EPiC Series in Built Environment
Volume 3, 2022, Pages 470–478
ASC2022. 58th Annual Associated Schools of Construction International Conference

Conscious Intelligent Buildings: Envisioning the Next Generation of Smart Buildings

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Abstract

As one of the major industries that consume vast energy annually, the built environment industry is continuously exploring new building designs that would satisfy both occupants and the sustainability requirements. Considered as a new trend of building design for achieving economic, environmental, and occupant satisfaction goals, smart buildings are gaining momentum in research and development. Occupant-based design is considered an innovative idea for smart building automation systems as it aspires to focus on satisfying occupant's needs while saving energy and reducing waste. This positioning paper argues that next in the evolution of buildings is conscious intelligent buildings, characterized by their cognitive capabilities, creativity, and empathy akin to human self-awareness. Based on the literature review which served as the methodology, the evolving advancements in meta-data, Internet of Things (IoT), and Artificial Intelligence (AI) are potentially making this next paradigm possible. As for results, this article proposes a framework for defining conscious intelligent building. Its unique characteristics and underlying vision provide a new paradigm for leveraging big data analytics in the built environment. Enabled with cognitive and empathic interaction with the occupants, this achievement of higher intelligence can alter human-building relationship toward trust and thus increasing occupants' satisfaction and emotional health in the built environment.

1 Introduction

The world population is estimated to become 9 billion within the next 30 years. The number of people moving to urban areas is estimated to increase from 2.5 billion to 3 billion approximately, which results in significantly increased energy consumption by 56% by the end of 2040 (Bakıcı, 2013). As per capita energy and electricity consumption is highly correlated with the quality of life globally (Mazur, 2011), approaches for improving our life quality while reducing the energy consumption per

[*] Revised and completed the first stable version of this document
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person are required for sustainable development (Indrawati, 2017). The most effective way to improve quality of people's life space would be through alternations and innovations on building design and construction, since 30-40% of energy worldwide is consumed within the built environment as humans spend almost 90% of their lifetime inside a building (Park, 2018). Therefore, demand for smart building design which is aimed at providing pleasant, affordable, and aesthetic spaces in a cost and energy-efficient way has been growing tremendously, almost doubling every three years globally (Jia R. J., 2018).

Unlike traditional buildings which may no longer satisfy the requirements of energy saving and NetZero Energy building (NZEB) (Karlessi, 2017), smart building design would become the future trend of the development. There are various definitions of smart buildings which may raise the need for additional clarity of the concept. Additionally, problems including high initial cost of acquisition for technology, increasing concerns for cybersecurity, and convincing stakeholders of the value of smart buildings are still under debates, hindering the development and acceptance of smart buildings. Hence, in order to fully realize the advantages and benefits of smart buildings, these barriers must be overcome. To save energy, the existing smart building automation system should be further evolved. According to the research conducted by the International Energy Agency (IEA) (IEA, 2019), among the six main factors that could cause variations in energy usage (Yoshino, 2017), studies about occupant's behavior are not as broad as the other five factors including climate, building envelope, mechanical and electrical systems, indoor design criteria, and operation & maintenance. That explains why numerous researchers have gained motivations to develop occupant-based design (Anand P. C., 2018) (Anand P. C., 2019) (Anand P. S., 2017). The purpose of this paper is to explore the evolution of buildings, simply clarifying a holistic definition of smart buildings along with their basic traits and establishing a vision for the future of buildings based on the evolution history of buildings and the emerging trends. A new concept of conscious intelligent building is provided for further realizing the occupant-based smart design vision. Conscious intelligent buildings characterized by their self-awareness and connectivity to a larger web of the built-environment infrastructure and meta-data are portrayed in this paper. This paper proposes a framework for conscious intelligent building definitions, its unique characteristics, values, and offers a new paradigm for leveraging big data analytics for increased sustainability in the built environment.

2 Methodology

To make sure the review is comprehensive, according to the guidelines of systematic literature review by (Thomé, 2016), at least four steps are required: problem discovery, database selection, keywords selection and final literature selection. As intelligent and smart buildings are the topic for literature review, the problem formulation focuses on deficiencies of current smart buildings and occupant-based ideas. Based on assessment of impacts for different data sources (Kousha, 2011) (Meho, 2007), articles from four high impact scholarly databases are selected including Google Scholar, Science Direct, Emerald insight, Electrical and Electronics Engineers (IEEE) Xplore. In order to satisfy the needs for selecting keywords which should not only restrict the number of study but also specific enough to contain the required subjects, words of "smart building", "intelligent building" and "occupant-based" are selected. A total of 252, 46, 270, 60 articles are shown individually in Google Scholar, Science Direct, Emerald Insight, and IEEE Xplore, serving as the resources for extracting the smart building definitions and ideas of occupant-based design in construction projects. Following the review and content analysis of articles, we synthesize the identified unique traits for occupant-based design (see Figure 1).

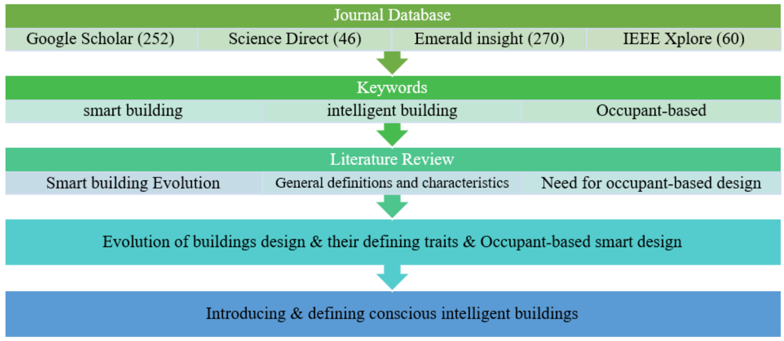

Figure 1: Research Process Leading to the conceptualization of conscious intelligent buildings

3 Literature Review Findings

3.1 Evolution of building design – from “primitive” to “intelligent”

Building design ideas and expected performance have been changing significantly throughout the history of human civilization (Buckman, 2014). According to the evolving process stated by (Fitch, 1960), early buildings are served as shelters which could protect people from unpleasant weather conditions, basically called “primitive buildings”. The standards of comfort and information sharing was relatively low, and the materials for construction were as simple as rock and wood. Later on, with the development of construction technology, availability of new materials, and information technology “primitive” buildings evolved into “normal” buildings and then to “automated” buildings (Drewer, 1994) and (Smith, 2007). In an automated smart built-environment, building systems would react to occupant’s needs by the means of Internet of Things (IoT) system (Jia M. K., 2019), which is called “adaptive” and “responsive” to proactively satisfy occupants’ needs based on the concept of intelligent building design (IBD) (Andrew, 1998). This promising future of buildings are introduced as “intelligent buildings” (see Table 1).

Building sorts	Primitive building	Normal building	Automated building	Intelligent building
Interaction	No interaction	Occupant’s fully control	Limited interaction	Highly interactive
Living standard	Low, only as a shelter	Comfortable and controllable	High standard automated	Optimized and sustainable
Materials	Rock or wood	Bricks, steel and concrete	Advanced materials	Advanced & sustainable
Technology level	No technology implementation	Basic electricity supply and MEP devices	IoT system devices, Advanced MEP system	Real-time integration and optimization system
Sources	(Fitch, 1960)	(Drewer, 1994)	(Jia M. K., 2019)	(Buckman, 2014)

Table 1: Evolution process of building design

3.2 General definitions and characteristics of smart buildings

According to different studies, numerous definitions about smart building are presented along with their expected features and functions. Most of these definitions are focused on the features that would benefit owners for smart building operation and maintenance. Here are some of the typical definitions of smart buildings provided by researchers in various scholarly publications.

(Jung, 2020) states that if a building is capable of managing and maintaining higher level of performance while having cognitive abilities similar to humans, the building could be identified as smart or intelligent. (Volkov, 2015b) believes that "learning from inhabitants", "adapting to their lifestyle" as well as "initiating decisions or actions to change the current status of indoor environment" are the core values for designing and constructing smart buildings. (Arditi, 2015) believe that smart buildings are comfortable, safe, and satisfy the economic goals set by owners. (Volkov, 2015a) makes the same argument and further emphasize the importance of energy saving combined with the increased level of occupants' comfort for building "smart" considerations. These studies have consensus that economic goals, energy saving, and occupant's comfort are the key indicators that determine the smartness of buildings. Additionally, (Batov, 2015) pays great attention to the technological implementation inside a smart building; the building could "program itself" by inputting data from monitoring occupants and environments with various sensors. After discovering the behavior patterns of occupants, relevant predictions of future actions are generated accordingly. But, as all the devices inside the building are becoming networked to the Internet, they could also become more vulnerable to cyberattacks. Consequently, new detective and responsive approaches in securing data from cyberthreats should also be considered rather than simply focus on data connectivity.

To sum up, three key aspects are concluded based on all the definitions for determining whether a building could be considered as smart or intelligent. First of all, the building has cognitive abilities and could learn from its occupants' routine behavior or lifestyle by monitoring through sensors and learning with algorithm. "Responsive actions" are then generated following the learning process. Secondly, three fundamental goals are to satisfy for the purpose of sustainability: decrease in energy consumption, saving in lifecycle costs and improvement of occupants' living or working standard. Lastly, a large amount of the utilities, equipment, components inside the building are connected and controlled through a cloud-based platform, along with relevant precautions to protect all the data from cyberattacks. Data are collected and stored for analysis, leading to predictions and recommendation for management or visualizations. The intersection of these three aspects makes smart buildings (see Figure 2).

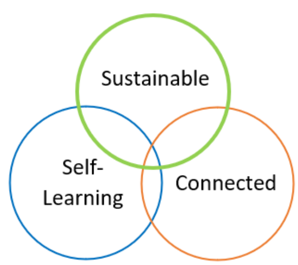

Figure 2: Key attributes of smart buildings

3.3 The need for occupant-based smart building design

Most of the smart building definitions are focused on technologies and functions that would benefit owners for sustainable construction and operation of their buildings. These definitions are seldom concerned with an occupant-based criterion (Janda, 2011). While owners should be satisfied given their time and money investment on the entire project life cycle from design, to construction, to operation, the needs of occupants are equally if not more important. The occupants could range from white-collar staff of office buildings, patients of medical centers, students and faculties of college buildings and residents for apartment or residential buildings, etc. In short, building users are core fabrics of society and their health, comfort, and productivity has immediate impact on the community's economic and social well-being, and yet building occupants' perception of the built-environment are often overlooked (Janda, 2011).

Occupant-based design centered on big data analytics could be a viable approach to further improving building performance (Kjærgaard, 2020). Different studies have demonstrated the significance of occupants' impact on energy consumption and thermal distribution inside buildings (Jia M. S., 2017) & (Dong, 2018). According to (Kjærgaard, 2020), the majority of building energy simulation applications concentrate on the factors embodying physical building design, such as materials, technological systems, and outdoor weather conditions rather than occupant-building interactions. As (Yang, 2014) points out, several traditional building operation approaches adopt schedules for HVAC control based on certain rules like ASHRAE 90.1 standard, resulting in huge energy waste and occupant discomfort and complaints. Consequently, more focus should be shifted on occupant's presence and behavioral actions in order to achieve both the goal of energy efficiency and occupants' comfort for occupant-based smart buildings. In order to demonstrate the increasing focus on occupant-based design, number of articles containing "occupant based" and "occupant centric" published on the mentioned four databases from 2017 to 2021 are displayed due to the increasing interest in this topic (see Figure 3).

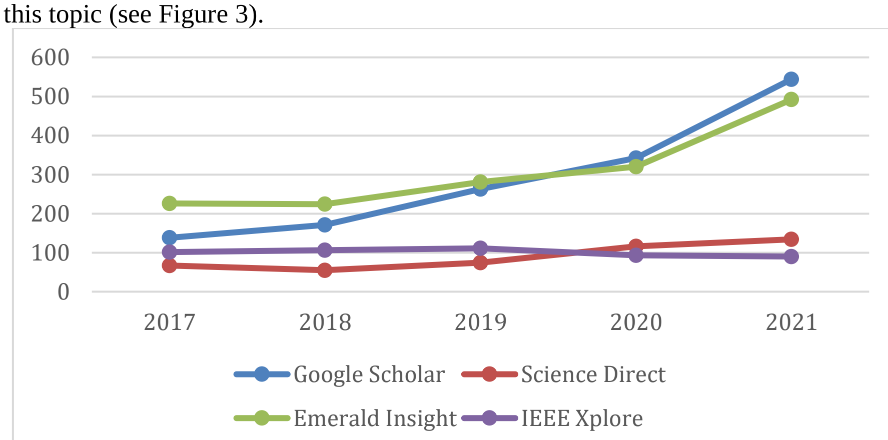

Figure 3: Number of articles concerning "occupant based" and "occupant centric" published on the four databases from 2017 to 2021

3.4 Building systems and requirements of occupant-based smart building design

Current building management systems' goal is to achieve energy efficiency. These control systems are centralized, operated by facility managers, and require high expenses for installation and operation. To enable occupants-based design, additional sensors and actuators are required but it is challenging to add them to current systems (Batra, 2013). Lack of the design for inputting dynamic variables about occupant, such as occupant number, movement and state of comfort, would be the problems that traditional building management system (BMS) are currently facing. For each 6 fundamental systems of traditional BMS, a complimentary element of occupant-based design is suggested accordingly (see Table 2).

Building System	Elements of Occupant-based design	References
HVAC Control System	Personalized ventilation approach,	(Sekhar, 2005)
	Occupancy-based zone-level variable air volume system for improving thermal comfort	(Anand P. S., 2019)
Fire alarm & detection system	Probabilistic occupant response model for fire emergencies	(Zhang, 2014)
Communication System	Sensekit, a modular hardware platform that allows for customized monitoring based on application requirements	(Batra, 2013)
Security System	Personalized warning system based on capacitive proximity sensing	(George, 2008)
Elevator System	Optimal elevator scheduling based on real-time occupancy patterns	(Wang, 2021)
Lighting System	Adaptive lighting control, based on occupancy detection	(Guo, 2010)

Table 2: Elements of occupant-based design for each building system

Figure 4 illustrates a framework for occupant-based building system operation in conjunction with traditional building system management to manage indoor environment (see Figure 4). Traditionally, occupants could control the indoor environment by manually controlling devices to ensure the perfect temperature, ventilation and lighting, with no automation but only manual instructions given from occupants. As for traditional building control system, managers would set the fixed standard including all the controlling parameters. Compared to these two approaches, control system of occupant-based smart design relies on data collected from user interface which reflects occupant's behaviors. By applying relevant algorithms, automatic operations will be generated to adjust indoor environment based on input data from the occupants and outdoor environment.

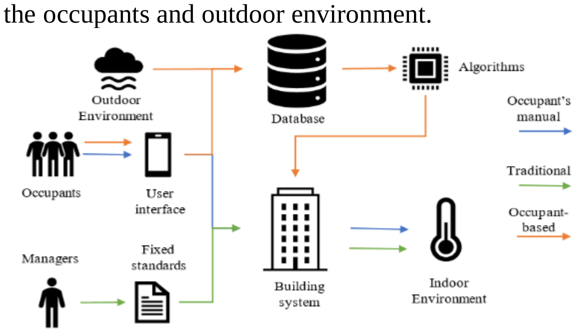

Figure 4: Framework of occupant-based control system

4 Discussion - Envisioning the Next Generation of Conscious Intelligent Buildings

As a dominant and rapidly evolving technology, Artificial Intelligence (AI) has demonstrated outstanding performance in well-defined domains such as image/voice recognition, and behavioral predictions. However, all these AI capabilities are rather primitive compared to those of nature-made intelligent systems such as humans because AI capabilities, in essence, are derived from classification or regression methods (Esmaeilzadeh, H. & Vaezi, R., 2021). Esmaeilzadeh, H. and Vaezi, R. identified four levels of AI intelligence and their corresponding service tasks: mechanical, analytical, intuitive, and empathic. While AI applications currently exist in the first two levels, the AI applications demonstrating intuition and empathy intelligence is still rate and considered to be the next disruptive wave of AI (Esmaeilzadeh, H. & Vaezi, R., 2021).

Similarly, current traits of smart buildings are relatively primitive compared to a futuristic conscious intelligent building this paper introduces, which is characterized by its autonomy and creativity in generating a healthy, comfortable, and sustainable built environment (see Figure 5). Besides being sustainable, connected and self-learning, conscious intelligent building should be cognitively self-aware and creative to occupant's response and requirements.

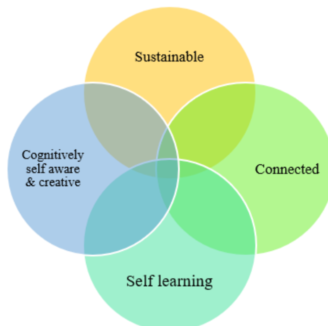

Figure 5: Key attributes of conscious intelligent buildings

From a futuristic perspective, conscious intelligent buildings could be defined as buildings that can "think on their own" with AI consciousness which allow them to be capable of limited decision-making on the basis of learning from occupant's behaviors and can demonstrate cognitive and empathic interaction with the occupants. This achievement of higher intelligence can alter human-building relationship toward trust and thus increasing occupants' satisfaction and emotional health. Through continuous two-way interaction with humans, sufficient data could be collected for controlling building systems automatically according to the occupant's individual habits, guaranteeing the maximum comfort for every occupant by optimizing indoor environment quality. Fundamental features for conscious intelligent buildings are listed (see Table 3).

Characteristic	Function
Occupant–building Interaction	Enrich occupants' living experience
Intuitive	Autonomy in decision making & knowing what's best to do
Empathic	Understand and empathize with occupants' needs
Autonomous	Allow for big data analysis to optimize indoor environment quality
Higher value	Provide better services catered to the occupants with less cost with greater efficiency

Table 3: Characteristic of Conscious Intelligent Buildings

5 Conclusion

This article highlights the evolution of buildings from primitive to regular, to automated, and most recently to occupant-based intelligent buildings. Unique features of the evolving buildings from primitive to intelligent occupant-based design is presented. Additionally, the unique features of occupant-based control system are presented in order to clarify the differences between traditional building system control and this new control system. As for the contribution to the body of knowledge, this paper provides a reflective insight into the evolution of the built environment as well as a vision for the futuristic paradigm of the built environment, which is informed by the emerging trends involving information technology and artificial intelligence and the need for enhanced human consciousness. Conceptual direction for future of the built environment is discussed. Future research experiments are needed to examine if the proposed conscious intelligent buildings would outperform the current occupant-based intelligent buildings both on energy consumption and occupants' health and wellness.

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