MODELLING THE COST EFFECTS OF THE INDOOR ENVIRONMENT

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ABSTRACT
A deteriorated indoor environment causes various symptoms, sicknesses, sick leaves, reduced comfort and losses in productivity. When all these items are estimated on an economic basis, the cost of a deteriorated indoor environment is high. Several calculations have shown that many of the measures taken to improve indoor air quality and climate are cost-effective when the potential savings are included into the calculations as benefits. However, general models on how to estimate the cost-effectiveness of various measures and strategies are missing. Two workshops within the Healthy Buildings 2000 conference discussed how to include the effects of the indoor environment on productivity into such models. The paper presents an approach based on the work of the workshops and developed further.

INDEX TERMS
Modelling, Cost effects, Productivity, Performance, Indoor environment.

INTRODUCTION
Deteriorated indoor environments cause various symptoms, sicknesses, reduced comfort and loss of concentration which may result in inconsistent work, longer breaks, less care of customers, shorter working hours and sick leaves. Many studies provide evidence that buildings and indoor environments influence the prevalence of respiratory illnesses, allergy and asthma symptoms, and sick building symptoms (Fisk 2000).

Buildings and their indoor environments incur considerable costs, both at the personal and building management levels as well as the community and national levels, which are obviously not being accounted for by those responsible. Rough estimates have been made which indicate that the annual cost of respiratory infections in the USA is approximately €73 billion (1 € = 0.8766 US$), the cost of allergies and asthma approximately €14.6 billion and the cost of SBS symptoms approximately €57 billion (Fisk and Rosenfeld 1997). Without adequate criteria or strict enough regulations to control the performance of the construction industry, maintenance and operating services, and building owners, necessary improvements in building and maintenance practices do not seem to come about. Legislative regulation, or insurance claims, may however turn out to be undesired procedures. On the other hand, if it were possible to demonstrate how to achieve cost avoidance in owning and operating buildings, and at the same time enhance the well-being of the occupants with economically feasible measures, the degradation of the existing building stock might be discouraged and healthier buildings designed in the first place.

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A CONCEPTUAL MODEL ON THE COST EFFECTS OF THE INDOOR ENVIRONMENT

The aim of this paper is to describe the principles of a model which will calculate the cost-effectiveness of various measures to improve the indoor environment. The conceptual framework of the model has been derived from the work of Sensharma and Woods who have developed a rational model, which goes much further than a traditional toxicologic dose-response model, and links exposures and human responses not only with indoor and outdoor sources and building systems, but incorporates economic factors into the model as well as encompasses psycho-social indicators such as job satisfaction, stress, motivators and risk perception (Sensharma and Woods 1997). The psycho-social factors, which may have a great influence on the various human responses, are left outside the scope of this paper.

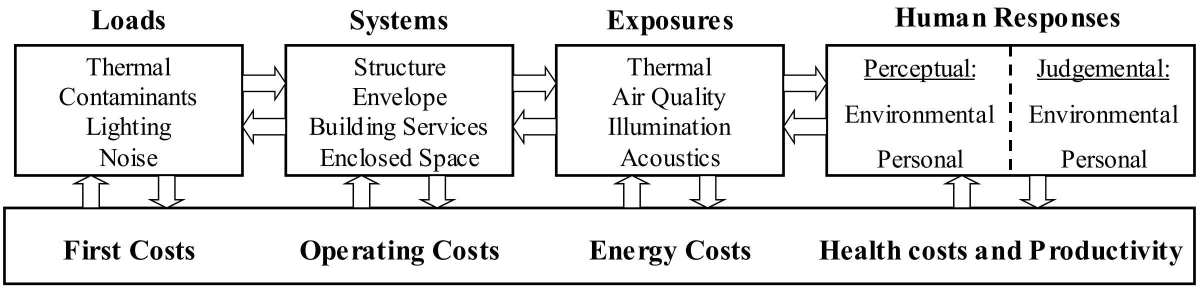

Figure 1. A conceptual model on the relationships of the cost effects of the indoor environment (modified from Sensharma et al. 1998).

Figure 1 shows that the exposure parameters in the model of system relationships include, beside indoor air quality, also three other environmental stressors, thermal, illumination and acoustics. The exposures result from the building system responding to internal loads that accumulate from indoor and outdoor sources. The building system comprises the building structures and envelope, the HVAC system performance, operation and maintenance procedures, the age of the building or HVAC system and codes and standards (Sensharma et al. 1998). Human responses result from physiological receptors reacting to exposure parameters and have been classified into four groups. Environmental-perceptual responses are external sensory responses that refer to the environment. Personal-perceptual responses include internal sensory responses and general physiological symptoms. Environmental-affective responses are judgements about the environment and personal-affective responses are subjective judgements about an individual's personal state (Sensharma et al. 1993).

BUILDING-RELATED COSTS

Building-related costs should be examined at both the micro-scale and macro-scale levels. The economic implications of the interactions between the loads, building system, exposure parameters and human responses are critical boundary conditions to the acceptable design and operation of the building systems (Sensharma et al. 1998). Parallel to the costs of design and construction (i.e. first costs), energy costs, and operation and maintenance costs are health costs and the concept of productivity. In the conceptual framework of Sensharma and Woods, productivity is the economic expression of human performance. The concept of productivity is vital to the whole framework because the most significant of all the owning and operating costs in office premises is the cost of salaries and wages which are in the range of 70 – 90% of the total costs (Woods 1989). Cost avoidance should, therefore, aim at preventing lost time of employees and enhancing their performance which means providing the employees with environmental conditions which satisfy their needs, reduce the adverse effects of exposures and promote health. Productivity enables the evaluation of the costs of reduced performance, taking into account the value of work, and the comparison of these costs with the operation and maintenance, energy costs or renovation costs of the building.

In addition to these costs at the micro-scale level, there are the macro-scale costs, in other words the expenses caused by adverse health effects and reduced gross national product on society. The main objective of developing a cost-effectiveness model is that it encourages the internalisation of the costs of deteriorated indoor environments which are at yet external to the building sector.

In order to introduce performance and productivity into a cost effectiveness model, the linkages between the interacting factors in the indoor environment, described in Figure 1, need to be properly assessed and validated. A lot of work in this field has been done (e.g. Sensharma et al. 1998, Seppänen et al. 1999, Wyon 1993, Wargocki et al. 2000), although further studies are needed (Sensharma et al. 1998). In addition to this, it is compulsory to quantify the linkages which often have been reported qualitatively (WS9 2000).

An efficient cost-effectiveness model should be able to assess the impacts of selected improvement measures on occupant performance. To achieve this aim, it must be ensured that performance can be converted into a financial figure, i.e. productivity. Literature pertaining to office environments reveals that some task-based measures of productivity have been found and used, such as the speed of text typing, the number of answered calls in a telephone service centre or the number of insurance claims processed. However, a lot of work in office environments is creative mental work, the objective measurement of which is difficult and prone to errors. Consequently, subjective measures, such as self-assessed productivity, are very often used, the advantages of which have been reported by Clements-Croome and Kaluarachchi (2000). Beside self-assessment, absence from work has been used as a non-output measure (Milton et al. 2000). Research has also used the linkages between human responses (symptoms) and performance from which productivity can be extrapolated (see the example on ventilation at the end of this paper).

THE MODEL ON THE COST EFFECTS OF THE INDOOR ENVIRONMENT

The above-described relationships between the indoor environment factors are embedded in the cost-effectiveness model being developed. At the core of the model shown in Figure 2 there is a calculation programme which has direct access to subroutines which consist of relations representing the links between the indoor environment factors and health, well being and productivity.

The calculation programme needs a lot of background data from the user to operate. At the interface level, the idea of various levels of degradation of a building during its lifecycle, developed in detail for example in Sensharma et al. (1998), has been adopted in the model. Thus, the basic idea of the model is that the user may determine the level of the indoor environment and identify the problems in the building that need mitigation. The users are presented with a list of possible problems in the indoor environment from which they may select the problem which needs assessing. The programme then goes through the database of improvement measures and proposes optional mitigation strategies to the selected problem. For example, if occupants of the building complain of too high temperatures in the summer, the user selects this problem from the various alternatives. The programme may then suggest such options as external shades or overhangs to limit solar gain, reflective glass for the windows, longer operation times of ventilation systems or mechanical cooling.

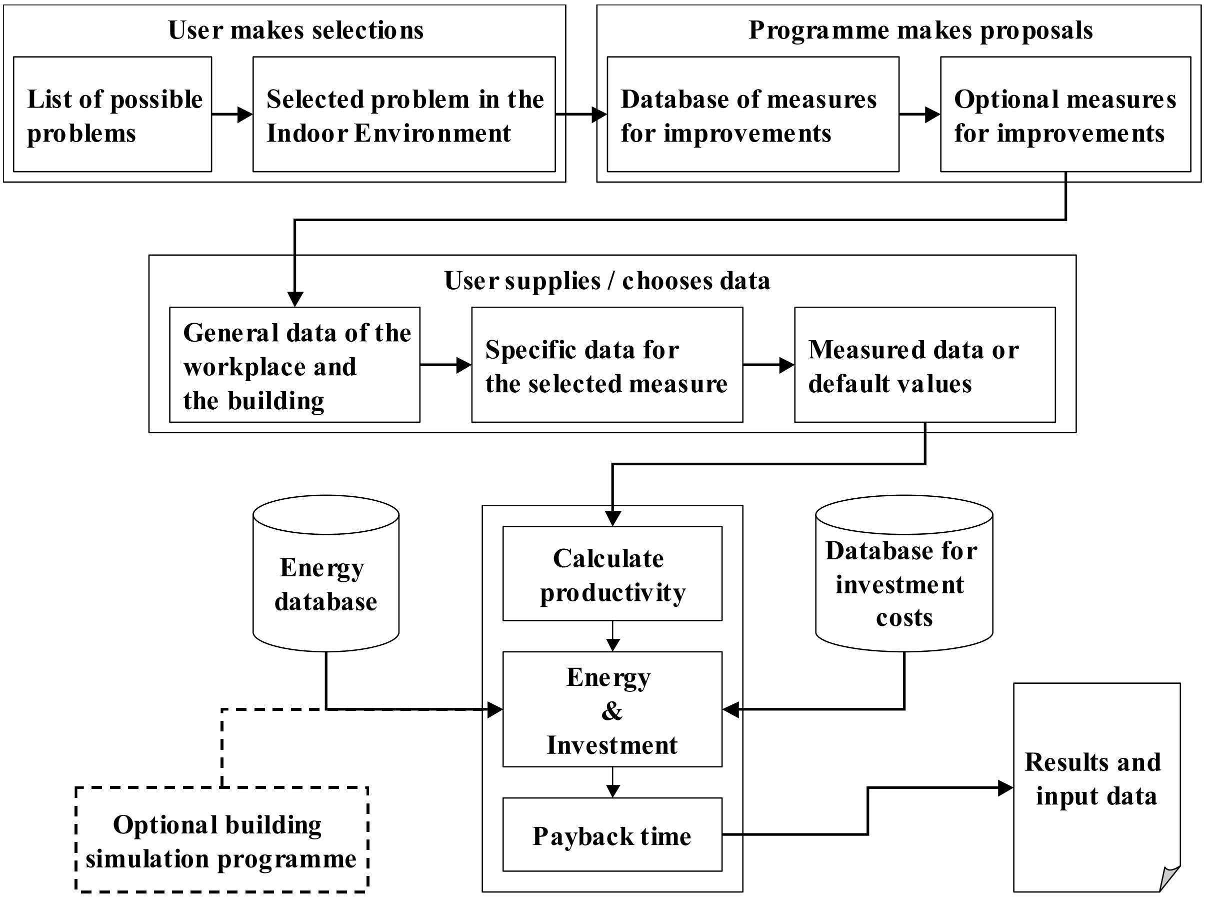

Figure 2. The principles of the cost-effectiveness model.

The programme will calculate the costs and benefits of the proposed mitigation strategies after the supplying of more background data by the user. Relevant data for the cost-effectiveness calculations comprise general data of the workplace and building, general cost data, specific data for the problem in question, and measured data of the indoor environment or default values. The general data of the building include the gross floor area, the age of the building, the quality of the building structures (heavy/medium/light) and the location (city, country) of the building. The general data of the workplace may consist of the number of employees, the average value of work, the type of office rooms (open plan or separate office rooms), etc. General cost data should include the costs of heating energy and electricity and the interest rate. Specific data in the case of high summer temperatures pertain to, among others, window data, such as the area and orientation of the windows, the number of panes and data on solar transmittance, solar protection and coating. The user may also provide measured data on the ventilation rate per person or per area, indoor temperatures and CO_2 concentrations. If no measured data are available, the programme uses default values based on the general description of the building.

The programme retrieves up-to-date information from external databases on weather data, emissions from materials, construction labour and material costs, etc. Energy data are retrieved from an energy database. The results of the calculations are then presented as the ratio of unsatisfied personnel (%), the increase in productivity (% / €), change in rent (€/a, m^2) or the expenses caused by the mitigations proposed (€). If the supplied data provides the possibility to use several relationships, the programme will use them all. The additional results are presented as alternative solutions. All the optional measures can be compared as the pay back time will be calculated for each option.

THE INFLUENCE OF INCREASING THE VENTILATION RATE ON SBS SYMPTOMS

In the following, the cost-effectiveness of improvements to a system parameter, the ventilation rate, is extrapolated using the linkage between human responses and performance. The ventilation rate has been shown to influence the prevalence of SBS symptoms and other illnesses. The prevalence of SBS symptoms is smaller when the ventilation rate is above 10 l/s per person than below this level and the prevalence decreases up to the ventilation rate of 25 l/s per person (Seppänen et al. 1999). Further, it has been estimated that productivity is reduced by 2.8% when an employee suffers from three SBS symptoms (Raw et al. 1990). This provides a chain to estimate the change in ventilation rate on productivity (Figure 3).

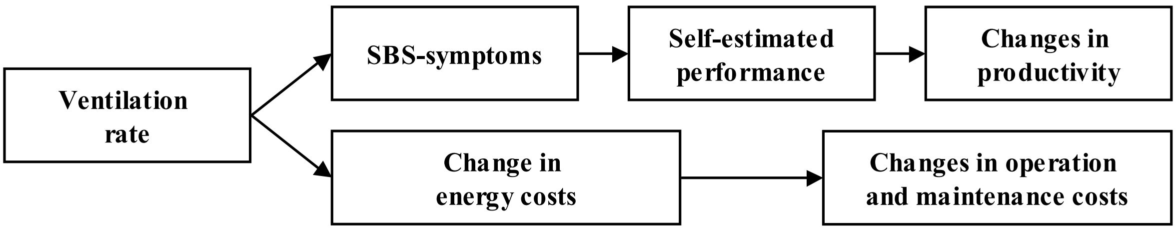

Figure 3. An example of how the cost of the change in ventilation can be estimated.

According to a Finnish office building study, the relative risk for SBS symptoms is 1.1 when the ventilation rate is reduced by 1 l/s per person in the range of 0 – 25 l/s per person (Jaakkola and Miettinen 1995). In European office buildings the prevalence varies in the range of 7 – 32% depending on the symptom and country (Bluyssen et al.1996). Taking 25% as an average prevalence of SBS symptoms, increasing the ventilation rate by 5 l/s per person at a relative risk ratio of 1.1 would reduce the prevalence of symptoms to $25\% / 1.1^5 = 15.5\%$. If increasing the ventilation rate by 5 l/s per person results in 9.5% (25% - 15.5%) of the employees experiencing no SBS symptoms at all, the increased ventilation rate would improve productivity by 0.028 x 9.5% which is approximately 0.27%. The gross national product (GNP) in Finland divided by the number of workers results in an average productivity of €50 000 per worker per year. The value of a 0.27%- rise in productivity is thus €135 per worker per year. With the energy costs of 0.03 €/kWh for heating and 0.06 €/kWh for electricity, the energy costs of increasing ventilation by 5 l/s per person at 3000 hours of operation per year result in €11.7 per year in the climate with heating degree days of approximately 4500 Kd (Finland). In most buildings the capacity of the HVAC system is sufficient to increase the ventilation rate without investments in new equipment. Therefore, the ratio of the benefits of increased ventilation, i.e. higher productivity, compared with the costs of higher energy consumption result in €135 / €11.7 = 11.5. The benefits are approximately 11 times greater than the costs.

DISCUSSION

The objective of the cost-effectiveness model is the integration of indoor environmental costs with the other costs of owning and operating a building. Even though the model is crude, it is needed to make building owners and employers understand the value of a good indoor environment. The straightforward example on ventilation shows how important a healthy indoor environment is. International effort is needed to develop the model further. It is important that the model should be easy to use and understand. It does not have to be exact but it should be based on scientific findings. Future research should focus on quantifying the effects of the indoor environment.

CONCLUSION AND IMPLICATIONS

This paper has presented an approach with which the ratio of savings in any of the costs of owning and operating a building can be compared with the real cost at risk which is reduced worker performance. An ISIAQ Task Force titled “The effects of the indoor environment on productivity in office environments” has been established to coordinate the international development of the model. More information on the Task Force is available at www.isiaq.org.

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