Sustainable Cities and Society 13 (2014) 57–68

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Monitoring building energy consumption, thermal performance, and indoor air quality in a cold climate region

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ARTICLE INFO

Keywords:
Sensor-based monitoring system
Energy usage
Building envelope thermal performance
Indoor air quality
Building management system

ABSTRACT

Buildings are major consumers of the world's energy. Optimizing energy consumption of buildings during operation can significantly reduce their impact on the global environment. Monitoring the energy usage and performance is expected to aid in reducing the energy consumption of occupants. In this regard, this paper describes a framework for sensor-based monitoring of energy performance of buildings under occupancy. Different types of sensors are installed at different locations in 12 apartment units in a building in Fort McMurray, Alberta, Canada to assess occupant energy usage, thermal performance of the building envelope, and indoor air quality (IAQ). The relationship between heating energy consumption and the thermal performance of building envelope and occupant comfort level is investigated by analyzing the monitoring data. The results show that the extent of heat loss, occupant comfort level, and appliance usage patterns have significant impacts on heating energy and electricity consumption. This study also identifies the factors influencing the poor IAQ observed in some case-study units. In the long term, it is expected that the extracted information acquired from the monitoring system can be used to support intelligent decisions to save energy, and can be implemented by the building management system to achieve financial, environmental, and health benefits.

1. Introduction

The building sector accounts for about 30% of total greenhouse gas (GHG) emissions in Canada (NRC, 2006). Furthermore, the construction and operation of buildings are responsible for over a third of the world's energy consumption (Straube, 2006). Data shows that energy consumption and GHG emissions in building sector are growing at an advanced rate than in other sectors (Akashi & Hanaoka, 2012). As a result, reducing energy consumption has become essential to planning, construction, and use of buildings from the environmental point of view (Stoy, Pollalis, & Fiala, 2009). This also entails that the building sector has considerable potential for energy and energy-related CO_2 emissions savings (Gökçe & Gökçe, 2013). According to the International Energy Agency, the building sector can reduce energy consumption with an estimated energy savings of 1509 Mtoe (million tonnes of oil equivalent) by 2050. Furthermore, through energy-efficient building design, carbon dioxide (CO_2) emissions can be reduced, which can possibly mitigate 12.6 Gt (gigatonnes) of CO_2 emissions by 2050 (International Energy Agency, 2010).

Energy consumption by built environments can be reduced through new designs, technologies, and materials; proper control; and the use of effective energy management systems by considering factors such as building orientation, shape, wall–window ratio, insulation, use of high-efficiency windows, and natural ventilation (Dawood, Crosbie, Dawood, & Lord, 2013). However, electrical loads, especially miscellaneous electrical loads (involving a range of products, devices, and electrical equipment in some combination, common in every household) consume a significant portion of total building energy (Hendron & Eastment, 2006). In Canada, the residential building sector consumes approximately 16% of total secondary energy usage (NRC, 2006). According to Statistics Canada, in 2007 the average Canadian household consumed 106 GJ (gigajoules) of energy, with the national total reaching 1,368,955 TJ (terajoules) (Statistics Canada, 2007). A substantial share of total energy consumption is due to improper use of appliances, and eliminating this wastage can reduce the overall energy consumption by approximately 30% in buildings (US DOE Energy Information Administration, 2003). Today it is important to focus on greater energy efficiency to reduce our impact on the environment by

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http://dx.doi.org/10.1016/j.scs.2014.04.009
2210-6707/

reducing fossil fuel consumption (Gua, Sun, & Wennersten, 2013; Sharmin, Li, Gökçe, Gül, & Al-Hussein, 2012).

Built environments also have a significant impact on human health. The extent of a building's impact on human health and the environment depends on the building design, materials, and the methods used for construction and operation (Vittori, 2002). According to the Science Advisory Board of the United States Environmental Protection Agency (EPA), indoor environment stands among the top five environmental risks to public health. In Canada, people spend an average of 89% of their time indoors and 66% of their time indoors at home (Leech, Wilby, McMullen, & Laporte, 1996), and there is a possibility that people with weak immune systems may suffer from asthmatic symptoms or other respiratory health problems as a result of exposure to poor indoor air quality (Vittori, 2002). Considering the fact that human health is affected by poor indoor air quality (IAQ), it is important to maintain a healthy IAQ in the interest of occupant health. Continuous monitoring of indoor environmental quality (IEQ) can thus play a significant role in maintaining healthy indoor environments.

A significant aspect of assessing the sustainability of a building is the monitoring of energy performance (Berardi, 2012). Recent innovations in sensing, data logging, and computing technologies have improved monitoring of indoor environment and energy performance of buildings. "Real-time" energy performance and IEQ monitoring are significant from the perspective of real-time feedback to promote energy-saving behavior, and also for maintaining healthy IAQ. Proper targeting and monitoring of energy consumption and continuous energy management can be effective strategies for improved energy performance of buildings, and can result in reductions in operating costs of facilities (Lee & Augenbroe, 2007; Sapri & Muhammad, 2010). Research studies examining the effect of energy feedback information on occupant behavior have shown that real-time feedback can be a powerful impetus for behavioral change. McClelland and Cook (1980) first tested the impact of continuous energy feedback on electricity usage. The results showed that on average electricity usage was lowered by 12% in the homes with continuous electricity usage feedback compared to the homes with no usage feedback system (as cited in Allen & Janda, 2006). In another study, a technical research university has monitored energy usage to reduce energy costs through an energy awareness program that offered departments a chance to receive payments of up to 30% of the savings achieved. The departments had accomplished energy savings (saving about $300,000 per year) after one and half years of monitoring through improved operations and maintenance procedures and reduced their usage from about 44 million kWh to 40 million kWh (Energy Star, 2002). Hutton, Mauser, Filiatrault, and Antola (1986) have shown how the feedback provided by monitoring helped to conserve energy for over 75% of the subjects in 25 households in three cities. In a case regarding water usage, the city of Boston, MA, USA was unable to account for the use of 50% of the water used in its municipal water system and, after installing meters, water that was unaccounted for had dropped to 36% (Grisham & Fleming, 1989). Another study has shown that an effective energy management system can identify problems in an operating system which might not otherwise have been identified (Mills & Mathew, 2009). Yang and Wang (2013) has shown that energy management systems can also provide comfortable building environments with high energy efficiency.

Literature reviews from the last ten years show that usage of energy can be reduced from 0% to 20% by using a variety of feedback mechanisms (Abrahamse, Steg, Vlek, & Rothengatter, 2005). However, despite the fact that providing appropriate feedback can significantly reduce the overall energy consumption, relying only on occupants' awareness and behavioral change might not be an effective approach. In a recent study, wireless AC plug-load meters and light sensors were deployed in a computer science laboratory as a case study in energy monitoring. The study reported that more than 30% energy savings were achieved immediately after installing a monitoring system, but that the savings were subsequently reduced to less than 4% of the week one level by the fourth week of the study. It light of this case, it might be considered that an effective solution for reducing energy consumption could be an automated energy management system, in addition to user cooperation (Jiang, Van Ly, Taneja, Dutta, & Culler, 2009).

Major progress has been made in recent years in accomplishing greater awareness (Jiang et al., 2009), showing that advanced measurement of energy usage enables reduction of energy consumption. While the approach of monitoring energy usage is useful to achieve financial benefits, a holistic monitoring of the performance of the building system can also be used to identify the factors influencing irregular energy usage or non-standard IEQ. Any information pertaining to irregularity of building system performance can contribute to building management systems intended to support operational improvement, and can also provide the information needed to encourage behavioral and operational changes by building occupants and operators. Monitoring is essential to achieving an energy-efficient building management system, but sensor-based monitoring is sometimes costly. In recent years more cost-effective high performance sensor technologies have been introduced, such that the benefits of utilizing this technology outweigh the associated costs. Continuous collection of the individualized energy use information would translate into increased energy use awareness, identification of problems in the building management system, and notification of irregular energy usage and non-standard indoor environmental parameters, all of which can lead to more sustainable building operations. However, it remains an open question whether the apparent additional understanding would be enough to justify the cost of installation, maintenance, and calibration of sensors. This paper thus offers a methodological approach by which to extract useful information by establishing relationships and studying patterns across different components of a building management system, facilitated by the installation of various sensors in a case study, the "Stony Mountain Plaza" project in Fort McMurray, Alberta, Canada.

1.1. *Objective and scope*

The objective of the sensor-based monitoring system adopted in this research is to provide relevant information regarding effective management of building systems in cold-climate regions. The implemented monitoring system can be used for increasing energy performance and occupant comfort while reducing energy and water consumption. In this study, the ASHRAE standard specifying environmental parameter ranges (indoor air temperature, RH, CO_2 level) has been used to define occupant comfort. A holistic examination of the performance of the building system (energy usage, thermal performance, and IEQ) helps to determine whether or not the system is working efficiently by identifying correlations across different monitoring components. A more advanced understanding of the recorded data is expected to result in changes in building operations through the use of intelligent controls that automatically adjust to environmental requirements. It is expected that the extracted information and strategies acquired from the monitoring system can be implemented within the building management system to achieve financial, environmental, and health benefits.

2. Methodological approach

In order to conduct a holistic examination of the performance of the building system under consideration, operating energy usage (e.g., electrical energy usage, space heating energy usage, and