] and the interplay of social dynamics with physical and spatial aspects of the built environment [7,8,32]. Data collection and analysis of these interactions, and understanding human occupant preferences, emotions, behaviors, and health outcomes requires collaboration among social and health researchers such as cognitive scientists, psychologists, occupational therapists, and public health scientists.

Contributors: Besides researchers in academia, numerous contributors are critical to include at early stages and throughout the research process. Conventional contributors involve professionals typically engaged in building projects such as architects and engineers, and industry partners in planning, design, construction, and other related areas. However, the cross-disciplinary nature of HBI requires the involvement of contributors with other specialized skills. Importantly, the technology industry has a significant role in the manufacture and supply of equipment and tools for HBI applications, such as sensors, as well as development of infrastructure for collecting and processing data (e.g., Building Information Modeling (BIM), virtual 3D models, and the Internet of Things (IoT). As data logging increases, contributors in information technology are increasingly important to monitor data privacy and ensure that the appropriate computing power, networks, and other data storage (e.g., cloud computing) or processing capabilities are in place to support the needs of smart environments. To promote effective behavioral, social, and health components of HBI research a variety of experts might be considered, for example artists to design soundscapes or murals to elicit specific emotions within a built environment, accessibility consultants to provide recommendations for universal design of physical spaces, or health practitioners to identify opportunities for health-promoting designs (e.g., green space).

Authorities: Multiple levels of authorities should be considered as key stakeholders in HBI efforts [26], beginning with building owners, managers, and local governments, expanding to regional and global authorities. At the most confined level, the owner or the organization that occupies a building can have a significant effect on its operations [33]. Additional local authorities who create regulations affecting a building's use, design, and operations include building managers or boards (e.g., condo owners association), and associated township or city agencies, policymakers, and legislators. Regional authorities at the state or national scales influence HBI through policies or regulations that either cause barriers or drive positive changes [26]. For instance, governments can improve smart home adoption by regulating the market, enforcing standards, safeguarding privacy, or subsidizing pilot projects or initial investment costs [34]. Global authorities most often create social policies through consensus building or facilitate a need for building design through broad reaching governmental actions. The media should also be considered a critical stakeholder for the field of HBI, as it often serves as an intermediary between traditional authorities and the public to facilitate change or adoption of new practices.

2.3. Q3: What societal goals can be addressed through HBI research?

Among many areas of broad impact, thoughtful HBI research can target three critical societal goals: (1) promoting *equity and inclusion* of individuals who engage within buildings and their surrounding features (e.g., entrances, walkways), (2) supporting *environmental sustainability and human resilience* in the face of environmental, social, or other hardships (e.g., disaster response, homelessness), and (3) addressing evolving concerns of *privacy, security, and trust* related to the increased use of technologies within everyday environments.

Equity and Inclusion: There is a vital need to undertake research that ensures building design is inclusive to the needs of diverse populations. HBI studies of building operations using limited populations are typically not generalizable to all building occupants (e.g., basing indoor thermal comfort on male samples) [27,35], and the development of HBI technologies using homogenous samples can lead to biased performance (e.g., racial bias in computer vision applications) [36,37]. In addition to building operations and technologies, the needs of many communities have often been overlooked in building design. As one example, low-income communities in urban settings face substantial disparities in accessing nature due to physical and social barriers [38, 39]. These neighborhoods present less open space for physical activities and greater density of fast-food restaurants, which is linked to obesity among children [40]. HBI solutions could be useful for rethinking the design of buildings within these neighborhoods to provide access to nature (e.g., rooftop parks), open spaces for play (e.g., courtyards), and integration of technologies to support healthy living. As another example, in the U.S., racial segregation has been associated with discrepancies in built environment conditions. In Southern California, children exposed to high levels of traffic-related air pollution at homes or schools were more prone to asthma; African American children were the most affected population [41]. Broadening recruitment within research studies to incorporate data from diverse samples who have varied physiological, psychological, and lived experiences will strengthen HBI research and promote equity and inclusion of all individuals within built environments. Research should incorporate meaningful engagement with diverse communities of occupants to ensure that the full spectrum of human needs is identified before initiating technology, operation systems, or building design. Moreover, deepening our understanding through HBI research on the impact of building design on human health and well-being can inform novel, low-cost solutions that can lead to meaningful increases in well-being. Attention to agency and sense of control in our increasingly digital building environments is crucial along with a shift in thinking about building operations not only as interventions but rather as interactions acknowledging that occupants are participants rather than recipients.

Sustainability and Resilience: In the U.S., buildings alone account for 36% of our Green House Gas emissions and 40% of U.S. energy consumption [42]. Buildings designed with environmental sustainability at the forefront (e.g., decarbonized or net zero-energy buildings) often fail to achieve their environmental goals, not due to their design but rather a lack of alignment with the needs and behaviors of occupants, which is clearly identified and highlighted by Annex 79 [30]. Through HBI research, we can prompt more sustainable behaviors, for example, through digital interfaces [43,44], lighting control strategies [45], and understanding of the impact of movable spatial layouts [46]. New technologies for lighting and air distribution as well as dynamic, mixed control systems that facilitate natural ventilation [47,48] can lower the environmental impact of our buildings and increase our resilience to climate change impacts. In addition to sustainability, HBI research can further societies' resilience against disasters, which are generally divided into two types: naturally occurring (e.g., tsunamis, earthquakes, hurricanes, pandemics) or human-generated (e.g., wars, terrorist activities, accidents caused by negligence or incompetence) [49].The resilience of the built environment is measured by its ability to resist and adapt to sudden changes caused by a disaster to maintain or resume adequate functioning levels. Examples of HBI frameworks applied to disaster resilience include how a schools' design can protect its occupants during active shooter incidents [50],how buildings can support vulnerable populations during natural disasters [51], and how to establish building preparedness plans to respond during extreme weather events [52].

Privacy, Security, and Trust: Privacy is a core component of any socio-technical system that collects personal data from its users [53]. HBI stakeholders must confront ethical challenges both directly and indirectly at every stage of the study, design and implementation process [54]. In developing HBI technologies, HBI researchers must responsibly manage captured data, especially highly personal and potentially sensitive, stigmatic, and exploitable personal data. Differential privacy [55, 56], as well as new vehicles for stewarding data through data intermediaries such as data trusts, offer a way to access the benefits and insights of aggregated individual data while preventing its access by a single entity with power over those individuals [57]. Contemporary solutions, such as edge computing, could be a solution for avoiding data storage and improving security and privacy while increasing reliability, resiliency, and scalability of HBI solutions. In addition to technical solutions for privacy and security, policy solutions are also needed and early engagement with stakeholders can facilitate their adoption. Finally, security must be considered during HBI research as it is fundamental to any system collecting information with privacy risks and can be challenging when handling multiple data sources simultaneously.

2.4. Q4: How can HBI research support human quality-of-life?

Through basic inquiries and subsequent development of applications, HBI research can support diverse preferences, needs, and dynamics among stakeholders to support overall quality-of-life. According to the World Health Organization (WHO), quality-of-life refers to "*a broad ranging concept affected in a complex way by the person's physical health, psychological state, level of independence, social relationships, personal beliefs and their relationship to salient features of their environment*" [58]. A brief overview is provided as a foundation for HBI researchers to consider how their work can support quality-of-life for building occupants and stakeholders who differ in gender, age, ethnicity, functional ability, and other personal factors across the six domains identified by the WHO.

Physical Health: Physical attributes of health include common medical diagnoses, as well as physical sensations, body functions, and sleep patterns. Novel HBI methods have been shown to significantly reduce physical discomfort by delivering services at the right time and at the right place. Mimicking a similar paradigm in "precision medicine," buildings can provide superior performance via personalization and optimization of services. Examples include personalization of thermal comfort [59–61]and visual comfort [62,63], personalized air delivery systems [64,65], and personalized sleep quality systems [66].

Psychological Health: Psychological health refers to the cognitive and emotional status of individuals. State-of-the-art HBI methods are now capable of measuring human activities [67] and emotions [68]in a non-intrusive manner. Such information can be leveraged to adjust building operations to enhance cognitive performance and productivity [69] and improve occupants' emotions [70]. There are opportunities for HBI to support the natural physiological decline that occurs with aging, such as lessened cognitive and sensory abilities, and to provide monitoring or assistance for other individuals with cognitive deficits or mental health conditions.

Level of Independence: Independence is closely associated with mobility and activities of daily living (e.g., cooking, laundry). There are a significant number of things that can moderate an individual's level of independence, including acute injuries (e.g., broken bone), congenital disorders (e.g., cerebral palsy), sudden-onset diagnoses with long-term implications (e.g., stroke), chronic conditions (e.g., arthritis), and a variety of aging related changes like frailty [71]. Novel HBI methods should consider how to support occupants across all types of needs that can promote movement around buildings, performance of daily activities, and engagement in all types of extra-ordinary activities. Navigation apps and robots [72] and assistive robots [73] are examples of emerging technologies to support independence within buildings.

Social Relationships: Social relationships involve personal interactions that benefit individuals through active participation in common activities and shared thoughts, feelings, and experiences. Such interactions enable the development of intimacy and the creation of support networks. Importantly, stronger social relationships are associated with longevity and studies have demonstrated a 50% increased likelihood of survival when compared to people with poorer social relationships [71]. An example of HBI research to support social relationships is peer-based eco-feedback (i.e., personal energy usage normalized based on peers). While promoting pro-environmental behavior change, these kinds of solutions can also lead to community engagement and the creation of support networks [74].

Environment: Environmental factors include aspects of the physical environment, as well as safety, security, and transportation. Physical factors are often core considerations in HBI research (as discussed in other questions), as they are intertwined with building design and operations and frequently intersect and impact other aspects of quality of life. The deployment of interactive user interfaces to enhance observability and controllability of the environment is a commonly used example [75].However, additional areas of opportunity related to other environment factors can also be considered in HBI research. For example, decentralized identification techniques could enable advanced safety and security in buildings [76].

Spirituality, Religion, Personal Beliefs: This quality of life domain relates to how individuals cope with and ascribe meaning to their engagement and participation in daily life, which is often (but not always) supportive to individual well-being [58]. Within buildings, this domain is most often considered in architectural and design choices that are related to a specific purpose or use of the built space (e.g., buildings for worship or gathering) but can also complement a building (i.e., a walking meditation labyrinth located in a hospital). There is a dearth of research that considers spirituality, religion, and personal beliefs within the context of HBI, which highlights an opportunity for innovation. For example, how to design spaces in multi-use buildings that support social gathering or quiet contemplation, how do spiritual practices or beliefs of occupants change the way spaces are used, and how can building technologies be designed to adaptively respond to different beliefs of multiple occupants [77].

2.5. Q5: What core concepts related to effective human engagement in daily activities should be considered in HBI research?

HBI research can identify and ameliorate challenges and barriers to successful human engagement in the buildings where we live, work, and play by addressing needs related to *efficient mobility* within the environment, *effective performance* of daily activities, and *meaningful interpersonal interactions*.

Efficient Mobility: To achieve effective human engagement in daily activities, it is essential to consider how buildings can be easily and equally accessed and navigated by all users while minimizing the requirement for individual accommodations. An important concept for HBI research to leverage is universal design, which aims to design building features that are inclusive and accessible for individuals with diverse demographic characteristics and abilities [78–80]. Seven principles for universal design include: equitable use, flexibility in use, simple and intuitive use, perceptible information, tolerance for error, low physical effort, and size and space for approach and use [81]. As an example, sloped entrances and automatic doors afford equitable access to buildings and rooms for individuals with all types of physical ability levels. A similar concept, 'aging in place,' refers to designing living and workspaces where people can remain as they age [82–84]. AI could boost such accommodations by adapting the space based on the (changing) needs of the occupants. HBI research can then further consider optimizing the efficacy, productivity, and performance of individuals and groups engaging in buildings.

Effective Performance: Building-specific characteristics can support effective individual engagement in daily activities (e.g., employee efficiency [85]), ongoing or long-term performance (e.g., older adults living at home [86]), efficient performance among and across occupants (e.g., traffic flow through airports [87]), and effective response in acute or emergent situations (e.g., successful wayfinding in emergencies [88]). Studies that have considered a building's environmental design(e.g., lighting, open space) relative to human performance have shown a direct association with design and overall performance across different occupant experiences, such as when utilizing both worker and patient perspectives in design of healthcare facilities [89]. An opportunity for HBI research is expanding support for a more diverse spectrum of individual occupants (see Q3). One example is designing building infrastructures to support the performance of neurodiverse individuals [90,91] who may be hyper- or hypo-sensitive to sensory stimuli (e.g., light, sound) [92]. HBI research is well-situated to examine aspects of the building and technologies that support such individuals, particularly for enhancing performance in workplaces that could, for example, minimize distractions, reduce noise, or alter other sensory features of an office environment [90].

Meaningful Interpersonal Interactions: Engagement and participation in social activities [93]are important to human health and well-being [94], and social isolation correlates with increased mortality in older populations [95]. Thus, promoting social engagement within built environments is a vital consideration for HBI research. Building design should consider how to best connect and strengthen the community using public or shared spaces [96] while balancing the needs of individual privacy [97]. The promotion of meaningful interpersonal interactions can support collective efficacy, that is, enhancing shared experiences among neighbors, co-workers, or other individuals working together for a common good [98]. Higher collective efficacy is associated with positive health outcomes [99], and lower collective efficacy has been associated with negative community-based outcomes (e.g., lower collective efficacy mediates the relationship between abandoned buildings and crime rates within a neighborhood [100]). Buildings can play a significant role in supporting collective efficacy in workplaces to improve group performance [101,102]. For example, studies have shown how aspects of the physical environment such as spatial organization, architectonic details, resources, views, and ambient conditions, can promote group creativity [103]. While social engagement and collective efficacy are examined in other design and engineering literature, the paucity of these concepts integrated within HBI research creates an opportunity for future work.

2.6. Q6: What types of buildings, features, and attributes should be considered within HBI research?

HBI research should consider private and public buildings across all functionalities (e.g., residential, commercial, educational, institutional buildings). Moreover, HBI research is not only restricted to buildings' indoor environments but also includes all types of built structures such as the adjacent indoor or outdoor areas in which activities related to the building take place. For example, with the recent global pandemic, the use of outdoor extensions of buildings has become more prevalent (e.g., restaurants using sidewalk dining). There is an opportunity for HBI research to leverage this shift to maximize building design, operations, and technologies to minimize barriers (e.g., mobility challenges) and promote human performance and well-being as occupants move between indoor and outdoor spaces. For example, open-air office work provides a connection with nature which can reduce work-related stress, provide an opportunity to disconnect from uncomfortable work conditions, and create a stimulating work experience [104]. Similarly, children seek recess time to leave the constraints of the classroom and enjoy their time in the playground, which presents physical benefits, social development, and positive emotional impacts [105].

Different building attributes shape occupants' experience and therefore lead to or influence interactions with the building. These attributes can be divided into two categories: static and dynamic. Static attributes represent building parameters that cannot be changed through occupants' actions, such as area or number of rooms, but define the human experience [106]. For example, an open-plan office setting can promote social interaction, collaboration, and creativity, but lead to privacy concerns or performance issues due to uncontrollable noise; such concerns are less prevalent among employees working in private offices [107], but these spaces may limit social interactions. Alternatively, dynamic attributes include mobile items (e.g., furniture, shades, doors/partitions) or operation systems (e.g., HVAC, electrical, lighting, security) that can be manipulated by occupants or automated technologies. Methods for temperature adjustment is one of the most common examples of dynamic attributes. Occupants can manually adjust thermostats, open/close windows, or turn on/off fans or heaters [108,109], and intelligent systems can make similar manipulations to adjust thermal environments based on occupants' preferences, outdoor weather conditions, or other daily activities [110]. Dynamic attributes often incorporate numerous features including physical structures, user-interfaces, sensors, and technological infrastructure enabling automation.

In addition to use and modification of existing structures, HBI concerns should be thoughtfully included in early stages of new building development. Simple decisions made during the design and construction phases by designers and contractors might have a tremendous impact on the way occupants interact with the buildings during operation phases. For example, installing proper thermal insulation to slow the transfer of heat through a buildings' enclosure has a ripple effect on numerous future static and dynamic attributes and human performance concerns [111,112].In building design, attention is often paid to overall room layout, but other factors may be just as important to future HBI concerns. For example, prominent location near a building's entrance makes elevators an appealing and easily accessible choice for occupants, whereas staircases are often inaccessible (e.g., narrow). Changing the design to make stairs centrally located and attractive can boost the usage of stairs by up to 70% [113]. Such design choices and altered usage patterns impact building-level operations (e.g., traffic patterns, elevator maintenance, stairwell cleaning or carpet wear) and can support occupant goals for improved physical activity and health.

2.7. Q7: How do buildings and their occupants influence each other toward individual and shared objectives?

HBI is a bidirectional process where the intention and behavior of buildings and occupants can affect each other via a wide spectrum of interaction interfaces [114]. The types of interfaces can significantly affect occupants' motivations for interaction, behavioral patterns, and outcomes (e.g., perceived satisfaction and building energy efficiency) [109]. Given such interdependent relationships, HBI research examines the dynamic interplay between characteristics of occupants and buildings using a variety of methods and technology applications.

One of the most widely studied interactions between occupants and buildings in HBI research is the interplay between indoor environmental quality (IEQ) factors (e.g., lighting, temperature, humidity, air quality) and occupant outcomes (e.g., comfort, attention, productivity, health, collaboration). Occupants can interact with buildings via various interfaces (e.g., windows, thermostats, lighting devices, appliances, etc.) and adjust environmental settings [109]. To further incorporate occupants' needs and objectives into building control, researchers in the HBI field have designed a multitude of interaction channels, such as programmable thermostats [115], mobile devices [116], web interfaces [117], and touchscreen interfaces [110] for occupants to provide their preferences and feedback, and for the building control system to interact with the occupants. An important HBI concern in this area is that the objectives of occupants and buildings may not always be the same. For instance, occupants may open windows to admit fresh airflow, but this behavior can greatly reduce building energy efficiency during the heating season [118]. Energy consumption reductions may also lead to (in some cases) decreased thermal comfort [116], improper lighting for activities [119], or reduced productivity [120]. To this end, prior studies have considered the balance between occupant comfort and energy efficiency and proposed control strategies to accommodate different objectives [121,122]. HBI researchers have also employed eco-feedback interfaces and information visualization systems to increase occupants' awareness of the building's objectives and adapt their behavior accordingly [123,124]. Furthermore, approaches to accommodate individual preferences for automation have been developed that enable sharing the control of the environment between occupants and the building under intermediate levels of automation [110].

Emergency response is a second exemplar of examining the interplay between buildings and occupants. The impact of various building attributes (e.g., signage [125], corridor configuration [126], visual access [88]) on occupant responses during emergencies has been widely examined in the HBI literature. For example, when navigating to a safe destination, occupants make wayfinding decisions based on visual access, the degree of architectural differentiation, signage, and layout configurations [127]. On the other hand, building safety design can be informed by the knowledge about occupant behavior through a "behavioral-design" approach [128]. The integration of building features and knowledge of occupant behavior can lead to novel and dynamic solutions to support emergency response, such as studies that have investigated intelligent signage systems that provide real-time instructions to occupants based on the location of hazards [129,130].

These examples demonstrate future opportunities for HBI research to better understand and leverage the dynamic process that occurs between occupants and buildings and individualized approaches that consider evolving factors such as building types [131], climates [132], occupants' demographic backgrounds [133], and occupant comfort with technology or automation [134]. HBI researchers are extending these inquiries to consider the dynamic interplay over time and exploring interactions across occupant outcomes (e.g., comfort, productivity [120]) with building goals (e.g., energy efficiency [135]). As an example, iterative analysis of changes in productivity coupled with changes in set-points have been examined [136] to identify the optimal compromise between goals, both in the moment and over time. Similarly, HBI research has been examining the changing number and compositional mix of occupants on outcomes in residential [74] and commercial buildings [137], and in some cases developing models based on more complex combinations of variables such as energy conservation, peer networks, and spatial location in a multifamily residential building [138]. Despite these efforts, understanding, modeling and ultimately optimizing how occupants and buildings influence each other toward shared objectives demands more sophisticated models to understand and characterize interdependencies that may exist across the spectrum of building characteristics, ways of measuring stakeholder outcomes, and the complex combinations of building and occupant goals.

2.8. Q8: What technological advancements enable HBI research?

Occupant behavior is influenced by many complex variables because of the need for collective integration of physical phenomena, physiological states, and social and psychological factors [29,139]. Furthermore, the operation of building systems, occupancy patterns, and occupant states can change dramatically over time (on a daily, weekly, or seasonal basis). To holistically capture and respond to these complex variables, HBI research enables "*self-driving*" buildings, where building systems can operate according to societal goals and/or support quality-of-life as discussed in Q3 and Q4, respectively. Historically, monitoring and control systems installed in buildings have been relatively unsophisticated. In residential buildings, most end-uses are controlled manually by occupants (e.g., lighting) [109] or by simple devices (e.g., thermostats) [140]. In large commercial buildings, more complex equipment (e.g., large HVAC systems) is controlled by building automation systems (BAS) [141] that are installed to automate multiple building services, such as thermal conditioning, lighting, and security systems [142].

Due to the recent advancements in sensing and automation, by combining embedded sensors, analytics, and control techniques, we can achieve personalized autonomy, where *bidirectional* interaction and communication between occupants and building systems is established. In the last decade, a multitude of groundbreaking products have gained traction in the marketplace, including cost-effective and reliable IoTs (Internet of Things) devices [143], smart home platforms [144], wearable devices [143], and energy management and information systems (EMIS) [145]. These technologies are rapidly transforming buildings into data-rich networks of sensors and actuators that are equipped with modern application programming interfaces to enable customization. These advancements contribute to enabling HBI by supporting more granular and occupant-centric sensing and control, systems and applications that deliver personalized services, and virtual representations of buildings that serve as the real-time counterpart (aka, digital twin) [146] of buildings with data and information from physical buildings and utilize AI and simulations to optimize the operation of building systems while preserving the privacy of occupants.

While existing buildings are often under-sensed [147], recent research has demonstrated that granular and accurate sensors to monitor indoor environmental conditions (i.e., temperature, humidity, illuminance, acoustics, and air quality) can *contextualize* those conditions. A variety of sensing modalities and computational techniques could be leveraged to enable this contextualization. Computer vision techniques applied to video and images collected from surveillance cameras can be processed to extract occupant-related information such as time spent in certain areas or more complex variables, such as emotions [148]. However, these devices could be perceived as privacy-invasive and, on many occasions, require storage and computationally expensive data processing. In contrast, non-intrusive technologies could improve privacy concerns. To this end, infrared (IR) and LiDAR technologies can provide body tracking, occupant action monitoring, posture recognition, and space use information [61,149], without conveying personal information [123,150]. Researchers have introduced approaches to indirectly infer information about the occupants and the surrounding environments by utilizing building structures as sensors [151–163]. For instance, building vibration responses can be used to sense occupants and identify their activities**,** and the number of occupants at a given location along with the direction of their traveling [164]. Similarly, CO_2, VOC, and acoustics data have been shown to accurately detect occupancy levels and activities [165,166]. Currently, such information is mainly utilized to optimize the control of HVAC, lighting, shading systems, and other building systems [143,167] are referred to as context-aware operations. However, with technological advances in furniture-integrated sensors [168], wearable sensors [169, 170], and smartphones, a wide range of occupant information (e.g., count, activity, and physiological and psychological data) can be collected and coupled with building performance and environmental data to facilitate more advanced HBI services.

Increasing adoption of sensors and smart devices, in combination with advanced artificial intelligence techniques/frameworks, affords the development and deployment of more optimized and occupant-centered control (OCC) strategies [171]. AI-based control algorithms are of interest [172,173], since they do not require the manual development of a mathematical model of the building, a major challenge in scaling up state-of-the-art solutions [174]. Some OCC approaches include reactive response to occupancy in real-time, control to individual occupants' preferences/needs, control catered to individual behaviors or activities, and control based on the prediction of future occupancy/behaviors [175]. The OCC research could benefit from a more holistic approach and integration with other disciplines, such as behavioral sciences. Specifically, an increasing body of research suggests psychological theories (e.g., theory of planned behavior) can explain occupant behaviors, judgment, and decision making. By applying psychological, sociological, and economic theories in building systems' optimization algorithms [114], future buildings can be more efficient in bidirectional HBIs.

Finally, AI has been successfully used to develop virtual assistants for smart homes, a significant improvement over traditional methods of interfacing humans with technology [176]. Similarly, through the integration of AI and building simulation platforms, the data streams available to BAS can be used to predict and forecast building operations and indoor environmental conditions to achieve societal and occupants' goals. Specifically, synthetic data streams based on the real sensor readings could be generated to capture the underlying distributions of the actual data without exposing user-sensitive information, addressing privacy concerns. HBI research should take advantage of these enabling technologies and keep exploring the interface between AI and humans and their respective agencies [177].

2.9. Q9: How is HBI applied across scales from a single building to a community, city, or beyond?

Humans develop goals and engage at individual, interpersonal, community, and societal levels, which can be enhanced or enabled by considering interactions across scales, from a single building (i.e., micro-level HBI) to multiple buildings (i.e., macro-level HBI). The scaling up process from micro to macro is a fundamental component of HBI that is often underrepresented in the literature, despite its outstanding opportunities. For example, in addition to considering the personal comfort and energy goals within an individual building, HBI explorations can be extended for optimization of these objectives among a community of occupants distributed across multiple buildings (especially if these buildings share resources). In this way, HBI research should not be constrained to the level of single buildings and, instead, can address issues across interconnected structures or communities. Macro-level HBI research and development should elicit preferences and objectives from multiple constituencies, design mechanisms for efficient deliberation and decision making across different buildings, explore effective mechanisms for transferring knowledge across the system or network, and identify solutions for coordinating efforts among various building-occupant systems. This work should include the development of practices, protocols, or applications to assist in sharing resources or facilitating occupant flows between buildings. Effective approaches to scale from micro-level to macro-level HBI will primarily be driven by development and implementation of innovative technologies focused on three primary objectives fundamental to HBI systems: *awareness*, *planning/learning*, and *control*.

Awareness: Macro-level HBI solutions that aggregate micro-level direct or indirect measurements of phenomena occurring across building networks can support increased awareness by both occupants and buildings. For example, tracking energy use and associated carbon emissions across collections of buildings used by a community [178] and displaying the results through eco-feedback systems [179] can drive changes in energy-use behavior by the community via raising awareness of a shared outcome [180,181]. Understanding how information is diffused across a community of occupants spanning multiple buildings is critically important for designing effective interfaces, interventions, and policies, which has been demonstrated in the context of disaster response [182] and energy conservation practices [183]. Increased building awareness can support efficiency in design, operation, and maintenance of collections of buildings and their surroundings. For example, information about user behavior (also called occupant-centric urban data [184]) relative to shared resources across buildings can increase awareness by the building systems and policies that mediate the exchange of information. A particular example is peer-to-peer energy markets based on user behavior [185]. Likewise, building networks can aggregate data to better understand naming conventions used by humans to describe sensing and control resources in building automation systems [186] or use time-series data to infer those descriptions [187].

Planning/Learning: Macro-level HBI can leverage micro-level awareness to derive improved plans of action for meeting broader occupant, building, or societal objectives. Traditionally, planning and learning processes for buildings and communities have been carried out by human institutions and sometimes codified into laws, bylaws, professional guidelines, and other policy instruments. For example, bylaws for condominium associations include documents that contain rules and regulations for human behavior and building design/operation that are hypothesized to support better quality-of-life for residents. Increased awareness from HBI technologies within a condominium network regarding behaviors and interactions between building systems and occupants can support planning and learning processes that will augment these bylaws to move beyond hypotheses to empirical and objective solutions to support quality-of-life. Information and strategies that are typically siloed at the building level can be shared and empirically compared against actual behavior and outcomes using sensors in multiple buildings to drive planning models. For example, macro-level HBI data could forecast shifting capacities required throughout a day or week for electricity usage in a particular community based on patterns or fluctuations in the use of individual residential appliances [188]. Planning activities can also benefit from the collective sharing of information across buildings without requiring new knowledge to be distilled. For example, wayfinding solutions that consider paths connecting multiple buildings can only be conceived if models for building layouts are available for all the buildings in the path [189].

Control: Awareness and planning provide a foundation for operational decisions in day-to-day, long-term, and situation-based circumstances across scales of the built environment. Macro-level HBI control applications can be used to achieve grid-level objectives that cannot be met by electrical loads in an individual building. For example, energy conservation through the coordination of minute-by-minute operation across hundreds of thermostatically-controlled electrical loads in buildings (e.g., electric water heaters or air conditioning units) [190–192] or allocation of distributed energy resources (e.g., solar panels and electric vehicles) and community storage [193,194]. Distributed operational strategies could be expanded to include more complex objective functions that account for indoor air quality [195–197] or human well-being [198–200] with varying short-term to long-term operational horizons. Enabling distributed control and operations (in addition to the need for awareness) calls for robust and scalable methods that empower the modeling of dynamics and behavior of systems at different levels to facilitate optimization. Beyond operations at the building systems level, by relying on the fast-paced growth of communication technologies that allow for communication between transportation systems and infrastructure, control strategies could be expanded to smart city/infrastructure with a focus on addressing buildings or neighborhood needs. An example application is the smart city control that facilitates the access of first responders that are addressing a health emergency or similar event [201]. Research on distributed real-time or predictive control calls for research not only on the control strategies but also their dependencies on sensing and awareness infrastructure, as well as human cooperation and response to account for the system's uncertainties.

2.10. Q10: What are the challenges that must be considered in HBI research and what are the opportunities?

Several challenges and opportunities that exist for expanding HBI research are described in the previous questions. Here, we identify several more of such challenges and opportunities.

Personal and geographical factors have not always been considered in HBI research and should be. Indeed, studies on sensing technologies, for example, mostly have been conducted in higher-income countries [202]. There is emerging evidence, however, that several personal and geographical factors (e.g., income) moderate the effectiveness of such technologies, which necessitates us to expand the scope of HBI research to focus on different populations. There is a need to include diverse populations in research studies, especially from underrepresented backgrounds and low-income communities, people with disabilities, and the needs of neurodiverse individuals to develop equitable, inclusive, accessible, and affordable solutions for improving the quality-of-life for all.

While there are notable efforts that bring together interdisciplinary experts for HBI research (e.g., Annex 79), aspects of HBI research have traditionally been conducted separately in the disciplinary silos of architecture, psychology, ergonomics, or engineering. There is a need to continuously develop and support interdisciplinary research efforts to tackle complex challenges that might not be addressed by a single discipline. Simultaneously, the HBI field should engage local authorities from cities and municipalities, policymakers, owners, and other stakeholders in research as well as to support practical HBI applications to address issues not just during design and/or construction but throughout the building lifecycle.

Getting large enough sample sizes has been another challenge for HBI research involving human subjects. Many studies [203–205] have relatively small sample sizes which limit the generalizability of their findings. To advance current HBI research and make meaningful generalizations across different contexts, there is a need to develop collective data repositories that will enable in-depth analysis of data from different studies. Some examples of efforts to gather data from different studies include the RP884 Database [206], Thermal Comfort Database II [202], ASHRAE Global Occupant Behavior Database [207], and longitudinal dataset of human-building interactions in U.S. offices [208]. While most of the existing large-scale databases have been focused on thermal comfort and energy, there are similar opportunities for developing datasets that focus on other aspects of HBI.

While some progress has been made to tackle various personal, group and societal objectives, the bulk of research in this area has focused on comfort, energy and building performance rather over other factors that contribute quality-of-life such as health, productivity, and well-being. However, they are difficult to assess, as common definitions have not been established [209]. To achieve truly adaptive buildings that promote quality-of-life, we need to establish common metrics (and identify/design effective sensing and data acquisition modalities) to measure different aspects (e.g., social wellbeing) of the quality-of-life. Similar to the widely accepted ASHRAE 7-point thermal comfort scale, there is a need to develop well-accepted metrics to measure the dimensions of other objectives to advance HBI research with the ability to compare generalized results across different studies and develop technological solutions that are scalable [7]. In addition to the focus on improving the quality-of-life for occupants, buildings also need to meet societal goals of improving sustainability, resilience, safety in general as well as during extreme events (e.g., heat waves) or rare events (e.g., a global pandemic), equity and inclusion. This requires consideration of different objectives not just at the building level, but to scale those objectives to a network of buildings at community and city levels. As buildings try to optimize different aspects such as health, productivity, and sustainability, an emerging challenge is to balance conflicting objectives with multi-objective optimization techniques and develop suitable modeling and simulation approaches to characterize different aspects of occupant behavior and building performance. Furthermore, as technological solutions scale, issues of privacy, security, and trust must be addressed to ensure that HBI data is used only for applications agreed upon by users and there is trust and collaboration between users and buildings.

Finally, HBI has largely focused on single buildings. Besides research on mathematical optimization and game theoretic approaches that enable human-centered distributed control, research has not considered the scalability of, for example, control and awareness technologies. Although studies have shown the efficacy of distributed control, implementation of those methods calls for solutions that enable scalable predictive models while accounting for sample efficiency and safety of the algorithms. In recent years, distributed ledgers and blockchain technologies have also contributed to facilitating distributed operations and are considered promising.

3. Conclusion

With technological advancements, the built environment is now considered an intelligent partner. Homes, office and industrial buildings, airports, or other infrastructure, as well as the furniture, appliances, and building materials that compose the built environment can engage in and be the subject of HBI applications in a technology-enabled intelligent partnership. Thus, this paper introduces HBI as a promising research field necessitating effective collaborations within and across disciplines. All stakeholders, occupants (inclusive of diverse populations), researchers, building contributors (managers, owners, operators, contractors) and authorities play a major role in shaping an effective HBI. As outlined in the paper, thoughtful HBI research and applications can (1) target societal goals such as equity, inclusion, sustainability, resilience, privacy, security, and trust, (2) support human quality-of-life by promoting physical health, psychological well-being, societal relationships, feeling of independence, and spirituality, and (3) ameliorate human engagement in daily activities by addressing needs for efficient mobility, effective performance, and meaningful interpersonal interactions. Towards these goals, researchers in HBI should engage all stakeholders and identify the most pressing issues in the built environment.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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