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Exploring the impact of HCI on smart buildings: A comprehensive literature review on user experience and sustainability

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Abstract. This paper provides insights into the application of human-computer interaction (HCI) principles in the field of smart building design, particularly their impact on improving occupant comfort, building energy efficiency, and the user interaction experience. The research context focuses on advances in HCI and the importance of smart buildings in enhancing quality of life and sustainability. The research theme focuses on how HCI principles can be utilized to improve the user interface design of smart buildings in order to promote more effective user-building system interactions. Through an extensive review of existing literature in the area of HCI and smart buildings, including recent research papers, case study reports, and technical overviews, this study concentrates on analyzing examples of HCI applications in smart lighting, temperature control systems, and energy management. Through this comprehensive literature review, this paper aims to illustrate how HCI principles can provide theoretical and practical guidance for the design of more humanized, interactive and environmentally friendly smart buildings, thereby providing insights and recommendations for future smart building design and research.

Keywords: human-computer interaction (HCI), intelligent buildings, user interface design, occupant comfort, building energy efficiency, literature review.

1. Introduction

Human-computer interaction is a bridge built through advances in industrial design that have become a channel for people to engage in everyday productive activities with machines. In today's world, where emphasis is increasingly placed on user experience and enhancement of life quality, human-computer interface design plays a key role, not only influencing the user operation process but also shaping their experience with technologies and is a cornerstone of usability and efficiency [1].

Incorporating human-computer interaction (HCI) principles into the architectural design of smart buildings represents a huge development in the relationship between people, computers and the built environment. Smart building involves the application of Internet of Things (IoT) systems and devices that bring efficiency and sustainability to the buildings as well as improved comfort for the occupants. Not that this can't be done in physical form but the buildings can deliver on their promises through design only if they would be keeping users in mind and not designing without user experience and interaction, meaning that designing with respect to users is the key. The fusion of HCI and architecture

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is reflected in the broad theoretical pattern where the emphasis is put on the frontline design for users. In conformity with Norman's design principle, devices, links, computers, and interfaces are developed taking into account the design of an easy-to-use, and functional results[2]. In the end, it would be particularly important, therefore, to create spaces that are professional and comfortable for the occupants, that are designed as the second nature for them so that operation would be easy rather than complicated. This paper explores the integration of HCI with the architectural design of smart buildings, focusing on user comfort, efficiency and environmental interaction.

2. Human-Computer Interaction

Human-computer interaction (HCI) is the study of how people interact with technology, focusing on the interface between users and technological systems. The interaction between people and machines, HCI, studies how people interface with technology, thereby concentrating on the interface between human users and technological systems. This multidisciplinary field combines the knowledge and skills of computer science, design, social and behavioral sciences, psychology, engineering, and sociology. HCI is the process of developing, testing, and applying interactive technological systems to make them friendlier and simpler to manipulate so the user will be able to utilize their system more effectively and safely, besides gaining satisfaction and positive feedback. As a multi-dimensional subject, HCI involves the research, design, and application of computing technologies on a broad and deep concept in which the user is given high interests and focuses on the computer-human interface. The concept of "interface" here is broadly understood and includes, but is not limited to, the following forms: graphics interfaces, which include web browsers, self-service terminals, hand-held systems, and telephones; voice interfaces, which are represented by intelligent assistants as well as other voice interaction systems; robotic interfaces which involve direct human interaction with robots or automated systems[3]. Through interaction HCI assists in such communication and cooperation through these interfaces, making certain the technology actually meets the users' expectations and needs. This eventually enhances people's productivity and their quality of life. The concept of smart buildings has grown from the automation of basic building systems to the location of advanced buildings with the ability to adjust to dwellers. Similarly, human-computer interaction (HCI) has evolved from designing computer interfaces to encompass human interaction with all types of systems and technologies, whether embedded in a physical space[3]. The convergence of these two fields demonstrates the growing emphasis on designing intelligent environments with user roles. As technology becomes more entrenched in our spaces, HCI offers extremely valuable prospects for developing spaces into more human, energized and even, to some extent, nature-friendly spaces.

3. Smart Building Design Principles

3.1. User-Centered Design in Smart Buildings

Bringing User Centered Design inclusivity into smart buildings poses a range of technical, ethical and user experience considerations, a few constituting the most complex in the field. Appending the preservation of user privacy and data security standing transparency and extremely useful services improvement aims at these challenges. In Harper's research, she indicates the level of transparency, strong security measures, policies and data should be in place to protect the occupation information. The supporters insist on the fact that consumers are forcing privacy talks to be established to build a culture of mutual trust. This is no less significant to avoid a user-centered threat. That is to say, system designs will have to be well-considered in a way that provides users with awareness and control over the data utilized[4].

Enterprise mobility with UCD principles in smart environments showcase the technological development, which is done to improve and enhance the human comfort and well-being as well as the ecological and environmental needs. Intelligent buildings therefore demonstrate the next level of creativity in the area of spatial design by personalizing the environment for each user following his particular tastes. A case in point would be a climate control system, which is designed to mimic

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occupants' historical preferences by setting temperature and moisture levels depending on them, the above clearly demonstrates UCD practicals which are to develop spaces, that dynamically adjust for human needs. Likewise, architecting smart lighting systems that adjust brightness and color temperature based on an occupant's natural circadian patterns or specific task requirementsbecomes a testament to the UCD approach, which generally complements the personalized comfort and productivity concepts that UCD's aim is to achieve. The master planner might provide a certain extent of individual attention by maintaining cohesion with architects, designers, and technology developers and keeping the dialogue open with occupants. Any stage of data procurement, storing, processing, and use should be an ingredient of user-centered design to ensure that they comply with the highest criteria of privacy and morality. In line with this, the residents should be supplied with all the required power to have their choice and control of their data and privacy spectrum in their hands.

As a primary aim, the smart buildings operate at a technology level that is not only innovation and solution-oriented but also user-oriented to a great extent and human-experience focused. This means that smart buildings must be designed and operated to implement UCD principles and establish that the technology serves human needs and well-being, rather than just being a showcase for technology. In this way, smart buildings can be powerful tools to enhance quality of life, promote sustainability and increase occupant security and satisfaction.

3.2. Interaction with the Internet of Things

User engagement with Internet of Things (IoT) devices is critical to the user experience in smart buildings. Enabling users to engage with the built environment effectively requires the design of device interfaces that are both intuitive and conveniently accessible. Apostolidou and Fokaides assert that creating intuitive and useful user interfaces improves user engagement with smart building systems[5]. It encourages users to interact with the building control system in a more natural way.

Siemens' building management system is a typical example of an Internet of Things (IoT) application that uses advanced sensors, control technology and data analytics to optimize a building's energy use, improve energy efficiency and reduce operating costs (Figure 1). The system enables real-time monitoring and management of a building's energy consumption by integrating data from various building systems such as lighting, air conditioning, heating and ventilation. With IoT technology, numerous sensors and devices allow Siemens' system to gather vast amounts of data. The system analyses this data to find areas where energy-saving measures might be implemented and then automatically modifies equipment settings to achieve maximum energy efficiency. Siemens also stresses the significance of user-friendliness, emphasising the ease with which maintenance personnel and building administrators can keep an eye on and manage the facility's energy use. Siemens' technology ensures consumers can optimise their energy management and savings potential by utilising the system efficiently without requiring in-depth technical expertise. This is achieved by offering clear data presentation and easy interfaces[6].

The major challenge in designing for interaction with IoT devices is creating robust and usable interfaces. The design of this technology can be quite new or even daunting for most users. Therefore, the interface design should be as simple as possible, with minimal barriers to use. This may include utilizing known interaction paradigms learned from other domains, such as gesture control or voice commands, to make smart building technology more approachable and interactive for users. Another important consideration is accessibility. Smart building interfaces must be designed to be used by people of all abilities, including those with visual, hearing, motor, or cognitive disabilities. This requires careful attention to design principles such as contrast, text size and alternative input methods to ensure that all users can benefit from smart building technology.

3.3. Energy efficiency and sustainability

The development of smart building technologies is now based on sustainability and energy efficiency. By incorporating human-computer interaction (HCI) principles into these systems, there is a special opportunity to influence occupants' behaviour and encourage a culture of sustainability. For example,

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as Kim and de Dear's research demonstrates, user interfaces can be an effective tool for raising awareness among building occupants and incentivizing energy-saving behavior[7]. These interfaces can encourage tenants to adopt greener behaviors by displaying real-time statistics on energy consumption, customized energy-saving recommendations, and comparative analysis. However, striking a balance between occupant comfort and energy economy is fraught with difficulties. Adaptive thermal comfort models explored by O'Brien and Gunay optimize energy use by adjusting indoor environmental conditions based on real-time feedback from occupants, while maintaining or enhancing comfort. These models demonstrate the potential for smart buildings to utilize HCI principles to create more energy-efficient environments responsive to the subtle needs of occupants[8].

More so, being able to integrate the renewable energy sources and the smart telephone technologies would give the smart building an extended energy potential to meet the broader sustainability goals. The alterations in HC I that will be demonstrated as these technologies continue to be used will show that the role of HCI in designing systems that raise occupants' behavior towards sustainability will keep evolving. Thus, there will need to be a lot of research and development in this area[9] .

However, designers face the challenge of designing for both energy efficiency and user comfort but they come with the adapted thermal comfort models of O'Brien and Gunay that adjust the indoor environmental conditions to occupants' satisfaction constant by real-time feedback can be possible while the energy use is optimized. These models demonstrate that smart buildings will use HCI paradigms in order to create spaces that can respond to occupant needs, making it possible to improve eco-friendliness and satisfaction levels[8].

4. Challenges

As the field of smart buildings continues to evolve, several challenges and opportunities for future research have emerged. The issue of privacy and security is one of the most important challenges, as the extensive collection and analysis of user behavior can pose a potential risk to individual privacy. Future research must address these concerns by developing stronger data protection measures and establishing clear, transparent policies that protect user data while enabling the personalization and efficiency benefits of smart technologies. Additionally, the digital divide issue highlights the importance of ensuring that smart building technologies are accessible and usable for a wide range of occupants, including those with limited access to technology or varying levels of technological literacy. This underscores the need to prioritize inclusive design practices emphasizing accessibility and user-friendliness.

5. Conclusion

In conclusion, incorporating human computers interactions (HCI) principles in smart buildings represents an area of application that is still in an evolving and dynamic state and has lots of prospects for occupant comfort, efficiency, and sustainability. This review will discuss the most influential role of HCI within the scope of smart buildings, exploring various areas such as user interface, interaction with Internet of Things (IoT) devices, energy efficiency, and future anticipates and challenges. User-centric design is critical in the smart building industry because it requires designers to explore the user's needs, functions, and preferences from the occupant's viewpoint. And finally, this approach allows for the smart building systems to not only be at the forefront of the technology but also be easy to use and provide functionality that is equally personal and reflects the occupant's experience. The ultimate success factor in smart building is humanity-oriented technology and creating spatial settings that target the experiences of humans.

Through leveraging forward thinking advanced technologies like Artificial Intelligence and machine learning, smart buildings could be set in motion and hence develop advanced personal policies and predictive capabilities for their residents. These technologies allow systems to pick-up noticed user behaviour and pre-tune environments for users needs, delivering a previously exceptional level of comfort and efficiency. Akin to VR and AR, immersive technologies enhance the user experience through more natural and interactive interfaces that help the users fully immerse themselves and interact

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with their environments in novel and captivating ways. Furthermore, the proposition of community-centric smart structures that put technology to use in favor of strengthening community interaction and enhancing social participation appears to be the most promising area of research in the near future. These buildings can incorporate tech tips into the design of public spaces and systems as they try to make it easy for people to socialize and engage with each other and, as a result, create a sense of community belonging.

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