Sensitivity analysis of building energy use in different climates

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Abstract: Key design parameters (in terms of their influences on building energy consumption) through sensitivity analysis for fully air-conditioned office buildings in five cities (Harbin, Beijing, Shanghai, Kunming and Hong Kong) representing the five major climate zones (severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter) across China have been identified. These include: i) building envelope - window shading coefficient, window U-value and window-to-wall ratio; ii) internal load – equipment, lighting and occupancy; iii) HVAC system - outdoor fresh air, summer and winter thermostat set points, fan efficiency and fan static pressure; and iv) HVAC plant – chiller COP and boiler efficiency. The influence coefficient (IC, a ratio of the percentage change in computed output (building energy use) to the percentage change in input design parameter was used to indicate likely energy savings. For instance, Hong Kong has a lighting load IC of 0.359, suggesting that a 20% reduction (e.g. from 18 to 14.4 W/m^2) in lighting load could result in more than 7% reduction in the total building energy use. Furthermore, Hong Kong also has a summer thermostat set point IC of -1.131, suggesting that a 5% increase in the indoor temperature during the summer (e.g. from 26 to 27.3^{o}C) could result in about 6% energy savings. Given the growing awareness of adaptive thermal comfort, this could be a no-cost energy-efficient measure with great energy saving potential.

Keywords: Sensitivity analysis; Building energy simulation; Climate zones; China

1. INTRODUCTION

In China, there has been steady increase in the use of energy since the adoption of the Policy of Reforming and Opening in the 1980s, and energy conservation is of vital importance both economically and environmentally [Quanguo et al. (1994), Zhang (1995), Wu and Li (1995), Martinot (2001)]. It was estimated that buildings stocks accounted for 24.1% of total national energy use in mainland China in 1996, rising to 27.5% in 2001, and is projected to increase to about 35% in 2020 [Lang (2002), Yao et al. (2005)]. Office building development is one of the fastest growing areas in the building sector especially in major cities such as Beijing and Shanghai. On a per unit floor area basis, energy use in large office building development with full air-conditioning can be 70-300 kWh/m^2, 10-20 times that in residential buildings [Jiang (2005), Jiang (2006)]. Because of the climatic diversity in China, the designs of these buildings and their thermal and energy performances could vary a great deal in different climate zones across China [Lam et al. (2008a)]. The objective of the present work was to identify key design parameters (in terms of their influences on energy consumption) through sensitivity analysis for fully air-conditioned office buildings in the major climate zones across China.

2. MAJOR CLIMATE ZONES

China is a large country with an area of about 9.6 million km^2. Approximately 98% of the land area stretches between a latitude of 20^{o}N to 50^{o}N, from the subtropical zones in the south to the temperate zones (including warm-temperate and cool-temperate) in the north. China also has a complex topography ranging from mountainous regions to flat plains. These diversity and complexity have led to many different regions with distinct climatic features [Zhao (1986), Zhang and Lin (1992)]. In terms of the thermal design of buildings, there are five major climates, namely severe cold (SC), cold (C), hot summer and cold winter (HSCW), mild (M), and hot summer and warm winter (HSWW) [Ministry of Construction (1993)]. This simple climate classification is concerned mainly with conduction heat gain/loss and the corresponding thermal insulation issues. The zoning criteria are mainly based on the average temperatures in the coldest and hottest months of the year. A major city within each of the five climatic zones was selected for this study. These were Harbin (severe cold, 45^{o}45'N & 126^{o}46'E), Beijing (cold, 39^{o}48'N & 116^{o}28'E), Shanghai (HSCW, 31^{o}10'N & 121^{o}26'E), Kunming (Mild, 25^{o}01'N & 102^{o}41'E) and Hong Kong (HSWW, 22^{o}18'N & 114^{o}10'E).

3. HOURLY WEATHER DATABASES AND GENERIC BASE-CASE BUILDING DESIGNS

Building energy simulation was conducted using the simulation tool DOE-2.1E [DOE-2 (1993)]. Two major inputs were developed for each of the five cities – hourly weather databases and generic base-case office building designs, details of which can be found in our earlier work on building energy simulation in different climates [Lam et al. (2008a)]. Briefly, typical meteorological year (TMY) consisting 8760 hourly records of dry-bulb temperature, dewpoint temperature, solar radiation, wind speed and wind direction for each city was developed for the simulation exercise [Yang et al. (2007)]. A base-case office building was developed to serve as a baseline reference for comparative energy studies. The base-case was a 35 m x 35 m, 40-storey building with curtain walling design, 3.4 m floor-to-floor height and 40% window-to-wall ratio. The total gross floor area (GFA) is 49000 m^2 (41160 m^2 air-conditioned and 7840 m^2 non-air-conditioned). The air-conditioned space had five zones - four at the perimeter and one interior. Obviously, each city would have rather different building envelope designs to suit the local climates. Generic building envelope designs were developed based on the prevailing architectural practices and local design/energy codes [Ministry of Construction (2005), Building Department (2000)]. Table 1 shows a summary of the key building envelope design parameters. The building and its lighting system operated on an 11-hour day (07:00-18:00) and 5-day week basis. Infiltration rate was set at 0.45 air change per hour (when the heating, ventilation and air conditioning (HVAC) system is off) throughout the year. For comparative energy studies, the same internal loads, indoor design conditions and basic HVAC systems were assumed for the 5 cities with the corresponding design data taken from local energy/design codes on the mainland [Ministry of Construction (2003)] as well as the prevailing engineering practices. A summary of the key data is shown in Table 2.

Table 1. Summary of base-case building envelope design parameters

City	Climates	Building element	U-value (W/m^2 K)	Shading coefficient	
				North	Other orientations
Harbin	SC	Wall	0.44	-	-
		Window	2.50	0.64	0.64
		Roof	0.35	-	-
Beijing	C	Wall	0.60	-	-
		Window	2.60	0.70	0.70
		Roof	0.55	-	-
Shanghai	HSCW	Wall	1.00	-	-
		Window	3.00	0.60	0.50
		Roof	0.70	-	-
Kunming	M	Wall	1.47	-	-
		Window	3.50	0.55	0.45
		Roof	0.89	-	-
Hong Kong	HSWW	Wall	2.01	-	-
		Window	5.60	0.40	0.40
		Roof	0.54	-	-

Table 2. Internal conditions and HVAC systems for the base-case

Indoor design condition		Internal load density			HVAC		
Summer	Winter	Occupancy (m^2/person)	Lighting (W/m^2)	Equipment (W/m^2)	AHU	Cooling	Heating
26^{o}C	20^{o}C	8	18	13	4-pipe fan coil	Centrifugal chiller (Water-cooled)	Gas-fired boiler

Notes: HVAC = Heating, ventilation and air-conditioning; AHU = Air-handling unit

4. PARAMETRIC BUILDING ENERGY SIMULATION SENSITIVITY ANALYSIS

Before conducting the simulation and subsequent analysis, it is important to understand what input parameters are to be studied. Selecting and defining the input parameters is often a difficult task that requires sound engineering judgment and a good understanding of the simulation system. Breakdown of the parameters was worked out according to the input building description language of the DOE-2 program so that maximum effectiveness and compatibility could be achieved. These were the common design parameters that architects and engineers usually consider during the design process. There were all together about 36 input parameters categorized into three main groups - building load (17), HVAC system (7) and HVAC plant (12). Perturbations were introduced by assigning a range of different values to each of the input parameters (IP), one at a time. Changes in the parameters might represent a certain energy-efficient measure proposed to the building for achieving energy conservation and control purposes. For instance, windows with smaller SC and WWR could lower the amount of heat gain through the building envelope and hence reduce cooling energy use. Tables 3-5 show the summaries of the base-case values, ranges of the perturbations and intervals used in the parametric simulation. There were altogether 320 perturbations among the 36 parameters and a total of 356 simulation runs were conducted for each city. The simulation output of interest was the total building electricity consumption (OP). As sensitivity tends to follow the end-use components that consume the most energy, it is believed that input design variables affecting these components will have significant influence on the total building energy consumption [Chou and Chang (1993), Lam and Hui (1996), Thornton et al. (1997), Lam et al. (2008b)]. To quantitatively assess how sensitive the total building energy use would be to changes in the input design parameters, the influence coefficient (IC) was determined as follows [Spitler et al. (1989)]:

$$IC = \frac{OP - OP_{bc}}{OP_{bc}} \div \frac{IP - IP_{bc}}{IP_{bc}} \qquad (1)$$

The IC is essentially a ratio of the percentage change (with respect to the base-case value) in computed output to the percentage change in input design parameter. Table 6 shows a summary of the ICs determined. In general, larger the IC, more important the design parameter would be as it tends to