Energy and Buildings 76 (2014) 278–283

Contents lists available at ScienceDirect

Energy and Buildings

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

Method for the determination of optimal work environment in office buildings considering energy consumption and human performance

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ARTICLE INFO

Article history:
Received 29 October 2013
Received in revised form 22 February 2014
Accepted 26 February 2014

Keywords:
Built environment design
Human performance
Energy consumption
Optimal environment

ABSTRACT

How to balance the contradiction between energy saving and improvement of indoor environmental quality which consequently affects human performance has always been a problem. We put forward the economically optimum condition as a concept that maximized economic benefit in terms of regulation of office environment parameters. The calculation method was provided by which energy consumption could be reduced without compromise of human performance. A regression model predicting the energy consumption of a typical office building was illustrated as a function of two indoor environment parameters, i.e., indoor air temperature and air ventilation rate. Practical factors including salary and electric price, which have impact on the condition determination, were discussed. As a prototype, an office building in Shanghai achieved its economically optimal conditions at an air temperature of 25.1 °C and an outdoor ventilation rate of 17.9 L/s-person in summer.

1. Introduction

The global energy use has rapidly grown in the past few decades, giving rise to more and more concerns over energy security, utilization efficiency and environmental impacts. It is also believed that the energy situation would become more and more serious in the future, especially in emerging economies [1,2]. Currently, buildings account for approximately 40% of the total energy consumption globally [1]. Forecast made by the EIA [3] suggests that energy use in the building environment will grow by 34% in the next 20 years. Energy consumption in HVAC systems, comprising heating, outdoor ventilation and air conditioning, has proved to be the largest energy end-use both in residential and non-residential sectors. In China, for example, the HVAC systems are responsible for about 65% of the energy use in building sector [4]. As there are strong relationships between HVAC energy consumption and indoor climate set point [5], reasonable indoor climate parameters are essential for energy saving today. However, the relationship between HVAC energy consumption and indoor environment quality (IEQ) factors is difficult to be theoretically deduced because of its variance with building envelope, HVAC performance, etc. Therefore, regression analysis and simulation methods have been widely used in the parametric studies of building energy consumption [6,7].

In office buildings, however, energy consumption is not the only priority for indoor climate design. Attentions are increasingly drawn to the human–work environment interaction [8]. A healthy and effective built environment was proposed in the domain of green ergonomics [9]. As the salary of office workers is an order of magnitude higher than the cost of maintaining and operating the building [10], even small improvements in productivity can result in a substantial economic benefit. Fisk and Rosenfeld [11] estimated that improved indoor environment can bring a direct increase in productivity, ranging between 0.5% and 5%. Proper thermal condition [12–14] and indoor air quality [15–18] have proved to be of great help for better performance. However, little is known on the combined effects of these factors. Qualitative studies have been conducted by Witterseh et al. [19] on the combined effects of temperature and recorded noise. Hygge and Knez [20] investigated how outdoor ventilation noise, air temperature, and illuminance combine or interact in their effects on cognitive performance. Clausen and Wyon [21] carried out an experiment with subjects exposed to different combinations of traffic noise, lighting, access to daylight, open-plan office noise, air temperature and air quality. Due to the lacking of quantitative studies, the combined effects of air temperature and ventilation rate on work performance were roughly estimated in this paper, while attention should be paid on the proposed methodology for determining economically optimum conditions.

Building services engineers gradually realize that not only energy consumption but also human productivity should be

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http://dx.doi.org/10.1016/j.enbuild.2014.02.077
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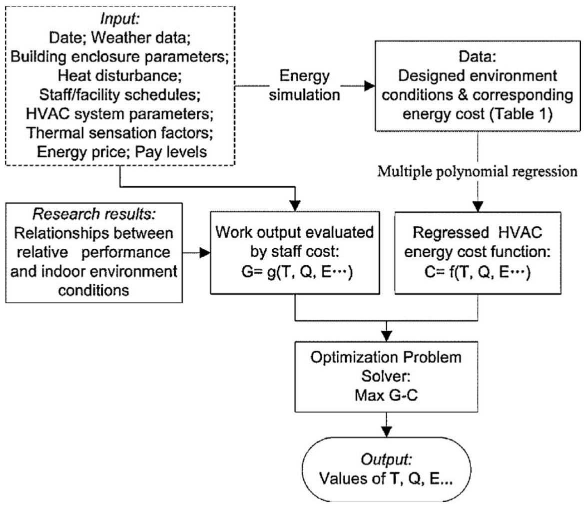

Fig. 1. A framework illustrating the core idea of the model.

incorporated into the economic calculations pertaining to building design and operation. However, there are few methods shed light on the global economic effects caused by energy consumption of HVAC systems and human productivity in the building. In this study we proposed a method to achieve such economically optimal indoor environment by balancing the contradiction between human performance and energy consumption of HVAC systems. Two important IEQ factors including indoor air temperature and outdoor ventilation rate were set as the example to illustrate how to achieve such economically optimal set points.

2. Methods

Improved indoor environment generally brings forth higher productivity while may cause extra investment in operating cost. To obtain economically optimum conditions, both the benefit from improved performance and the corresponding energy cost should be quantitatively analyzed. A subtraction model instead of the cost–benefit ratio was selected in Eq. (1) since energy charge was only a small part in total inputs and much less than the economic returns.

$$\max G(T, Q, E\ldots) - C(T, Q, E\ldots) \quad (1)$$

where T, Q, $E\ldots$ were the IEQ factors, T was indoor air temperature, Q was outdoor ventilation rate, E was illuminance level, G was the economic returns decided by the employee working performance and influenced by the IEQ factors, C was the HVAC energy consumption which also depended on the IEQ factors.

The core idea of the model was illustrated in Fig. 1. It worked like an open-loop control strategy. Two functions representing the work output and energy cost of the certain office were processed to build the optimization model as shown in Eq. (1). And the input data of the whole model decided what the two functions would be. After using the optimization method and theory, the optimal indoor environment conditions could be achieved.

Due to the lack of quantitative relationship between human performance and other IEQ factors, two important parameters were discussed in this study: air temperature T and outdoor ventilation rate Q. Nuisance factors affecting either economic returns or energy consumption were kept constant here.

2.1. The relationship between office work output and IEQ factors

Taking air temperature as its horizontal axis and outdoor ventilation rate as the vertical axis, a Cartesian plane could be drawn in which each point had its corresponding value of work performance, as shown in Fig. 2. The origin point (T_0, Q_0) was the reference point where the relative performance was set to be 1. Both T_0 and Q_0 were set at the values when human performance was poorest. Assuming the magnitude of the combined effects was the sum of independent parameters, RP_H represented the relative performance, but if the combined effects were replaced by the greater of the single parameters, the relative performance was then expressed as RP_L. At present there was a study reporting the combined effect of outdoor ventilation and temperature on human performance. Wargocki and Seppänen [22] suggested that the magnitude of the combined effect was at least the effect of the greater of the single parameters, and not more than the sum of the independent parameters. So we proposed the mean value of RP_H and RP_L as the final relative performance (Eq. (2)). α_1 and α_2 represented the change in relative performance when the indoor environment improved along with the coordinate axes.

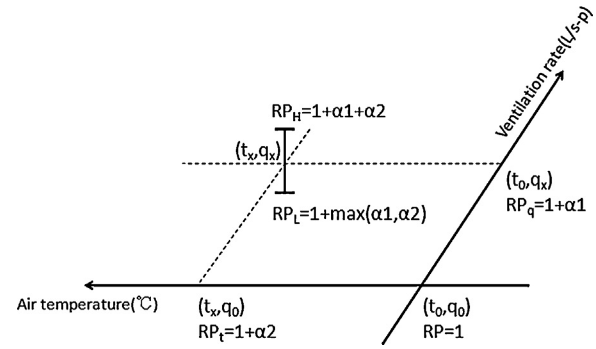

Fig. 2. Method to obtain the relative performance in different conditions.

$$RP_x = \frac{1}{2} \times (RP_H + RP_L) = 1 + \frac{1}{2} \times [\alpha_1 + \alpha_2 + \max(\alpha_1, \alpha_2)]$$
$$= \frac{1}{2} \times [RP_t + RP_q + \max(RP_t, RP_q) - 1] \quad (2)$$

Given the varying trends of the relative performance along coordinate axes, the relative performance interval from RP_L to RP_H could be figured out for the office environment conditions (T_x, Q_x).

As shown in Fig. 2, when the air temperature was kept to be constant, the relative performance would be RP_q if the outdoor ventilation rate increased from Q_0 to Q_x L/s-person. Similarly, when the outdoor ventilation rate was kept to be Q_x L/s-person, the relative performance would be RP_t by reducing the air temperature from T_0 to T_x °C.

The effects of air temperature or outdoor ventilation rate on human performance have been estimated in existing studies. In this paper, the quantitative relationship between productivity and thermal sensation vote (Eq. (3)) developed by Lan et al. [23] was used. Based on this relationship, the economic optimization model could illustrate the optimal conditions for different seasons and could allow for the changes of factors including clothing thermal resistance, relative humidity and so on [24].

$$RP = -0.0351 \cdot tsv^3 - 0.5294 \cdot tsv^2 - 0.215 \cdot tsv + 99.865 \quad (3)$$

where RP was the relative performance when compared to the maximum performance and tsv was the thermal sensation vote (−3 to +3 on the ASHRAE seven-point thermal sensation scale) [23].

Seppänen et al. [15] established a quantitative relationship (Fig. 3) between outdoor ventilation rate and productivity. The following equation (Eq. (4)) could be obtained from Fig. 3.

$$RP_q = 0.021 \cdot \ln(Q) + 0.960 \, (6.5\,\text{L/s-person} \le Q \le 30\,\text{L/s-person}) \quad (4)$$