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.

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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
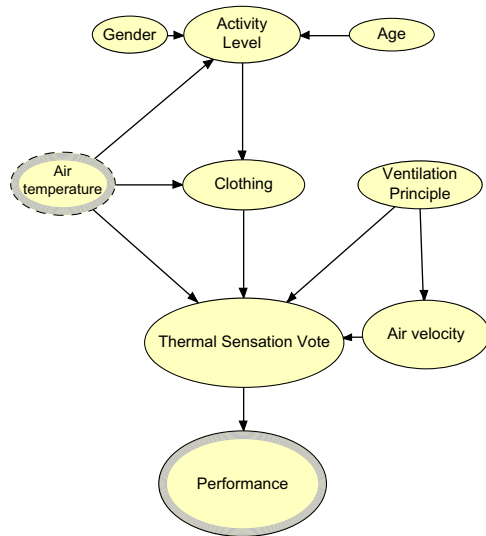
Fig. 1. A Bayesian Network showing the causal relationship between different temperature-related variables and mental performance of office workers.

Table 1
States of the different variables in the Bayesian Network

Age (year)	14–20, 20–25, 25–35, 35–45, 45–55, 55–inf
Gender	Male, female
Activity level (Met)	0–0.6, 0.6–1.2, 1.2–2, 2–inf
Clothing (Clo)	0–0.75, 0.75–1.1, 1.1–inf
Type of ventilation	Mechanical, natural, hybrid
Air temperature (°C)	18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33
Thermal sensation	−3, −2, −1, 0, 1, 2, 3
Air velocity (m/s)	0–0.05, 0.05–0.1, 0.1–0.15, 0.15–0.2, 0.2–0.25, 0.25–0.3, 0.3–inf
Performance (%)[a]	85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 95, 96, 97, 98, 99, 100

[a] The performance index was not a part of the ASHRAE RP 884 project measurements [20].

differences between people and how they react to the indoor environment. Some of the intervals were chosen by logical reasoning, while age, activity level, clothing and air velocity were chosen to get a detailed description of the data distribution.

Different computer programs can structure data in a BN. Hugin® was used in this paper to learn from observed data and present the BN [9].

The strength of the relationships is given by the Conditional Probability Distribution (CPD) for each variable; this can be shown in a Conditional Probability Table (CPT). The probabilities in a BN can either come from measured data; the data can also come from a model or data can come from experts' opinions or combinations of real data, models and expert opinions. The data used to create the conditional probability tables, describing the strength between the variables in the current network, was adopted from the data that was used to develop the ASHRAE adaptive model [10]. The dataset consists of information from over 12,700 occupants in 124 different buildings. Subjective assessments of the thermal conditions (people's thermal sensation) and physical indoor climate parameters (e.g. air temperature, air velocity, relative humidity) were monitored. The buildings were primarily office buildings. The data from ASHRAE RP-884 Adaptive Model Project was classified into three broad classes: Class I, Class II and Class III. Class III field studies were based on simple measurements of temperature and simple questionnaires, and these data were excluded from the present investigation. Only data from investigations that were classified as Class I or Class II were included in the present analysis. Class II data include data where all indoor physical environmental variables necessary for the calculation of PMV/PDD indices were made at the same time and place as the thermal questionnaires were administered. Class I data consist of data of the same type as Class II data, but the measurements and procedures were in 100% compliance with ASHRAE Standard 55 (1992) [11] and ISO 7730 (1984) [12] (e.g. measurements in three heights, measurement of turbulence intensity, etc.).

The data from the ASHRAE RP-884 Adaptive Model Project serve as the basis for the conditional probability tables in the BN, simply by calculating the probability for every possible combination of a given node. In Fig. 1, the thermal sensation node is affected by four other nodes (air temperature, clothing, ventilation principle and air velocity), so a combination could for example be [23 °C, 0–0.75 clo, HVAC, 0.1–0.15 m/s]. And in exactly this

combination, the frequency of each thermal sensation vote from the dataset is found, which forms the basis of the conditional probability table [−3: 1.9%, −2: 11%, −1: 30.6%, 0: 37.5%, 1: 15.6%, 2: 3%, 3: 0.4%]. Due to the many possible combinations in the BN shown in Fig. 1, the data from the ASHRAE RP-884 Adaptive Model Project was not always sufficiently complete to serve as the sole basis of the conditional probability tables. One of the advantages of a BN model is that when data is insufficient, missing data can be estimated using a believed probability based on expert knowledge. In cases where data is missing between known distributions derived from real data, a most likely distribution would be a mixture of the two known distributions (a mixture of real data and use of expert knowledge).

In the above example shown in Fig. 1, Π can be calculated using the following equation:

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

where w is the weighting factor, i the time segment when the performance is calculated, BN the performance output from the BN as a function of the temperature, temp_i the air temperature at time segment i and Π is the Performance Index.

At a given work hour (i), the effect of temperature on mental performance is calculated using the BN. This performance is then weighted by the total number of work hours and each weighted performance is averaged over a year.

2.3. Dynamic calculations

The results of dynamic simulation of the indoor environmental conditions during a longer period, e.g. 1 year, allow for the estimation of an annual Performance Index (Π), by the use of which, different building designs may be compared. Depending on the indoor climate parameter in question, the duration and intensity of the exposure may vary. In most buildings in northern Europe, exposure to high temperatures will be restricted to relatively short periods during the summer season, while the exposure time to poor air quality could be much longer.

The use of dynamic calculations enables identification of the periods (during a day or season) when occupant performance is affected the most by the indoor climate according to the defined metric, and thus to control the indoor environment according to its impact on performance.

Many commercial building simulation programs are available; they are all capable of calculating hourly temperatures, ventilation rates, CO_2 concentrations, etc., in a building or in zones of a building. The building simulation tool used for the examples in this paper is the Danish building simulation program called BSim, developed by the Danish Building Research Institute [13].

2.4. Dose–response relationships between the indoor climate and mental performance

Dose–response relationships between indoor climate parameters and mental performance are essential elements in the calculation of Π. Relationships between temperature and human performance are documented in Refs. [4,14]. However, in order to take into account the individual differences in thermal sensation between people exposed to the same temperature, it is desirable to use a dose–response relationship between *thermal sensation* and mental performance. The dose–response relationship between thermal sensation and mental performance used in this study was derived from data from field and laboratory experiments that investigated the effects of changes in temperature on thermal sensation and on common addition tests (which is a component skill used to simulate office work [15]) in mechanically ventilated buildings [16–18].

From these experiments, a total of 339 subjective thermal sensation votes with corresponding performance measurement were included in a polynomial regression model using the statistical software R to test the model's significance [19]. The outcome of the analysis showed that the derived model with thermal sensation vote as explanatory variable can significantly predict the relative mental performance of office work ($p < 0.05$).

Fig. 2 shows the relationship between subjective thermal sensation vote and relative performance (addition task) that was obtained using data from the abovementioned experiments.

The dose–response relationship can also be expressed by the following equation:

$$RP = -0.0069tsv^2 - 0.0123tsv + 0.9945,$$

where RP is the *Relative performance* (relative to a maximum mental performance of experiments of repeated measures, where people either performed better or worse than their average, when exposed to different thermal sensations) and tsv is the *thermal sensation vote* (−3 to +3 on the seven-point thermal sensation scale).

This relationship is in good agreement with the dose–response relationship between temperature and relative performance determined by Seppänen et al. [14]. Seppänen's relationship has an optimum relative mental performance at temperatures between 21 and 22 °C and the present relationship has an optimum relative mental performance between −1 and 0 on the thermal sensation scale. Approximately 60% of sedentary, non-exercising occupants exposed to 21–22 °C will have a thermal sensation between −1 and 0 [20].

Fig. 2 shows that the optimal performance level for this type of office work occurred when people perceived the thermal environment as slightly cool (sensation vote −1 on ASHRAE's seven-point thermal sensation scale). Many previous studies have shown that optimal performance for office employees' component skills (tasks commonly performed in normal office work) is
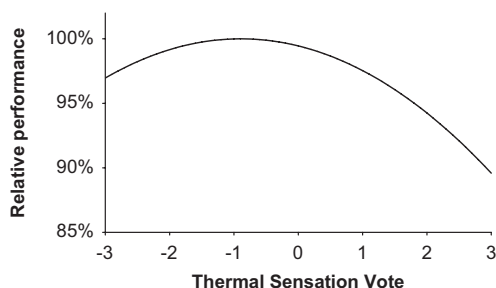
achieved at a slightly cool thermal sensation. Nevertheless, when employees are performing tasks that demand creative and logical thinking, optimal performance is typically achieved at a slightly warm thermal sensation [15,21,22].

Dose–response relationships between performance and other indoor parameters such as air quality and acoustics in offices have also been developed [2,23,24]. These relationships will not be discussed in this paper.

3. Results

In Section 3, different cases/scenarios, representing different installations in an office, are analysed to illustrate the practical use of the proposed method. The simulation is made for a mechanically ventilated office occupied by two persons. An hourly temperature output is calculated using the Danish building simulation tool BSim2002 [13]. The electricity consumption in the room includes general lighting (not task lighting), fans and mechanical cooling (COP = 2.5). Heating energy is provided by radiators and the supply air and the heat recovery unit operates with an efficiency of 60%. The price for electricity and heating are 0.18 and 0.07 €/kWh, respectively, which are average prices for commercial buildings in Denmark. Total financial income per square metre (including performance and energy cost) and benefit of cost ratio of the installations are compared. The benefit-to-cost ratio (BCR) accounts for how well the investment in installations is utilised. For example, BCR = 10 indicates that €1 spent gives €10 back. The higher the benefit-to-cost ratio is, the better investment is done. The rationale for using financial income is that employees are hired to earn money for a company, and when their performance decreases the income of the company decreases. An average overhead of 1.3 for all types of employees is chosen. Table 2 lists some general characteristics of the input data used in the analysis.

Six different cases are analysed: a reference case and three alternative designs of an office located in northern Europe (Copenhagen, Denmark) and two cases located in Los Angeles, California, USA. Table 3 describes the different cases.

The results of the analysis and computer simulations can be seen in Table 4.

It is seen from Table 4 that in Case 2, where the thermal environment is below 26 °C (except during 5 working hours during a year), the investment in a cooling system and the increased running cost for night ventilation results in a total financial income of €6714 m^{-2} compared with the total income of the reference case of €6673 m^{-2}, which gives an annual increase

Fig. 2. Relationship between relative performance of office workers doing normal office work and thermal comfort sensation.

Table 2
Input data in the building simulation computer program

Floor area	19 m^2
No. of occupants	2
Ventilation type	Mechanical
Facade area	10.8 m^2
Facade coefficient of heat transmission	$U_{value\text{-}façade} = 0.28$ W/m^2
Window area	5.3 m^2
Window type	$U_{value\text{-}window} = 2.6$ W/m^2
Internal heat loads (light+equipment+people)	570 W
Total working hours during a year[a]	2349 h
Electricity price	0.18 €/kWh
Heating/cooling price	0.07 €/kWh
Annual salary per worker[b]	€50,000
Overhead[c]	1.3

[a] Nine hours a day for 261 weekdays a year.
[b] See reference [1].
[c] Each employee has to earn more for the company than the company pays in salary.

Table 3
Description of the different cases used in the building design comparison

		Note
Case 1	Daytime operation of ventilation system, supplying $2.3\,l/s\,m^2$. Shading of windows when solar heat load exceeds $150\,W/m^2$	Typical office room constructed in 1980–1990. Fulfilling present national building energy requirements in Denmark
Case 2	Case 1+nighttime ventilation+cooling during office hours ($25\,°C$ setpoint)	Fulfilling thermal requirements in CEN 1752 (1998), [25] category 2 (temperature below $26\,°C$ during the summer season)
Case 3	Case 2+increased air supply ($3.2\,l/s\,m^2$)	Slightly cool room to increase performance
Case 4	Case 1+reduced air supply ($1.4\,l/s\,m^2$)	Air supply according to CEN 1752 (1998), [25] category B building. Energy saving scenario
Case 5	Case 1 in Los Angeles weather conditions	This scenario is included to compare the importance of the outdoor climate conditions
Case 6	Case 2 in Los Angeles weather conditions	

Table 4
Results of the analysis and computer simulations

	Case 1 (ref)	Case 2	Case 3	Case 4	Case 5	Case 6
Average office temperature (°C)	24.0	23.0	21.8	24.2	27.5	24.4
Working hours $>26\,°C$	474	5	0	643	1801	67
Working hours $>27\,°C$	282	0	0	358	1274	0
Supply air ($l/s\,m^2$)	2.3	2.3	3.2	1.4	2.3	2.3
Night cooling	–	+	+	–	–	+
PI (%)	97.7	98.4	98,6	97.2	95.0	97.8
Heating (kWh/m^2)	47	48	54	44	3	4
Cooling (kWh/m^2)	0	7	15	0	0	37
Electricity (kWh/m^2)	48	60	73	12	40	74
Total energy (kWh/m^2)	95	115	142	56	43	116
Financial income per m^2 corrected for PI (€)[a]	6685	6733	6746	6651	6500	6692
Energy cost ($€/m^2$)	11	14	17	5	7	16
Cost of investment ($€/m^2$)[b]	0	5	8	0	0	5
Total income ($€/m^2$)	6673	6714	6721	6646	6493	6671
Benefit-to-cost ratio (productivity/energy consumption, investment cost)	–	5	3	0	–	13[c]

[a] 100% performance is equal to an income of $€6842/m^2$.

[b] The remedial cost for cooling is $€49/m^2$ and $€26/m^2$ for increasing the airflow with $1\,l/s\,m^2$. Making the annual cost of investment over 15 years with 7% interest, respectively, $€5/m^2$ and $€3/m^2$ [1].

[c] Case 6 is compared to Case 5.

of $€41\,m^{-2}$ year. The additional investment of Case 2 of $€5\,m^{-2}$ and additional electricity cost of $€3\,m^{-2}$ gives a benefit-to-cost ratio of 5 ($€41\,m^{-2}/€8\,m^{-2} = 5$). In Case 3, when the thermal environment is slightly cool, the increased energy and investment cost reduce the benefit-to-cost ratio to 3. Saving energy as demonstrated in Case 4 is not an economically feasible solution, as the loss of productivity is higher than the reduced energy cost. When moving the same building to Los Angeles and thereby increasing the outside air temperature in working hours, the benefit-to-cost ratio is increased considerably to approximately 13, as seen in Table 4 when comparing Case 5 (without cooling) and Case 6 (with cooling).

4. Discussion

The results from the analyses and simulations in this paper indicate that economic benefits for a company of improving the thermal environment are immense. The benefit-to-cost ratios show that even small improvements in Π indicate great economic potential. For buildings located in a warmer climate than the northern European, the economic potential is even more significant if the buildings initially are not designed appropriately. However, the purpose is not to promote thermal solutions that use large amounts of energy to make the thermal conditions better. The Performance Index is intended to be an index that can be used in the design phase of constructing or renovating buildings to compare different building designs. In terms of energy, comfort and performance, it will quantify the benefits of low energy building designs having an indoor environment that is near-optimal for mental performance. When comparing different building designs, the main focus is on reducing energy consumption, but if this compromises the thermal environment, the economic savings obtained by reducing the energy consumption could easily be counterbalanced by the resulting decrease in employee productivity. The examples given in this paper indicate the importance of investigating different building designs before the building is constructed.

The Performance Index calculated using a BN and the causal relations derived for it provide an estimate of the implications of the thermal environment on the monetary value of the annual performance of office workers. This outcome variable allows for the inclusion of occupant comfort and performance in future evaluations of building design, along with routine simulations of building energy consumption. The fundamental advantage of using the BN as a model for the Performance Index calculations is that it takes into account the uncertainties that inevitably remain when dealing with humans in the indoor climate. The differences in occupant behaviour and sensation are converted to a probability which, depending on the causal relationship between the indoor climate variables, affects the final performance outcome of the BN.

A BN represents a model of the real world. Such a model will always have its limitations as it represents a perceived causal relationship as seen by the modeller. What is important is whether the established BN can give those answers that are sought in the given model domain. The advantage is that the BN model is transparent and thus may be easily criticised by peers.

When used in artificial intelligence, the BN can be used to model human behaviour, since the probabilities may easily be modified when new knowledge becomes available. By adding new knowledge such as data from new experiments, a BN in the indoor climate context would continue to be more and more precise in the estimation of the consequences of improving the indoor climate in relation to its impact on human performance. BN models have several advantages when dealing with data regarding the effects of indoor climate factors on mental performance, though compared to multivariate models, two shortcomings have to be pointed out. First of all, when it is possible to make a multivariate model it will be more precise than a BN model, thus a BN model only yields probability of the effect of a variable. Secondly, a BN does not give a model expression, but shows the variable dependencies graphically.

A crucial assumption in the calculation of the Performance Index in this paper is the relationship between thermal sensation and mental performance. The use of thermal sensation, rather than temperature, as a predictor of performance is among others supported by findings in an experiment investigating the performance of people working in an average thermal environment of 23.2 °C with light clothing (0.6 clo) and people working in an average thermal environment of 18.7 °C with heavy clothing (1.15 clo). The results indicated that when subjects were exposed to different air temperatures and thermal neutrality balanced with clothing level, no difference in performance was observed [26]. Witterseh et al. [27] also found an association where people who felt warm were less productive and made more errors. It can be quite difficult to measure the overall performance of office workers, as opposed to their ability to perform specific office tasks, but in general when people feel satisfied and comfortable or are highly motivated they are less likely to be distracted by the indoor climate and a higher performance can be expected. In this paper, it is assumed that office workers are neither over- nor under-motivated for their job. This could affect their concentration and thereby the performance output. When people have possessed a job for a certain time, only specific events such as a deadline, bonus, recognition, etc., will increase their motivation to perform more. It is assumed that no outside factors affect motivation during working hours.

There are limitations in the dose–response relationship between thermal sensation and relative mental performance suggested in this paper. First of all, it consists of both laboratory and field experiments. Furthermore, the laboratory experiments were not designed to investigate the effects of thermal sensation on mental performance. Hence, economic calculations that are based on this relationship should be taken as an illustrative example of the ratio of the economic potential of improving the thermal conditions in an office environment. Nevertheless, there is a good agreement with the present relationship and the relationship suggested by Seppänen et al. [14] that was developed with complementary data.

This paper concerns only the effects of the thermal environment on mental performance. The effects of air quality are not considered in the calculation of the Performance Index. The duration of exposure to poor air quality may be much longer than for sub-optimal temperatures, especially in climate conditions such as those of northern Europe. An analysis of the effects of air quality on the mental performance of office workers, using a BN, is at present being undertaken. It is hoped that in the near future, it will be possible to combine the effects on office work performance of both thermal and air quality factors.

It is important that the appropriate relationships with indoor climate are eventually developed for different performance tasks, since mentally requiring tasks (problem solving, creative thinking, etc.) may respond differently to the indoor environment than do component skills (typing, adding, etc.). The latter may, however, be considered as the best paradigm for office work, since problem solving and creative thinking are normally performed in more stimulating environments than traditional office environments.

The potential benefit of developing a reliable Performance Index calculation tool may be potentially very large. It would give developers, architects, and consultants, the possibility of designing an indoor environment that satisfies both occupants and employers. Such a tool would enable the comparison between radically different building designs, ranging from designs with and without mechanical cooling to hybrid and naturally ventilated buildings, and evaluate such designs not only in terms of energy consumption, but also in terms of the resultant effect on occupant performance.

5. Conclusion

The present paper introduces a Performance Index (Π) determined by a BN, which can be used to compare different building designs in terms of their estimated economic consequences, by including effects on occupant performance as well as energy use. The Performance Index is calculated using a BN as the platform so any uncertainties associated with human performance and perception can be included in the estimates of the overall Performance Index. The design examples compared in the paper indicate considerable benefits from improving the indoor thermal environment, particularly in the warm climate areas of the world with poor building designs.

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