A conceptual model to estimate cost effectiveness of the indoor environment improvements

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ABSTRACT
Macroeconomic analyses indicate a high cost to society of a deteriorated indoor climate. The few example calculations performed to date indicate that measures taken to improve IEQ are highly cost-effective when health and productivity benefits are considered. We believe that cost–benefit analyses of building designs and operations should routinely incorporate health and productivity impacts. As an initial step, we developed a conceptual model that shows the links between improvements in IEQ and the financial gains from reductions in medical care and sick leave, improved work performance, lower employee turn over, and reduced maintenance due to fewer complaints.

INDEX TERMS
IAQ assessment; Health effects; Productivity; modelling; Costs

INTRODUCTION
The evidence that IEQ substantially influences health and productivity is becoming strong. Some calculations show that the cost of deteriorated indoor environments is higher than building heating costs (Seppanen, 1999). Macro-economic estimates indicate that large economic benefits are possible from improved IEQ (Fisk, 2000; Mendell *et al.*, 2002). Building professionals desire to quantify the costs and benefits of measures that improve IEQ; however, suitable models are not available. Only initial costs and energy and maintenance costs are typically considered in economic calculations pertaining to building design and operation. However, a few sample calculations have shown that measures to improve IEQ are very cost-effective when the financial value of health and productivity benefits is considered (Hansen, 1997; Seppanen *et al.*, 2000; Djukanovic *et al.*, 2002). Thus, there is an obvious need for tools and models that enable economic outcomes of health and productivity to be integrated with initial, energy and maintenance costs in cost–benefit calculations. Broad use of such models would be expected to lead to improved IEQ, health and productivity.

THE MODEL
We developed a conceptual model for estimating the cost-effectiveness of changes in building design or operation that affect IEQ. The model, illustrated in Figure 1, shows the multiple pathways between measures that improve IEQ and the financial gains resulting from better health and productivity. In the model, a design or retrofit measure leads to an improvement in one or more IEQ conditions (e.g. pollutant concentration), which in turn influences one or more human responses (Boxes 3–9), such as a health condition or complaint frequency. Human responses are linked to benefit categories (Boxes 10–14) such as the health care cost or sick leave days. Finally, changes in the outcomes in boxes 10–14, lead to economic gains (boxes 15–19). The arrows between boxes represent quantitative mathematical functions that link conditions or outcomes in the two boxes.

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Human Responses
Human responses to IEQ are denoted in boxes 3–9. The evidence that IEQ affects these human responses is discussed briefly in the next paragraphs.

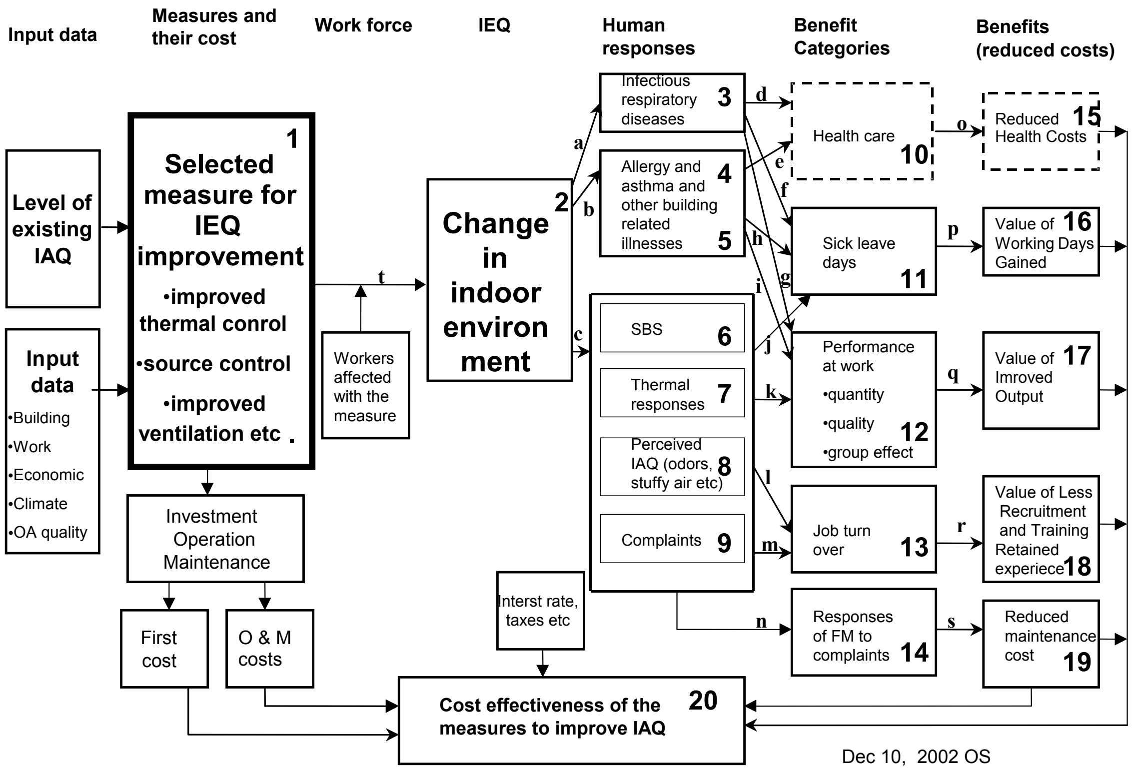

Figure 1 Conceptual economic model for owner-occupied buildings.

Some transmission of *infectious respiratory diseases* (#3), including some common colds and influenza, is known to be by aerosols containing virus or bacteria. In the United States, four common respiratory illnesses cause 176 million days lost from work and additional 121 million working days of substantially restricted activity (Fisk, 2000).

Although the primary causes of *asthma and allergy* (#4) are not always related to IEQ, the symptoms are commonly caused by indoor allergen exposures (IOM, 2000). The annual cost of asthma and respiratory allergies in the US is estimated to be $15 billion (Fisk, 2000).

Prevalences of SBS symptoms (#6) are the commonly used outcomes in building-related health studies. Representative data from US office buildings found that 23% of workers (15 million workers) reported two or more frequent SBS symptoms that improved when they were away from the work place (Fisk, 2000).

The thermal environment (#7) is not ideal in many buildings. While the criteria for thermal comfort are well established, the thermal environment may also directly affect productivity or affect SBS symptoms, which in turn may affect productivity.

Perceived indoor air quality (PAQ) (#8), a commonly used as a metric of IEQ, can be evaluated with trained or untrained olfactory panels. Many ventilation standards are based on the dilution of body odour by ventilation and resulting level of PAQ.

Complaints about IEQ (#9) to facility managers (FM) are very common. Federspiel (2001) has shown that temperature-related complaints lead to a significant maintenance cost.

Linkages between Building Features, IEQ and Human Responses

To use the model, we normally require quantitative estimates of how a building design or operational change influences IEQ conditions and, in turn, quantitative estimates (indicated by functions d–n in Figure 1) of how these conditions affect health, absence, performance, and other financial outcomes. After reviewing existing literature, it became apparent that better data are highly desirable for all functions (a–s) relating IEQ conditions to human outcomes. However, it is not essential to quantify all functions because some data directly link building design (HVAC type) or operation (ventilation rate) to a health or performance outcome. This type of linkage is not shown in Figure 1. In the following paragraphs, we summarize the information available on these links.

IEQ-respiratory diseases. The relation between the indoor environment and prevalences of respiratory diseases was reviewed by Fisk (2000) and is supported by a theoretical model of disease transmission. The prevalence of respiratory diseases seems to be affected by the ventilation rate (Seppanen *et al.*, 1999) and by occupant density. Milton (2000) found that higher ventilation rates were associated with reduced short-term absence, much of which is caused by respiratory illnesses.

IEQ-allergy and asthma. A recent summary (IOM, 2000) shows that symptoms of asthma and allergy may be triggered by indoor allergens, which have concentrations affected by building design or operation. Allergy and asthma symptoms are also linked also to the dampness problems in buildings (Bornehag *et al.*, 2001). Viral respiratory infections, which may be influenced by building factors, also appear exacerbate asthma (IOM, 2000).

IEQ-SBS symptoms. Increased SBS symptoms have been linked to higher temperatures, more dust on surfaces, higher concentrations of certain volatile organic compounds, lower ventilation rates, and presence of air conditioning (e.g. Mendell, 1993; Seppanen *et al.*, 1999; Seppanen and Fisk, 2002). However, most studies express only statistically significant relationships, while mathematical dose-response relations are needed for our model. Approximate quantitative relationships could be developed only between ventilation rates and SBS symptoms and between temperatures and SBS symptoms.

Thermal environment. The relation between building design and operation and thermal conditions is well established and modelled with existing building simulation tools. Some models estimate human comfort ratings, but health and productivity are not modelled.

Perceived air quality. Perceived air quality (PAQ) is affected mainly by pollution sources in the building, ventilation rates, outdoor air quality, and air temperature and humidity.

Benefits

The potential benefits of improved IEQ include reduced medical care cost, working days gained due to reduced sick leave, better performance in work, lower turnover of employees, and lower cost of building maintenance due to fewer IEQ complaints.

The financial benefits of reduced sick leave (#11) are obvious. Performance at work (#12) is more complicated to quantify. Three distinct aspects of performance are: quantity (speed), quality (e.g. number of mistakes), and group effect (e.g. how well group works together). The quantity of work has been used as a metric in laboratory and field studies. The measurement of work quantity and quality is much easier for repetitive work (e.g. processing of forms). Poor IEQ conditions may also lead to complaints and to communications among employees which may change attitudes about the employer, and, in turn, affect work performance. If IEQ problems are not dealt with properly, employee-management conflicts may develop and complicate the problem solving process (Lahtinen *et al.*, 2002) and reduce productivity; however, the magnitude of this effect is unknown.

A reduced job turnover (#13) may significantly reduce costs to employers. Goetzel *et al.* (2001) estimated that turnover costs per employee were $3700.

Reduced responses of FM to IEQ complaints (#14) are an economic benefit. Federspiel (2001) analysed data from 575 buildings and reported that 18.4% of complaints were IEQ complaints. About 77% of IEQ complaints were about conditions perceived as too hot or too cold. He showed that the rate of complaints depends on the average temperature and its standard deviation and he estimated maintenance cost savings of $0.0035/ft^2 per year.

The magnitude of many financial benefits depends on the change in work time (e.g. days at work), or speed, or quality. As a first approximation, financial benefits can be based on employee compensation. Ideally, changes in group performance should be assessed.

Linkage between Human Responses and Potential Benefits

Some of the links between human responses and financial benefits are obvious (e.g., illnesses cause health care costs and sick leave). Berger et al. (2001) concludes that employee health also affects work performance. The link between prevalences of SBS symptoms and productivity has been summarized by Fisk (2000) and Mendell et al. (2002). The number of SBS symptoms has been linked to self-estimated productivity and the prevalence of symptoms has been linked to self-reported sick leave. However, a mathematical relationship of SBS symptoms to absence and work performance could not be determined, although analyses of some existing data sets might provide information on the SBS-absence linkage. Thermal conditions outside the thermal comfort zone have been linked to deteriorated work performance in call centres (Federspiel, 2002; Niemela *et al.*, 2002) and in laboratory experiments (e.g. Wyon, 1996). Finally, in laboratory tests with variable ventilation and pollution loads (Wargocki *et al.*, 2000), PAQ was correlated with work performance.

Investment and Operational Cost

The model includes the cost of investments and building operation and maintenance. We do not discuss the estimation of those costs, which is a well-developed practice.

Perspective

The cost effectiveness of measures that improve IEQ conditions varies with the perspective taken (e.g., building owner, employer, broader society). Different benefits would be considered for a rented building from the perspectives of lessor and lessee. Benefits from IEQ improvements may be transferred to a building owner (lessor) via increased rent; however, minimal information is available about how IEQ affects rent. The market value of a building and the ability to renew leases or attract new lessees may also be increased by a reputation of high IEQ. Hanssen (1997) refers to a study which concluded that a tenant does not renew the lease agreement (e.g. due to frequent IEQ complaints) the costs of lost rental income, remodelling, etc. to the owner will be equivalent to one and half years rent. The owner (lessor) may also benefit from reduced maintenance costs resulting from fewer IEQ complaints. An employer (lessee) receives the benefits of improved productivity. Lessees will generally not directly experience the costs of building design or operational changes. Lessees might benefit from lease terms that require IEQ maintenance measures. In general, neither the owner (lessor) nor the employer (lessee) benefit from reduced medical care costs which are usually covered nationally or by insurance.

DISCUSSION

For cost–benefit analyses, the relationships between IEQ conditions (or IEQ improvement measures) and financial outcomes related to health and productivity must be quantifiable.

Thus, we need mathematical functions for each of the arrows between the boxes in Figure 1. An absence of these mathematical functions is the primary barrier to performing cost–benefit analyses, and is a major obstacle to better indoor environments. To date, we have derived only a few quantitative functions, and even these functions have much uncertainty. In papers submitted to this conference, the relationships of ventilation rates to absence and between absence and absence-related productivity losses have been estimated, and the relationships of temperatures within and above the comfort zone to work performance have been estimated. Also, Federspiel (2001) has quantified the relationship of temperatures to hot and cold complaints and the costs of responding to these complaints.

A few complications have been ignored in the previous discussion. First, it is important to note that the benefits of IEQ improvement measures will depend on the initial condition in the building; for example, increased ventilation will be more helpful in a building with strong indoor pollution sources. However, at present we have, at best, information about how a measure affects health or productivity in the average building. Hence, uncertainty about the magnitude of benefits in specific buildings will remain an obstacle, even when average benefits can be estimated. IEQ improvement measures should be most cost effective when targeted at buildings poorer IEQ or more IEQ complaints. Second, the susceptibility of occupants to different levels of IEQ may vary among and within buildings. Generally, the population affected by poor IEQ is primarily the most susceptible sub-population. Theoretically, it would be more cost effective to target remedial actions for those who suffer most from poor IEQ. Such targeting will often be impractical, but there are exceptions, e.g., provision of individual temperature control with local heaters. Third, we note that one cannot always add the benefits of separate IEQ improvement measures as the effects of different measures may be linked or overlapping. Finally, we note that a small company may not be able to fully benefit from modest increases in performance. For example, reducing sick leave per person by a few days per year will not enable a ten-person company to reduce the number of staff.

We acknowledge the high level of uncertainties associated with incorporating health and productivity within cost–benefit analyses related to building design and operation. However, we believe that evaluating cost and benefits based on the best available information is preferable to current practice, which is to ignore health and productivity.

CONCLUSIONS

The conceptual modelling for considering IEQ-related effects on health and productivity in cost–benefit analyses of building designs and operational practices is only a first step in, what we hope will be on ongoing process of model development. The conceptual model provides a framework for cost–benefit calculations and demonstrates the large need for more quantitative information relating IEQ measures and conditions to health and productivity outcomes. The model also illustrates the special value of data relating SBS symptoms to absence and work performance productivity because we have much data relating building design and operation to SBS symptom prevalences.

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