Living Lab Integrates IEQ Technologies in Singapore

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Indoor environmental quality (IEQ) monitoring and control are important in the operation of a smart building. Focus has been placed on minimizing energy consumption while ensuring the health, safety and comfort of the occupants. Through tailoring air conditioning, ventilation, lighting and electrical power services, significant levels of energy efficiency can potentially be achieved (Ratliff et al., 2014). However, to be more effective in providing customized services, the building must be able to respond to occupant feedback. In this project, we deploy several technologies that incorpo-rate both user preferences and sustainability goals seamlessly into a building opera-tion. The Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST)* programme has partnered with the Building and Construction Authority (BCA) to build a living laboratory for this purpose, visualized as an "Office of the Future."

Technologies

Buildings involve a complex integration of multi-physical systems and subsystems. Besides the obvious civil engineering infrastructure, thermal, electrical, mechanical, control, communication and computing subsystems must co-exist and be operated such that the overall operation is smooth and efficient. Design and deployment of these subsystems is rarely synchronized; lighting, security, heating, ventilation and air conditioning systems are often designed and operated independently. In this building, we focused on providing an integrated solution that links various state-of-the-art technologies utilizing a system-level approach to provide comfort, safety and functionality while minimizing energy cost, supporting a robust electric grid and mitigating environmental impact.

The technologies are being implemented in the entire first floor of the three-story BCA Zero Energy Building (ZEB) Singapore.† (Witkopf, 2015) located in the central part of Singapore and recently retrofitted. The indoor space comprises two zones with open plan office for occupants and a zone for three meeting rooms and common areas. The office is a mix of 51 smart permanent

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†The Zero Energy Building (ZEB) was named one of Singapore's top 50 engineering feats by the Institution of Engineers.

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FIGURE 1 SinBerBEST technology on workstation desk.

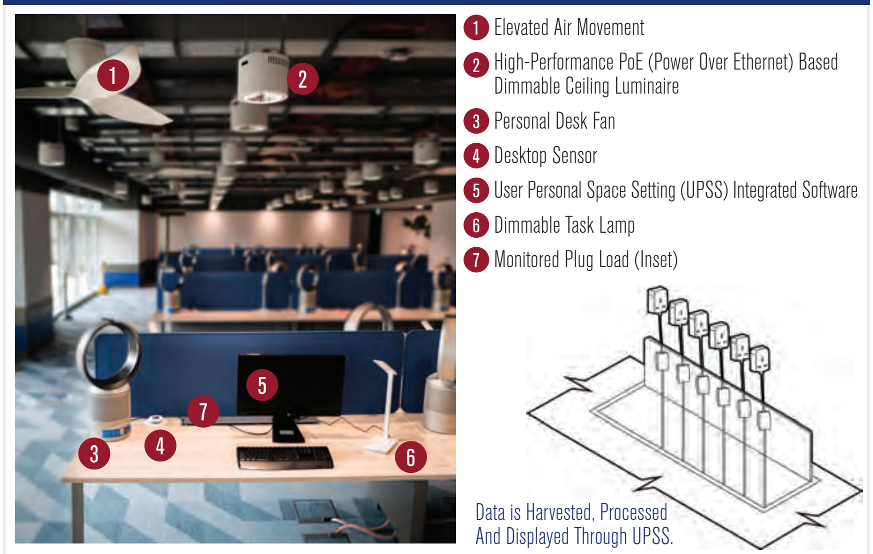

FIGURE 2 Closed-loop control over PoE lighting and roller blinds utilizing desktop sensor maximizing daylight while providing individual task lighting.

and hot desks (*Figure 1*). Each work desk is equipped with an environmental sensor that senses temperature, relative humidity, CO_2 concentration and lux levels (*Figure 2*). The building technologies used in this space include 1) elevated air movement and increased temperature setpoint air-conditioning system; 2) demand control ventilation (DCV); 3) occupancy positioning system (OPS); 4) user-personalized space setting (UPSS) software; 5) plug load monitoring and control; and 5) Power over Ethernet (PoE) lighting. More than 1,000 sensors and monitoring devices have been installed to provide real-time data on occupancy and occupant activities as well as system performance. The data is fed into a smart building management system that adjusts air conditioning, air movement, lighting and power controls to optimize energy usage while providing a comfortable environment for its occupants. All computational programming and algorithms were custom-made.

Elevated Air Movement and Increased Temperature Setpoint Air-Conditioning System

Reducing air conditioning (AC) reliance is becoming increasingly important due to the growing population in tropical countries. Many commercial buildings in the tropical climates are overcooled, causing energy waste and occupant dissatisfaction. This problem can be addressed in part by increasing the indoor air temperature, and simultaneously increasing the air movement with fans as needed. This approach can enhance the thermal satisfaction of the occupants as they prefer air movement to still air and have direct control of the environment. Also, this option can provide substantial energy savings. Our energy analysis for tropical buildings has shown that up to 45% in mechanical energy savings can be achieved by increasing the cooling temperature setpoint.

Through laboratory and field testing, we found that changing the setpoint from 23°C to 26°C [73°F to 79°F] with ceiling fans increased satisfaction from 60% to 90% (Schiavon et al., 2017; Lipczynska et al., 2018). Also, the best cognitive performance (as indicated by task speed) was obtained at 26°C [73°F] (Schiavon et al., 2017). In this smart building, 27 ceiling fans have been installed while the air temperature is set at a minimum of 26°C [73°F]. Additionally, each work desk has a desk fan for personalized comfort to achieve higher satisfaction rates (*Figures 1* and *2*). Most importantly, a smart control based on occupant feedback tells the system whether it is preferred to increase or decrease air movement or temperature using the UPSS (*Figure 3*).

Demand Control Ventilation (DCV)

At the core, the smart ventilation system automatically adjusts the space ventilation requirements according to the occupancy level of the office, saving up to 20% of AC energy. Using CO_2 sensors in the indoor environment, the control algorithm modulates the volume of outdoor airflow into the entire office via the air-conditioning mechanical ventilation equipment (Chao et al., 2004). The new innovation in this

FIGURE 3 The UPSS software dashboard displaying individual energy (plug load) consumption and scheduling, environmental levels and preferences.

design involves the occupancy positioning system (see below) within the zones that detect the actual number of occupants to provide accurate outdoor airflow in compliance with ASHRAE Standard 62.1 and Singapore Standard SS554.

PoE Lighting and Active Use of Daylight

The central lighting system utilizes ultra-low power LEDs powered by Ethernet instead of normal power cables, which is expected to save up to 30% of lighting energy. A total of 53 PoE lights were installed in a closed-loop design configuration to ensure light is delivered into the space to achieve a minimum level of light that is uniformly distributed on desk level surfaces (*Figures 1* and *2*). Since this light can originate from either artificial or natural sources of illumination, active use of daylight in the space is designed to reduce the reliance on electrically powered lights and thus save more energy. Conversely, should the incoming daylight excessively exceed the target light level, a feedback signal will be sent to the roller blinds to reduce the harsh light received on the surface. These controls are also programmed so that when the light is below the target level, the roller blinds will be retracted (*Figure 3*). Because of the high degree of control over many important lighting parameters, the SinBerBEST team has been able to develop and test the lighting controls under a wide range of conditions in a relatively short period of time. Additionally, should occupants prefer a more personalized lighting level on their desks, they can rely on task lighting or request more lighting using the UPSS.

Occupancy Positioning System (OPS)

Currently, many buildings are incapable of detecting occupancy causing energy waste by providing services to empty rooms. With the pervasive and wide availability of Wi-Fi infrastructure and use of Wi-Fi module equipped mobile devices, we have developed an international award winning OPS system for indoor context-aware services and location-based services (Zou et al, 2017). This cost-effective OPS system not only knows how many people are present but also knows their identity and indoor service preference in a totally non-intrusive manner. Novel localization algorithms empowered by advanced signal processing and machine learning methods are used to overcome device heterogeneity, system robustness, environmental dynamics and signal feature selection. A total of nine software upgraded commercial off-the-shelf Wi-Fi routers are installed in the space to overhear existing Wi-Fi traffic and accurately retrieve data. The OPS allows the building to provide the right and personalized level of plug load, lighting, air movement and air conditioning service only where it is needed and at the required level.

Plug Load Monitoring and Control and User-Personalized Space Setting (UPSS) Software

The task of plug-load reduction has been difficult because of the limited understanding of energy efficiency opportunities and equipment needed to address energy use in office spaces (Krishnanand et al., 2018). In this building, each desk is fitted with six plug load devices, which are essentially power sockets equipped with energy metering capabilities: smart plugs to control and monitor energy consumption (*Figures 1* and *3*). Occupants can visualize their own energy utilization behavior and schedule when to turn power on and off. The facility manager can also analyze energy consumption patterns across occupants, and encourage behavior to reduce energy consumption without effecting their day to day work and productivity (Ratliff et al., 2014).

Presently, buildings do not take into consideration occupant's preference. Despite low levels of satisfaction from occupants (Frontczak et al., 2012), they often receive the same levels of thermal conditions, air quality and lighting. In this building, the UPSS software is able to solicit occupant's non-weighted preference in terms of air temperature, air movement and lighting that is processed by the control layer (*Figure 3*). The control algorithms will then tweak the system to adapt to their needs, thus increasing the likelihood of a high level of satisfaction while simultaneously minimizing energy use.

Summary

A typical office in Singapore uses 221 kWh/m^2 in a year with most of this energy attributed to cooling. The ZEB currently has an overall energy surplus of an average of 9% per year cumulatively. The SinBerBEST technologies that have been installed can improve energy efficiency of the ZEB at both the occupant and building level. The overall energy efficiency is expected to increase by at least 20% with high levels of occupant satisfaction.

Acknowledgments

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