Building and Environment 122 (2017) 15–22

Contents lists available at ScienceDirect

Building and Environment

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

Method for including the economic value of indoor climate as design criterion in optimisation of office building design

Steffen Petersen*, Michael Dahl Knudsen

Department of Engineering, Inge Lehmanns Gade 10, Aarhus University, DK-8000 Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form
24 May 2017
Accepted 25 May 2017
Available online 29 May 2017

Keywords:
Indoor climate
Productivity
Thermal comfort
Air quality
Economic optimisation

ABSTRACT

Several studies have indicated that work performance can be used as an indicator that articulates the relation between humans and indoor climate in office buildings. But does this knowledge affect the optimal office building design? This paper presents a method for simulation-based investigations on the extent to which optimisation of the relation between indoor climate (whole-body thermal comfort and perceived air quality) and productivity, instead of – or in combination with – comfort based acceptance criteria, affect the cost-optimal design of office buildings. For this purpose, a single-objective optimisation problem was formulated and a calculation procedure was proposed. The results of a retrofit case study indicate that energy use and productivity loss can be reduced if building designers optimise with respect to productivity instead of comfort based constraints. Optimising productivity while respecting comfort based constraints led to a less but still profitable solution. The composition of an economic optimal retrofit solution thereby strongly depends on whether the building owner is willing to put an economic value on the effect of the retrofit solution on comfort and/or the relation between indoor climate and productivity.

1. Introduction

An important task of office building designers is to ensure that the indoor temperature and perceived air quality live up to the expectations of the building's owner and occupants. When designing a new office building or energy-retrofitting an existing one, designers can assess how potential design decisions would affect indoor temperature and perceived air quality before making any actual design decisions by using one of the numerous computer-based building performance simulation tools (BPS tools) available; see e.g. Crawley et al. [1]. Meaningful use of BPS for this purpose requires that building designers set up quantifiable criteria that are expressed when occupants' indoor climate expectations are fulfilled. Current practice is to use the guidelines in prevailing international comfort based standards like EN 15251 [2] and ASHRAE standard 55 [3] to decide on an acceptable interval for the indoor operative temperature, and a certain accepted minimum ventilation rate that ensures an accepted level of desired perceived air quality. In addition, it is practice in some countries to allow a small expected number (or percentage) of occupied hours to exceed a certain indoor climate acceptance criterion – a so-called exceedance metric. This practice is especially widespread in Europe where many countries traditionally have based their national legislative requirements for e.g. indoor temperature on an upper threshold temperature while permitting a certain exceedance of this, see Lomas and Giridharan [4] and Petersen [5] for examples. Furthermore, the European standard EN 15251:2007 introduced that “deviations from selected criteria shall be allowed” and recommends criteria for acceptable deviations expressed as ‘length (time) of deviation’ (annex G) if no national criteria are available.

Overall, there are a number of good practical reasons for the use of time-based exceedance metrics when designing and operating buildings. It helps address comfort trade-offs in building design and operation [6], e.g. by allowing a short period of increased air velocity when opening windows [7], and it reduces investment cost for peak capacity in HVAC systems significantly (e.g. for mechanical cooling which tends to rise exponentially at the end of its duration curve). However, whether a time-based exceedance criterion is fulfilled will be very sensitive to the nature of the assessment method for internal temperatures [8]. In the case of a modelling study, different weather files or choice of BPS tool might put the

---

* Corresponding author.
E-mail address: stp@eng.au.dk (S. Petersen).

http://dx.doi.org/10.1016/j.buildenv.2017.05.036

design on one side or the other of the exceedance threshold [9]. This predicted exceedance may also be significantly influenced by the choice of comfort model, uncertainties in predicted neutral comfort temperatures, and variations in building envelope performance, solar heat gain, thermal mass, and control precision [6]. Consequently, the exact formulation of a time-based exceedance metric can have a marked influence on the building design, such as the allowable window area and size of HVAC systems [5,10,11].

As mentioned above, the prevailing practice when evaluating outcome of BPS tools for office building design is the use of a comfort based indoor climate paradigm. However, research indicates that indoor thermal conditions and ventilation rate in offices not only affect comfort but also work performance [12–14]. Several studies on the relation between indoor thermal conditions and productivity have indicated that the optimal predicted mean vote (PMV), in terms of objectively measured productivity, is slightly lower than for subjectively assessed thermal comfort [13]. In other words, office workers do not necessarily need to be in a neutral thermal state to be most productive. This was supported by the study reported in Li et al. [15] who, consequently, suggested that PMV in workplaces should be in the range between −0.5 and 0 instead of between −0.5 and 0.5 as stipulated in prevailing comfort based standards. Furthermore, studies on the relation between ventilation rate and productivity have indicated an average improvement of 1–3% in objectively measured work performance per 10 l/s-person increase in ventilation rate [18]. Ventilating office spaces to optimise work performance therefore quickly leads to a remarkably higher ventilation rate compared to the ventilation rates needed for a certain subjectively perceived air quality according to prevailing comfort based indoor climate standards. Besides work performance, ventilation may also affect productivity due to the relationship between ventilation and building-related disease. A review of the epidemiological evidence from studies investigating the link between outdoor air ventilation rates and health have shown that there are minimum rates of ventilation above which some health outcomes can be avoided but evidence is missing for establishing a universal applicable ventilation-health relationship [16]. As an example, Milton et al. [17] found a decrease of 1.53% in relative risk for short term sick leave for an estimated ventilation rate of 24 l/s-person compared to 12 l/s-person.

The above-mentioned studies indicate that using optimal relations between indoor climate and productivity to set up design criteria for indoor climate leads to a different set of criteria compared to the comfort based indoor climate paradigm. However, it should be noted that the relationships between indoor climate and productivity are still quite uncertain because of limitations in the number and scope of underlying studies [19]. Despite of this, the following point of view has been expressed by Seppänen et al. [13], Fisk et al. [19] and Wargocki et al. [20]: It is preferable to use uncertain but credible estimates of benefits rather than ignoring the effects on performance when designing buildings and selecting building operation practices. A key rationale behind this point of view is that building related costs are significantly smaller than wages [21] which means that investments leading to even the smallest change in productivity are important for profit. Practical examples of this can be found for investment in HVAC systems [20–22]. However, there is a lack of more broad analysis on the practical implication of using a productivity-based acceptance criterion as boundary condition in office building design. Using productivity to articulate the relationship between humans and indoor climate would be a paradigm shift in general design practice, and it is thus worthwhile to investigate how a criterion based on productivity affects the cost-optimal design. This paper therefore presents a method for simulation-based investigation on the extent to which optimisation of the relation between indoor climate (thermal and air quality) and productivity instead of – or in combination with – comfort based acceptance criteria affects the cost-optimal office building design. The outcome of the method is illustrated using a retrofitting case as example.

2. Method

The investigation was based on an optimisation problem with the objective of minimising the following economic cost function:

$$F(X) = I(X) + \sum_{k=1}^{n}\left(M(X,k)\cdot\frac{1}{(1+r_g)^k}\right) + E(X)\cdot\frac{1-(1+r_e)^{-n}}{r_e} + P(X)\cdot\frac{1-(1+r_g)^{-n}}{r_g} + R(X)\cdot\frac{1}{(1+r_g)^n} \tag{1}$$

where $F(X)$ is the total costs in net present value (NPV) and $X = \{x_1, x_2, \ldots x_i\}$ is a certain combination of design measures (e.g. insulation thickness and window type) in the user-defined solution space. $I(X)$ is the investment costs (monetary unit) of X, n is the investment horizon (years), $M(X,k)$ is the maintenance cost in year k (monetary unit), $E(X)$ is yearly energy consumption costs (monetary unit) due to X, $P(X)$ is yearly productivity loss due to X (monetary unit), and $R(X)$ is the residual value of $I(X)$ after n years. r_g and r_e are the real interest rates:

$$r_e = \frac{1+r_{nom}}{1+q_e}, \quad r_g = \frac{1+r_{nom}}{1+q_g} \tag{2}$$

Where r_{nom} is the nominal interest rate, q_g is average annual general inflation rate in society, and q_e is average annual energy inflation rate.

As for any optimisation problem it is possible to add constraints, e.g. boundary conditions for thermal comfort which a feasible X must respect. The following sections describes how to calculate $P(X)$, a proposed calculation procedure (method) for minimising $F(X)$, and the prerequisites for a case used to illustrate the use of the proposed method.

2.1. Capitalising the relation between indoor climate and productivity

As mentioned in the introduction, current studies have linked the quality of the indoor climate to two productivity indicators, namely sick leave and work performance. In this study we only consider work performance as an indicator of productivity.

The approach used in this study is inspired by Wargocki et al. [20] who provided examples on how the current knowledge on the relation between indoor climate and productivity in principle could be capitalised when making life cycle cost calculation of measures that improve the indoor climate in an office building. The capitalisation is based on the productivity loss, $P(X)$:

$$P(X) = (S_{year}\cdot m)\cdot O_{year}\cdot T_{year}\cdot\sum_i \Delta RP_i\cdot p_i$$

where S_{year} is the average annual gross salary for the m persons in the office (monetary unit), O_{year} is the annual overhead costs (−), T_{year} is the annual desired profit (−), ΔRP_i is the relative change in productivity compared to maximum performance (−) due to changes in the indoor climate in the time step i, and p_i is a factor expressing the number of people present in the office in time step i relative to n.