Human-Building Interaction (HBI) (Occupant comfort and wellbeing, Human-centered IoT design, Adaptive workspaces and behavioral analytics

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ABSTRACT

The article offers a comprehensive integrative review of the interdisciplinary field of human–building interaction (HBI), aimed at systematizing its theoretical, technological and applied components. The introduction substantiates the relevance of the topic against the background of the rapid expansion of the intelligent building development segment and identifies a key research gap associated with the fragmentation of existing studies. The purpose of the study is to advance a dynamic process model of HBI by integrating three critical domains: occupant comfort/well-being, human-centered IoT design, and behavioral analytics. Unlike previous static taxonomies, this research posits a causal feedback loop where behavioral analytics serves as the mediating mechanism that translates raw IoT data into adaptive environmental responses, while human-centered design acts as the antecedent condition for user trust. The proposed framework redefines the intelligent building not merely as an automated facility, but as a sociotechnical system dependent on recursive learning between the occupant and the built environment. The study employs a systematic literature review (SLR) methodology following PRISMA guidelines to map the fragmented HBI landscape. The search strategy targeted peer-reviewed articles published between 2015 and 2025 in Scopus, ACM Digital Library, and IEEE Xplore, using the Boolean strings: ("Human-Building Interaction" OR "HBI") AND ("IoT" OR "Ambient Intelligence") AND ("Comfort" OR "Well-being"). Inclusion criteria prioritized studies offering empirical evidence of user-in-the-loop controls and adaptive systems. This academic corpus was triangulated with high-impact industry reports (e.g., Gartner, McKinsey) to ground theoretical models in current market technological capabilities. This dual approach facilitates a valid transition from theoretical synthesis to the proposed conceptual framework. The results obtained encompass: the development of a classification of conceptual HBI models; an analytical assessment of technological solutions for monitoring and maintaining comfort parameters (BEMS, adaptive façades, PCS); a systematization of human-centered design principles for the intelligent environment; as well as an assessment of the impact of adaptive spaces on work performance based on case studies. The conclusion demonstrates that the effectiveness of HBI is determined not by the degree of technological sophistication but by the quality of integration of human-centered principles and by the overcoming of sociotechnical barriers, above all the deficit of trust caused by data privacy risks. The information presented in this study will be of interest to the academic community, architects, engineers and specialists in real estate facility management.

Keywords: *human–building interaction, HBI, intelligent building, user comfort, Internet of Things, IoT, human-centered design, adaptive workspace, behavioral analytics, indoor environmental quality, user well-being.*

Introduction

The contemporary human-made environment is undergoing a radical restructuring as a result of the convergence of architecture, digital technologies, and the human sciences. At the epicenter of this transformation lies the concept of the intelligent building, which is ceasing to be a static object and is functioning as an active, self-adaptive ecosystem. The study of human–building interaction (HBI) is gaining particular importance against the backdrop of pronounced market dynamics: according to estimates, the volume of the global smart building market will increase from 98.5 billion USD in 2024 to 277.6 billion USD by 2034, with a compound annual growth rate of 11.00% [1]. This growth is fuelled by two main drivers: the tightening of public regulations in the field of energy efficiency (including the EU Energy Performance of Buildings Directive) and the large-scale deployment of Internet of Things (IoT) ecosystems [1].

At the same time, despite the technological momentum and favorable market expectations, the body of knowledge on HBI remains a saturated yet fragmented corpus of studies, bringing together heterogeneous perspectives, methods, and disciplinary approaches [2, 4]. A fundamental gap persists between the technical capabilities of intelligent buildings and the subjective, personal experience of users, for the enhancement of which these capabilities are intended [3, 4]. The historical priority of energy optimization has often been achieved at the expense of compromises in occupant comfort and well-being [5]. It is crucial here to distinguish these constructs: comfort is defined as an immediate physiological state of satisfaction with the thermal, visual, and acoustic environment (ASHRAE 55), whereas well-being represents a broader, longitudinal construct encompassing physical health, cognitive function, and psychological satisfaction [8]. This entrenched "one size fits all" practice ignores these individual nuances and, as a result, generates dissatisfaction with the environment [6]. Thus, the research problem takes shape as the need to integrate dispersed knowledge in order to construct a holistic, human-centered model of HBI.

The aim of the study is to provide a systematic, integrative analysis of the field of HBI by developing a coherent conceptual foundation that links theoretical models, technological tools, design principles, and application practices, and that also incorporates a critical assessment of the sociotechnical barriers to their implementation.

The scientific novelty lies in the proposed integrative synthesis of three key directions of HBI that are often considered in isolation – user comfort, human-centered IoT design, and behavioral analytics in adaptive spaces – into a single conceptual framework.

The working hypothesis advanced in this paper is that the effective implementation of HBI capable of genuinely enhancing user well-being and productivity is determined not by the degree of technological complexity as such, but by the quality of integration between human-centered design principles and robust feedback loops that can reconcile data-driven algorithmic optimization with the user's right to privacy.

This research holds direct relevance to current U.S. priorities in sustainable infrastructure and human-centered design. It aligns with the objectives of the U.S. Department of Energy's Building Technologies Office and the federal "Grid-interactive Efficient Buildings (GEB)" initiative, which promote the integration of adaptive systems and behavioral analytics into energy-efficient building design.

Materials and methods

The present study is based on the methodology of a systematic literature review, selected to map the multidirectional and interdisciplinary field of HBI research, to identify dominant thematic clusters, and to integrate results obtained in various domains of knowledge. This framework makes it possible to structure a fragmented body of work, to reveal stable concepts, and at the same time to diagnose gaps in existing research. The analysis of academic literature is complemented by an examination of high-level industry and market reports in order to align theoretical conclusions with actual economic and technological conditions.

The source base was formed in a targeted manner, with a focus on high academic and industry authority in accordance with current standards of scientific publishing, and includes two types of materials.

The core consisted of peer-reviewed articles selected from leading scientometric systems such as Scopus, ACM Digital Library, IEEE Xplore, and Springer. These publications provided theoretical, methodological, and empirical foundations for the analysis of conceptual HBI models, comfort-enhancing technologies, design

principles, and case studies of adaptive spaces.

To assess market dynamics, projected growth trajectories, and implementation barriers, analytical materials of key consulting companies, including Gartner and McKinsey, were used, along with specialized reviews of the smart building market. These sources provided critically important quantitative indicators of macrotrends and practical challenges relevant to the industry.

At the selection stage, all materials underwent filtering that excluded non-authoritative formats, which ensured the reliability of the empirical base and the validity of the conclusions obtained.

Results and discussion

Human building interaction (HBI) is a convergent research domain at the intersection of HCI, architecture, and urban design that goes beyond classical building science and systematically examines the dynamic, bidirectional relationships between people and the built environment, mediated by technologies [4, 12]. From this perspective, the building is considered not as inert infrastructure but as an active co-actor that shapes human experience and influences user behavior [4].

The theoretical landscape of HBI is composed of two complementary strands. The first follows the logic of HCI and interprets HBI as the transfer of human computer interaction principles into architectural practice: the emphasis is on designing effective and expressive digital interfaces through which users control building engineering systems and services [14]. The second is rooted in the Ambient Intelligence paradigm and focuses on the dissolution of computational intelligence into the environment itself: spaces become context aware, adaptive, and respond proactively to needs without an explicit request from the user [14, 15].

This article proposes a causal process model for HBI, moving beyond simple thematic aggregation. In this framework, Human-Centered IoT Design is the foundational layer that enables data capture without intrusiveness. Behavioral Analytics functions as the dynamic engine, processing this data to identify patterns (e.g., occupancy rhythms, thermal preferences). The output is a modification of the Building State (adaptation), which directly impacts Occupant Comfort. Crucially, this relationship is cyclical: improved comfort fosters trust, which encourages users to share more granular data, thereby refining the analytical model.

Thus, the effectiveness of HBI is not linear but recursive; a failure in 'trust' breaks the feedback loop, rendering the analytics ineffective regardless of sensor precision. These domains intersect in three interdisciplinary knots: Control systems, Trust and collaboration, and Modelling and simulation. The framework of the model is grounded in the fundamental values of fairness, privacy, and sustainability, which set ethical and normative constraints and quality criteria for solutions [12]. This foundation also serves as the organising principle for the subsequent analysis in this article.

The coexistence of HCI and AmI logics creates a productive tension. The HCI line strengthens agency and a sense of involvement by providing transparent control to the user, whereas AmI minimises cognitive load by striving for seamless, effectively invisible automation. Neither philosophy is self-sufficient: excessive automation can undermine the sense of control and trust, while overloaded control facilities provoke frustration and abandonment of use [17]. The most viable configuration appears to be a hybrid one, in which intelligent automation provides a reliable background level of functioning and the user always has access to a simple, intuitive channel for manual intervention. Such a mode of intelligent support simultaneously respects the autonomy of the subject and capitalises on the advantages of automation, thereby resolving the identified paradox.

Contemporary design practice is shifting from a narrowly conceived focus on energy efficiency to a holistic orientation toward indoor environmental quality (IEQ) and its impact on user health, comfort, and productivity, directly linked to the United Nations Sustainable Development Agenda Goal Good health and well-being [8, 9]. In this logic, a central role is played by building energy management systems (BEMS), which integrate sensors, controllers, and communication subsystems to optimize the operation of the complex. Modern BEMS employ IoT, cloud computing, and artificial intelligence methods, moving from statically predefined schedules to dynamic, context-sensitive control in real time [21].

Modern BEMS have evolved from simple reactive systems to predictive platforms. Rather than listing standard sensor typologies, it is more analytically relevant to focus on their integration capabilities. Contemporary architectures leverage distributed sensing (temperature, IAQ, occupancy) processed via edge computing to minimize latency. This shift allows BEMS to transition from maintaining static setpoints to

executing dynamic "comfort policies" that weigh energy costs against real-time user requirements [7, 21].

Adaptive facades are envelopes capable of real-time adjustment of their optical and thermal properties in response to solar radiation and changes in outdoor temperature, thereby maintaining thermal comfort and daylighting while reducing the load on energy-intensive heating, ventilation, and air-conditioning (HVAC) systems [19].

Personalized comfort systems (PCS) create a local microclimate around a specific user by means of individualized devices, ranging from smart desks with integrated fans/heaters to chairs with heating/cooling functions. Empirical evidence indicates that such solutions substantially increase satisfaction, as they account for interindividual variability in thermal and lighting preferences, which cannot be achieved with centralized schemes; at the same time, a potential productivity gain in the range of 0.5–5% is observed [6].

Human-centered design of IoT in the built environment reflects a paradigm shift from a technocentric logic focusing on functionality to a prioritization of the quality of user interaction with the building (UX) [26, 27]. This approach is becoming critical for enhancing satisfaction and ensuring successful technology adoption [14]. Non-intuitive, overloaded interfaces consistently lead to abandonment of systems, regardless of their technical strengths [17, 18].

Thus, there is a need for the systematic application of human-centered design (UCD) principles in the development of building engineering systems and their interfaces [17]. A basic step is the early identification of key user groups and their specific tasks before the development of an HBI strategy begins [14]. For example, the demands of a student in a university building (navigation to suitable study places) differ fundamentally from the needs of a facility manager (e.g., energy consumption control) [14, 16].

Among the key tools of human-centered design are building information modeling (BIM) and digital twins. These tools provide pre-occupancy evaluation (PrOE) of user experience by modeling comfort parameters, the luminous environment, and even probable affective responses to space prior to the start of operation [7]. In this way, the assessment of human-related factors is shifted to the early design stages rather than being postponed to the post-occupancy phase.

The integration of HBI, UCD, and digital twins radically redefines the ontology of the building. A traditional building is a static asset; a smart building with basic automation is a reactive system. A human-centered intelligent building operates as an interactive system that adapts to user actions and state [14]. Embedding a digital twin raises the system to the level of a learning one: it continuously models, simulates, and predicts optimal conditions, relying on real-time telemetry and user feedback. As a result, the building is transformed from a physical asset into a dynamic service platform, where the service is an optimized environment that supports well-being and productivity. This has direct business implications: owners cease to act only as landlords and become providers of measurable, high-quality experience, which justifies higher rental rates/valuation and opens new revenue streams (for example, well-being as a service).

Adaptive workspaces demonstrate HBI in action: ecosystems of IoT sensors (wearable electronics, smart desks, environmental sensors) provide real-time collection of biometric and behavioral data, forming loops of continuous feedback and adaptive environmental control [20, 25]. The analysis of specific precedents makes it possible to assess the feasibility and effectiveness of these approaches in practice.

Mediated Atmospheres (MIT): a prototype in which computationally controlled light, sound, and video projections create typologies of atmospheres, while biosensors (heart rate variability, facial expression tracking) register physiological responses. It has been demonstrated that such configurations affect concentration and recovery from stress, demonstrating a causal relationship between the characteristics of the digital environment and the physiological well-being of the user.

Smart desks: the workstation is considered an intelligent agent equipped with sensors and a PCS that monitors and personalizes the microenvironment, learning individual preferences and automatically adjusting conditions to increase comfort, preserve health (including reminders to change posture from sitting to standing), and enhance productivity [6, 25].

IoT-based performance monitoring: a study in the manufacturing sector revealed that the use of IoT for attendance tracking and control of labor indicators increases personal performance and operational efficiency by enhancing accountability and providing

real-time feedback.

Figure 1 presents a conceptual diagram of the adaptive workspace ecosystem that visualizes the feedback loop.
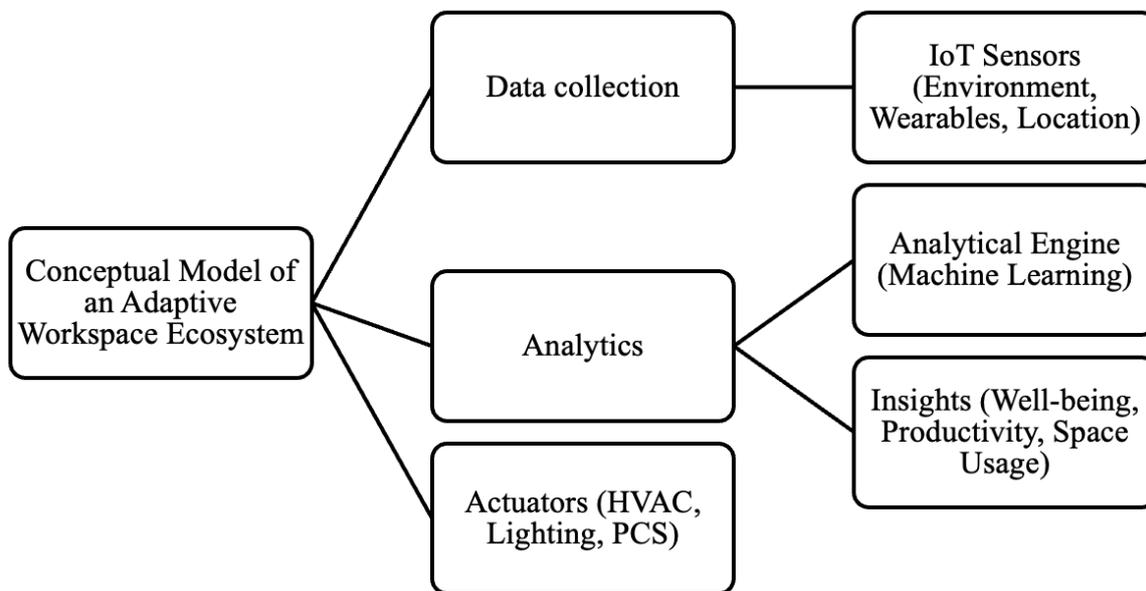
Fig. 1. Conceptual model of the adaptive workspace ecosystem (compiled by the author based on [6, 24, 25]).

Behavioral analytics based on IoT data demonstrates high accuracy in predicting employee performance (in particular, 89.2% when applying the XGBoost model). The greatest contribution to the prediction is made not only by metrics directly related to task execution, but also by contextual environmental characteristics, as well as behavioral aspects. Fig. 2 presents a characteristic relationship between CO2 concentration and the number of people in an indoor space, which underlies demand-controlled ventilation algorithms (Demand-Controlled Ventilation) [22].
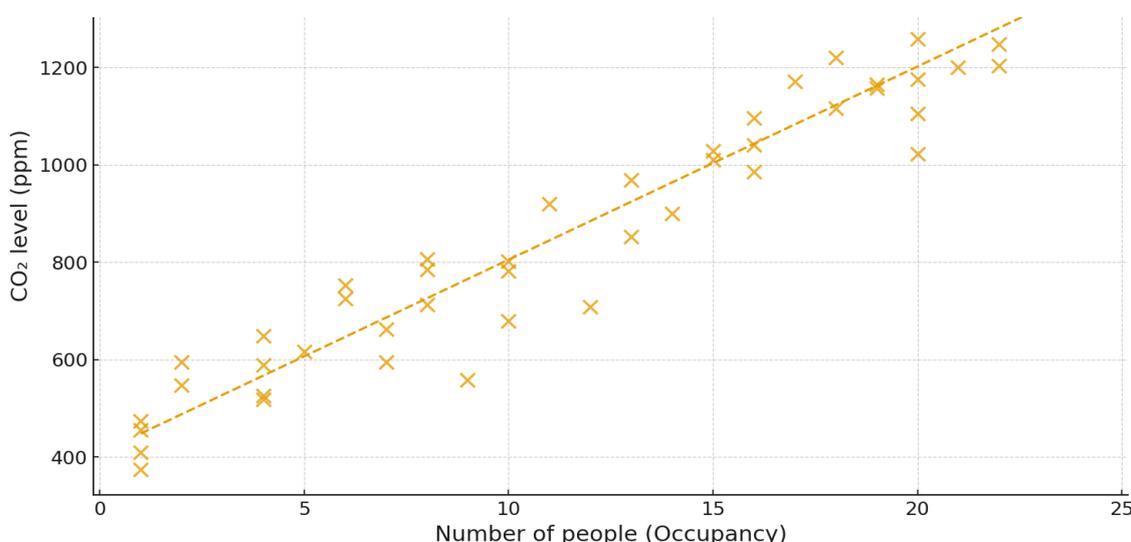

Fig. 2. Example of correlation between CO2 level and number of people (compiled by the author based on [22, 23]).

The smart buildings segment demonstrates stable expansion, forming a favorable framework for the

implementation of HBI technologies. The dominant share is constituted by the commercial real estate sector, supported by sustained demand for smart and adaptive office spaces. In regional terms, North America remains the largest market by volume, whereas Europe exhibits outpacing growth rates, largely driven by strict regulatory requirements [1]. The structure of the market by application areas in 2024 is presented in Fig. 4.
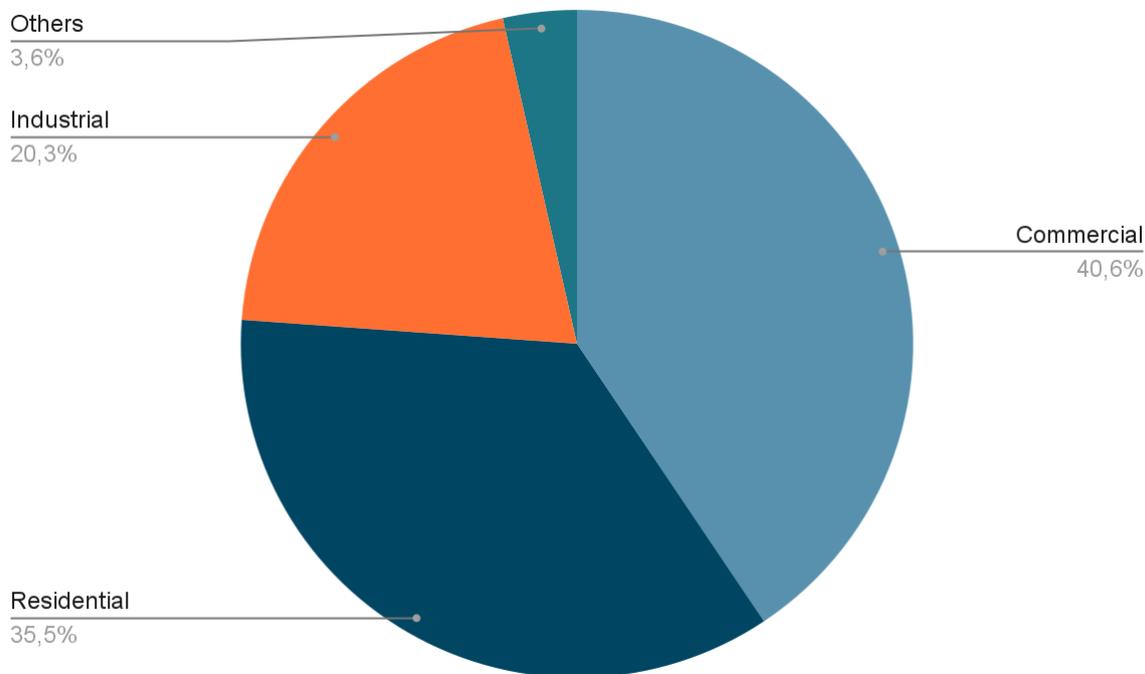
Fig. 3. Segmentation of the intelligent buildings market by application (2024) (compiled by the author based on [1]).

Despite the favorable market trajectory, large-scale implementation of HBI is constrained by a set of significant and mutually reinforcing barriers. Their systematic analysis is presented in Table 2.

Table 1. *Synthesis of key barriers to the implementation of intelligent buildings (compiled by the author based on [10, 19, 25]).*

Barrier category	Specific problem	Description and supporting data	Consequences
Economic	High initial investments	Intelligent buildings require significantly higher capital expenditures for sensors, actuators, and control systems compared to traditional buildings.	Discourages owners and developers, especially when retrofitting older buildings lacking the necessary infrastructure. Reduces investment attractiveness.

Technological	System complexity and interoperability	Integration of disparate systems (HVAC, lighting, security) from different vendors with conflicting protocols is a serious challenge. The lack of standardization exacerbates the situation.	Leads to the creation of fragmented, unreliable systems. Requires the availability of scarce and costly specialists for installation and maintenance.
Social / Regulatory	Privacy issues	IoT systems collect enormous volumes of sensitive data: occupancy, behavioral patterns, preferences, and even users' physiological state.	Generates resistance and distrust among users. Creates significant legal and ethical risks associated with data protection laws (for example, GDPR).
Social / Regulatory	Cybersecurity vulnerabilities	Increased connectivity makes building management systems targets for cyberattacks (extortion, malware), which can disrupt the operation of critical services.	Slows down implementation due to perceived risk. May lead to physical consequences (for example, shutdown of HVAC in a hospital) and significant financial losses.
Social / Regulatory	Resistance to change	Owners, operators, and users may resist new technologies due to the difficulty of mastering them, fear of uncertainty, or disruption of established habits.	Slows down the pace of implementation. Requires substantial investments in training and change management to ensure effective use of the systems.

Against the backdrop of high costs and technological complexity, the most fundamental and difficult-to-remove obstacle turns out to be the trust deficit. Economic constraints can to some extent be managed through verifiable payback models and the gradual reduction in technology costs [10, 11]. Interoperability challenges, as a rule, are mitigated as industry standards take shape. In contrast, issues of privacy and security have a mixed nature – technical, social, and ethical-legal – and directly rest on the quality of trust relations between the building operator/employer and the user/employee. Paradoxically, it is behavioral analytics – the key to genuine adaptivity of workspaces – that simultaneously creates the most significant area of privacy risk, provoking a direct conflict of interests. The long-term viability of HBI requires theorizing trust not as a static "check-box" compliance issue, but as a dynamic relational construct. In the context of the workplace, the deployment of behavioral analytics risks creating a "panoptic" effect, where surveillance undermines the perceived autonomy of the user. Consequently, Privacy-by-Design is not merely an ethical preference but a functional prerequisite for system efficacy. If users perceive the building as a surveillance apparatus, they engage in obfuscation behaviors (e.g., disabling sensors, falsifying feedback), which degrades the data quality essential for the HBI loop. Therefore, the architectural design of digital systems serves as a governance mechanism that mediates the power differential between the building operator and the occupant.

Conclusion

The analysis conducted demonstrates that human–building interaction has evolved from a niche research topic into a strategically significant direction for designing the anthropogenic environment of the future. The results indicate that an effective HBI strategy should be: 1) holistic, integrating human well-being with energy efficiency; 2) human-centered, focusing on user needs and experience already at the design stage; and 3) data-driven, employing real-time analytics to shape genuinely adaptive environments.

The empirical findings confirm the initial hypothesis. The analysis of case studies and barriers shows that the central problem is not purely technological but sociotechnical in nature: it requires a delicate balance between the volume of data needed for personalization and the user's basic need for privacy and trust. The most productive trajectory appears to be solutions that embed robust mechanisms for feedback and user control.

The results of this research have direct implications for the advancement of energy-efficient and human-centered architecture in the United States. These findings align with federal goals outlined in the DOE's Building Technologies Office and the U.S. Infrastructure Investment and Jobs Act, supporting nationwide initiatives to modernize smart and sustainable infrastructure.

The practical significance of the study lies in targeted recommendations for key stakeholders. For architects and engineers, it is advisable to implement UCD methodologies and pre-occupancy modeling tools. Technology developers should prioritize interoperability and confidentiality-by-default architectures. Building managers need to transform from operators of physical assets into providers of high-quality user experience. Future research should be oriented toward longitudinal designs for the quantitative assessment of the long-term impact of HBI on health indicators and toward the development of robust ethical frameworks for the use of behavioral data in the anthropogenic environment.

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