Energy Conversion and Management 49 (2008) 3170–3177

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Sensitivity analysis and energy conservation measures implications

Joseph C. Lam [a,*], Kevin K.W. Wan [a], Liu Yang [b]

[a] Building Energy Research Group, Department of Building and Construction, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, China
[b] School of Architecture, Xi'an University of Architecture and Technology, Shaanxi 710055, China

ARTICLE INFO

Article history:
Received 11 October 2007
Accepted 25 May 2008
Available online 7 July 2008

Keywords:
Sensitivity analysis
Energy conservation measures
Office buildings
Subtropical climates

ABSTRACT

Electricity use characteristics of 10 air-conditioned office buildings in subtropical Hong Kong were investigated. Monthly electricity consumption data were gathered and analysed. The annual electricity use per unit gross floor area ranged from 233 to 368 kWh/m^2, with a mean of 292 kWh/m^2. The ranges of percentage consumption for the four major electricity end-users – namely heating, ventilation and air-conditioning (HVAC), lighting, electrical equipment, and lifts and escalators – were 40.1–50.7%, 22.1–29%, 16.6–32.9% and 2.2–5.3%, respectively. Ten key design variables were identified in the parametric and sensitivity analysis using building energy simulation technique. Analysis of the resulting influence coefficients suggested that indoor design condition (from 22 to 25.5 °C), electric lighting (a modest 2 W/m^2 reduction in the current lighting code) and chiller COP (from air- to water-cooled) could offer great electricity savings potential, in the order of 14%, 5.2% and 11%, respectively.

1. Introduction

Buildings, energy and the environment are key issues facing the building professions worldwide, and energy is a key element in the overall efforts to achieve sustainable development [1,2]. In Hong Kong, there is a growing concern about energy consumption in buildings, especially non-domestic buildings, and its implications for the environment. In 2005, nearly two-thirds of the imported primary energy requirement (mainly coal and oil products, including natural gas) was used for electricity generation [3]. Electricity use in buildings is thus a key energy end-user. Earlier work on the energy consumption situation revealed that electricity consumption in non-domestic buildings, particularly fully air-conditioned office buildings continued to grow even during the economic downturn in the late 1990s [4]. Recently, the much publicised report by the Inter-governmental Panel on Climate Change (IPCC) [5] has helped generate a lot of interests in having a better understanding of the energy use characteristics of fully air-conditioned office buildings in Hong Kong, especially the likely impacts of changes in the building and building services designs would have on the thermal performance and energy use. This information is useful in any building energy efficiency programmes, whether it is related to the formulation of energy guidelines/codes for new building designs or the estimation of energy savings potential of energy conservation measures (ECMs) for retrofitting existing buildings [6,7]. There had been several studies on the energy performance of office buildings in subtropical Hong Kong. These were largely on energy simulations using generic building types [8–10] or energy signatures involving energy audits and surveys of existing commercial buildings (office and shopping complexes) [11–14]. The primary aim of the present work is to investigate the sensitivity of energy performance of purpose-built fully air-conditioned office buildings in subtropical Hong Kong through parametric analysis of existing buildings. The purposes of the analysis are to assess the significance and impact of input design parameters, and to identify important characteristics of the input and output variables and the corresponding energy conservation measures.

2. Methodology

When performing building energy simulations, certain energy changes from the input variables are more significant than others. Such selected inputs should, therefore, be given particular attention during modelling. Also, high-sensitivity elements are important from both technical and economic point of view and should be designed with utmost care if optimization of the system performance is to be achieved. A great deal of works are devoted to testing the sensitivity of systems and these studies are collectively called sensitivity analysis and may involve a range of different analytical methods [15]. Sensitivity analysis has been used for assessing the thermal response of buildings and their energy and load characteristics [16–19]. The aim of sensitivity analysis is to observe the system response following a modification in a given design parameter. For example, one may want to know to what extent building loads and energy consumption is responsive to changes in the coefficients of material properties, design of building

* Corresponding author. Tel.: +852 2788 7606; fax: +852 2788 7612.
E-mail address: bcexem@cityu.edu.hk (J.C. Lam).

0196-8904/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2008.05.022

envelope, selection and operation of heating, ventilation and air-conditioning (HVAC) systems, etc. If we can understand the relationships and relative importance of these parameters, we will be able to achieve optimum building energy performance through proper selection of design variables and conditions. There is no formal rule/procedure for conducting sensitivity analysis for building design because the objective of each study may be different and building descriptions are quite complicated. In general, perturbation techniques and sensitivity methods are employed to study the impacts of input parameters on different simulation outputs, as compared to a base case situation. Then, the results are interpreted and generalized so as to predict the likely responses of the system.

The present work involved the followings:

(i) A sample of purpose-built office buildings was selected. Computer simulation was conducted and compared with the metered electricity consumption in the 2000. The aim was to make sure that simulated results could reflect the real situation.
(ii) Parametric analysis – identifying key design parameters and conducting a series of simulation runs by changing one parameter at a time.
(iii) Sensitivity of energy performance of office buildings in Hong Kong was examined by observing the response of computed output (annual building energy consumption) to changes in the input design variables. This helps identifying which building elements to focus on for a retrofit.
(iv) Illustrate the energy saving potential of energy conservation measures in possible retrofits of the sample buildings by considering discrete design changes in the key building elements identified.

3. Descriptions of the buildings and electricity use characteristics

A total of 10 purpose-built office buildings were selected for this study. The building sample was based on our earlier work on energy use characteristics in office buildings [14] and the selection criteria were as follows:

(i) High-rise (10-storey or more), and the sample should include the two major building envelope designs in Hong Kong – reinforced concrete with inserted windows and curtain walls.
(ii) The sample should include the three major glazing types – clear, tinted and reflective glass.
(iii) All buildings should have centralised HVAC systems.
(iv) Most important of all, availability of energy consumption data for at least one complete year, and the logistics of conducting energy audits and site surveys.

In order to retain the individual building anonymity, they are referred to as Building 1, Building 2, and so on. Information on the building designs and the building services installation was obtained from the original design and contract document wherever possible. Additional data were obtained through site visits, discussions with the architects, engineers and building management personnel. Table 1 shows a summary of the key building data and information on the building envelope designs. These design data were real inputs (not design assumptions) used in the subsequent building energy simulation. The gross floor area (GFA) ranges from 12,118 m^2 (Building 4) to 98,197 m^2 (Building 2) and the number of storey from 11 to 48. Most of them were completed during 1980s to early 1990s, the "booming" period of the local economy in general and the construction industry in particular. In general, there are two major building envelope designs, namely curtain walls and reinforced concrete with inserted windows. Buildings completed in the 1980s and early 1990s tend to have curtain wall designs. The windows area varies a great deal; the smallest window-to-wall ratio (WWR) is 0.33 in Building 8 and the largest 0.65 in Building 2. With a typical floor-to-floor height of 3.5 m, these represent window heights of about 1.2 and 2.3 m, respectively. In subtropical Hong Kong (latitude 22.3°N), solar altitude often exceeds 60° during hot summer days resulting in significant solar heat absorption by the horizontal roof. The roof structures, therefore, tend to be massive, usually no less than 300 mm thick consisting of roof tiles, waterproofing asphalt, cement and sand screed, thermal insulation (e.g., 50 mm expanded polystyrene), reinforced concrete plus the final internal finish of at least 10 mm gypsum plaster and a layer of enamel paint; with a common U-value range of 0.4–0.5 W/m^2 K. The 10-building sample covers the two major air-conditioning systems commonly found in office buildings in Hong Kong – fan coil units (FAU) and variable air volume (VAV). Both air-cooled and water-cooled (heat rejection) chiller plants were considered with a coefficient of performance (COP) ranging from 2.7 in Building 4 to 4.2 in Building 5. The normal operating schedule is a 10 (08:00–18:00) to 12 (08:00–20:00) hours working day and $5\frac{1}{2}$ days week with an indoor temperature of 23–25.5 °C for summer and 21 °C for winter.

Monthly electricity consumption data metered during the year 2000 were gathered from each of the 10 buildings. To account for the differences in building size, annual electricity use data for each building were divided by the corresponding GFA to give the normalised performance indicator (NPI). Energy use per unit floor area is used to compare the energy use intensity among different buildings and a summary is shown in Fig. 1. It can be seen that NPI varies from 233 kWh/m^2 in Building 3 to 368 kWh/m^2 in Building 2, with a mean consumption of 292 kWh/m^2. The difference in NPI is due mainly to the variations in lighting and equipment load density (Building 2 had large computer suites with mainframe computers and peripherals on 24-hour operation) and the electricity use for vertical transportation (i.e., lifts and escalators). A breakdown of the electricity use was conducted to establish a list of the major services or end-users. Four major services or electrical end-users were identified, namely HVAC, lighting, electrical equipment and lifts and escalators. Electricity consumption for the four major end-users among the 10 buildings were analysed and compared. HVAC was by far the largest electricity end-user. Ranges of the NPI for HVAC, lighting, equipment and lifts and escalators were 92.7–164.5, 71.5–81.3, 40.8–121 and 5.1–14.8 kWh/m^2, respectively. Fig. 2 shows a summary of the percentage breakdown for the four major electricity end-users. The percentage ranges for HVAC, lighting, equipment and lifts and escalators were 40.1–50.7%, 22.1–29%, 16.6–32.9% and 2.2–5.3%, respectively.

4. Parametric and sensitivity analysis

Energy performance of dynamic building systems can be assessed using detailed computer simulation programs so that designers can adopt a prototype and test approach for selection of appropriate design options. Detailed building energy simulation programs incorporate sets of mathematical models that seek to explain quantitatively how each component of a building behaves under given circumstances. Modelling and calculations of load and energy characteristics of the building are performed hour-by-hour for all the 8760 h in a year. The heating and cooling loads and the year-round energy consumption are then determined from the simulation results. The simulation tool employed in the present study was the DOE-2.1E building energy simulation program [20]. It has been used in many parts of the world for analysing energy