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A Bayesian Network approach to the evaluation of building design and its consequences for employee performance and operational costs

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ABSTRACT

A Bayesian Network approach has been developed that can compare different building designs by estimating the effects of the thermal indoor environment on the mental performance of office workers. A part of this network is based on the compilation of subjective thermal sensation data and the associated objective thermal measurements from 12,000 office occupants from different parts of the world. A Performance Index (Π) is introduced that can be used to compare directly the different building designs and furthermore to assess the total economic consequences of the indoor climate with a specific building design. In this paper, focus will be on the effects of temperature on mental performance and not on other indoor climate factors. A total economic comparison of six different building designs, four located in northern Europe and two in Los Angeles, USA, was performed. The results indicate that investments in improved indoor thermal conditions can be justified economically in most cases. The Bayesian Network provides a reliable platform using probabilities for modelling the complexity while estimating the effect of indoor climate factors on human beings, due to the different ways in which humans are affected by the indoor climate.

1. Introduction

Until now, it has been problematic to integrate the effects of indoor climate on office workers' performance in a total economic review of the cost of a building. Total economic calculations have so far been based on scenarios where workers' performances have been assumed to be reduced between 1% and 10% on average on a yearly basis as a result of a sub-optimal indoor environment [1]. Such general statements, and the fact that building owners and employers know that the occupants of a workspace are different, hence also differently affected, is a barrier for the more widespread use of total economic building calculations in practice, which in addition to energy consumption, investment costs, maintenance costs, etc., take office worker performance also into account. It will be essential to improve total economic building calculations so that they fit each new individual building or renovation project. There is also a need then to make dynamic calculations so that the daily and seasonal variations of the indoor environment are properly accounted for when assessing performance.

On a routine basis, simulation tools are used in the building design phase to evaluate indoor environmental conditions and estimate the energy consumption of different design alternatives. However, the comparison of different designs may occur at a late stage in the design phase, thus reducing the significance of the simulation results and making it almost impossible to modify the design accordingly. By including the effect of employee performance in the evaluation of different designs, the total economic consequences would promote the possibility of placing more emphasis on simulation results and thus achieving a better building design.

In recent years, there has been increased focus on the way in which different indoor climate factors affect employee performance. A systematic review of all available data on the effects of temperature and air quality on health and performance was conducted by Fisk and Seppänen [2] and Seppänen et al. [3]. This work resulted in the development of initial dose–response relationships between selected indoor climate parameters and performance. So far, all attempts to derive economic estimates of the effect of indoor climate on performance have been very crude. The economic losses of a sub-optimal indoor environment have been calculated mostly at the national level, revealing the enormous economic potential of improving indoor environmental quality in commercial buildings [4]. However, with current

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knowledge, the benefit for individual companies of indoor environmental quality (IEQ) upgrades has been difficult to quantify.

This paper proposes a new method of assessing the effects of the indoor environment on office workers' mental performance. The method is based on probabilistic knowledge of indoor climate variables and how they are inter-related. The platform for the method is the Bayesian Network (BN) theory. So far, BN has been used very little in the field of indoor climate, whereas its use in artificial intelligence and in medicine is well established, e.g. for estimating the risk of disease [5–7]. In Naticchia et al., a BN is used as a multi-criteria decision tool to choose an optimal building design for buildings equipped with a roofpond [8].

Central complexity in predicting the effects of the indoor climate on humans relates not only to the number of factors that interact, but also to modelling the differences in human perception of the indoor climate. This complexity is handled by the BN by modelling a perceived causal relationship between indoor climate factors and human perception. Furthermore, probabilities are used to model the "weight" of the causal relationship so that a qualified assessment of the effects of indoor climate factors on human sensation and performance may be established. These probabilities (or weights) can be learned from observed data.

Section 2 of this paper presents a general approach to the way in which the performance of office employees can be estimated. In Section 3, a comparison between four different building designs located in northern Europe and two different building designs in Los Angeles, California, are used as examples to analyse the effects of temperature on the mental performance of office workers in a specific building. In general, in this paper, focus will be on the effects of temperature on the mental performance and not of other indoor climate factors.

2. Method

In order to include the effect of office worker performance in the total economic evaluation of different building designs, it is necessary to formulate an index that provides a quantitative estimate of the economic gain achieved by improving the indoor environment.

2.1. Performance Index

The Performance Index (Π) describes the time-weighted performance of office employees in a given building design alternative and the ensuing thermal environment during a longer period, e.g. a year. A mathematical expression for calculation of Π is shown as follows:

$$\Pi = \sum_i w \times \mathrm{BN}(E_i),$$

where w is a weighting factor, i is the time segment for which the performance is calculated (e.g. working hours in a year), E_i is the environmental input parameter (e.g. air temperature or ventilation rate) in time segment i and $\mathrm{BN}(E_i)$ is the performance output from the BN as a function of E_i.

The weighting factor is normally the number of working hours during the period in question, e.g. if the daily work duration is 8 h, the annual work duration accumulates to 2080 h (during vacation periods, the number of people at work will be reduced, and this number will differ from company to company), which gives $w = 1/2080$. The parameter i is then a number between 1 and 2080, representing one *BN* performance calculation at the given working hour during a year.

A method for calculating the Performance Index, Π, to compare different building designs with different indoor environmental qualities is described hereafter.

Three elements are needed in order to compare different building designs and hence estimate the economic consequences (e.g. to assess the value of the investments) of improving the indoor climate.

(1) Establishment of a framework that provides an assessment of individual differences and the inherent uncertainties of the empirically derived dose–response relationship.
(2) Dynamic calculations of the indoor environment and of the energy consumption
(3) Reliable dose–response relationships between indoor climate parameters and mental performance

2.2. Bayesian Networks

A BN is well suited for estimating the effects of the indoor climate on the performance of office employees, since it takes into account the uncertainty that inevitably will be present when trying to estimate human output as a function of the indoor environment. Other advantages of the BN as compared with normally used multivariate models are that it is suitable when few data is available, and when there is a correlation between parameters in the dataset, the nature of the BN incorporates this in the probabilistic dependencies.

A BN is a graphical representation of uncertain quantities that reveals the probabilistic relationship between a set of variables. A BN is a directed graph with no cycles. The nodes represent the random variables and the arcs represent causal or probabilistic dependence between the nodes. The diagram is compact and intuitive, emphasising the relationship among the variables, and yet it represents a complete probabilistic description of the problem. In the graphical model, the node that causes another node is called a parent and the affected node is called its child. The child is conditioned by the parent. Given A is a parent and B is a child of A, the probability of B conditioned by A is noted $\mathrm{P}(B|A)$. Bayes theorem describes probabilistic dependencies between A and B as follows: [5]

$$\mathrm{P}(B|A) = \frac{\mathrm{P}(A|B)\mathrm{P}(B)}{\mathrm{P}(A)},$$

$\mathrm{P}(A)$ can also be written as: $\mathrm{P}(A) = \mathrm{P}(A/B)\mathrm{P}(B) + \mathrm{P}(A/\bar{B})\mathrm{P}(\bar{B})$, where $\mathrm{P}(\bar{B})$ is the probability of B *not* happening.

Since the causal relationship does the model building most effectively, the BN becomes designed as a knowledge representation of the problem under consideration. This implies that a BN becomes a reasonable realistic model of the problem domain that is useful when trying to gain an understanding of a complex problem domain (such as the indoor climate). The model building through causal relationship makes it easier to validate and convey the model to third parties. Hence, the BN may be considered as an appropriate vehicle to bridge the gap between model formulation and analysis.

Fig. 1 is an example of a BN containing nodes that are relevant to the relationship between indoor climate variables affecting the thermal sensation and mental performance of office workers.

Each node in the graph represents a discrete random variable in the causal system, which has a specific number of discrete states. When the state of one or more variables is known, the probability propagation can be performed upon introduced evidence. Table 1 gives an overview of the states of each variable in the network. The intervals initialise the conditional probability tables in the BN, thus making it possible to incorporate the