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Development of a model to calculate the economic implications of improving the indoor climate

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Preface

This Ph.d.-thesis sums up the work carried out at the Technical University of Denmark, International Centre for Indoor Environment and Energy, Department of Civil Engineering, Lyngby, Denmark, and the consulting company Alectia A/S, Teknikerbyen, Virum, Denmark from September 2005 to December 2008. The work was composed under the Industrial Ph.d. scheme (see Appendix A) and was funded by the Birch & Krogboe Foundation and Ministry of Science, Technology and Innovation. Supervisors during the Ph.d.-study were Associate Professor, Ph.d. Jørn Toftum from the International Centre for Indoor Environment and Energy, and Research Director and Head of Work Space Design department, Lic.Tech Lars D. Christoffersen.

I would like to express my gratitude to my supervisors for supporting me during the process of writing this thesis. Jørn, for always having the door open and willing to discuss the direction I chose to take the study in, for reading through my material, commenting and asking questions and always supporting me. I sincerely appreciate this. The same support Lars also gave me. Even though Lars was financially in charge of the whole project, he never questioned the scientific direction we at DTU, chose to take. From the first day he gave me a "scientific carte blanche" within the projects main objectives and did not expect an output that could be utilized as a commercial product for Alectia A/S. Lars also gave valuable practical input during the project period and together with my other colleagues at Alectia A/S established a research environment that was inspiring.

I want to thank Professor Peter Friis-Hansen and Professor Henrik Spliid for co-authoring two of my papers. Peter Friis-Hansen introduced me to the Bayesian Network theory and Henrik Spliid to more complex statistical analysis. Sometimes I wish I had graduated as a statistician and then afterwards became interested in the indoor climate research. Then I would have been able to develop my models even more.

Thanks to my colleagues at DTU. Many lunches have been eaten and it was always nice to talk to inspiring people. It has been a privilege to know some of the best researchers in the world in field of the indoor climate research. I know we will keep in touch.

A special thanks goes to my family and my farther in particular for the discussions about research in general, my Ph.d.-project in specific and the cross-disciplinary similarities we found between dealing with humans in the indoor environment and dealing with humans in the field of medicine. Something I will take with me when I go out in the "real" world.

Finally I dedicate this work to my one and only, Maja. She has always been there for me, allowed me time and space for working with the project and during the Ph.d. period she gave me the greatest gift of all, our beautiful daughter, Beate.

Copenhagen 1st of December 2008

Kasper Lynge Jensen

List of papers

The thesis is based on the following papers:

Paper I – Jensen, K.L, Toftum, J., Friis-Hansen, P. (2009) "A Bayesian Network approach to the evaluation of building design and its consequences for employee performance and operational cost", *Buildings and Environment*, **44**, 456-462

Paper II – Jensen, K.L and Toftum, J. (2009) "Feasibility study of indoor air quality upgrades and their effect on occupant performance and total building economy" *Indoor Air,* Submitted

Paper III – Toftum, J., Andersen, R.V, Jensen, K.L (2009) "Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions", *Buildings And Environment,* Submitted

Paper IV – Jensen, K.L, Spliid, H., Toftum, J. (2009) "Implementation of multivariate linear mixed-effects models in the analysis of indoor climate performance experiments" *Indoor Air*, Submitted

Abstract

The present Ph.d.-thesis constitutes the summary of a three year project period during which a methodology to estimate the effects of the indoor environment on performance of office work and the consequences for total building economy of modifying the indoor environment was developed. During the past decades several laboratory and field studies have documented an effect of the indoor environment on performance, but so far no calculation methodology or tool has been developed in order to utilise this knowledge.

In the present project two models based on Bayesian Network (BN) probability theory have been developed; one model estimating the effects of indoor temperature on mental performance and one model estimating the effects of air quality on mental performance. Combined with dynamic building simulations and dose-response relationships, the derived models were used to calculate the total building economy consequences of improving the indoor environment.

The Bayesian Network introduces new possibilities to create practical tools to assess the effects of the indoor environment on performance. The method evaluates among others the inherent uncertainty that exist when dealing with human beings in the indoor environment. Office workers exposed to the same indoor environment conditions will in many cases wear different clothing, have different metabolic rates, experience micro environment differences etc. all factors that make it difficult to estimate the effects of the indoor environment on performance. The Bayesian Network uses a probabilistic approach by which a probability distribution can take this variation of the different indoor variables into account.

The result from total building economy calculations indicated that depending on the indoor environmental change (improvement of temperature or air quality), location of building and design of building a difference in the pay back time was observed. In a modern building located in a temperate climate zone, improving the air quality seemed more cost-beneficial than investment in mechanical cooling. In a hot climate, investment in cooling resulted in short pay back periods.

Still several challenges exist before a tool to assess performance can be used on a daily basis in the building design phase. But the results from the present Ph.d.-thesis establish the framework for a performance calculation tool that with further development has the possibility to help improve indoor environment conditions to the benefit of office workers and employers.

The thesis is composed of a summary and four articles submitted to international, scientific journals.

Paper I – "A Bayesian Network approach to the evaluation of building design and its consequences for employee performance and operational cost" introduced the development of a Bayesian Network, combined with a dynamic simulations and a dose-response relationship between thermal sensation and performance, which estimated the effects of temperature on office work performance. The developed BN model consisted of eight different indoor variables all assumed to eventually affect performance. The probability distribution which is a fundamental feature of a BN model, were based on data from over 12.000 office occupants from different parts of the world. It was shown by comparison of six different building designs (four in Northern Europe and two in USA) that investment in improved thermal conditions can be economically justified, especially in a hot climate and/or if the building originally was poorly designed leaving a large potential for improvement. The developed BN model offers a practical and reliable platform for a tool to assess the effects of the thermal conditions on performance.

Paper II – "Feasibility study of indoor air quality upgrades and their effect on occupant performance and total building economy" documented the development of a BN model used to estimate the effects of air quality on performance. The BN model consisted of three elements: i) An estimation of pollution load dependent on building type, ventilation rate, occupancy etc. ii) Pollution load dependent distributions of the perceived air quality. iii) A dose-response relationship between perceived air quality and performance. A previously developed model was used to estimate element one; six independent experiments (over 700 subject scores) were used as the basis of the perceived air quality distributions in element two, and three experiments (over 500 subject scores) were used to develop the dose-response relationship between air quality and performance used in element three. Different building designs were compared to estimate the consequences on total building economy of improving (or reducing) the indoor environment quality. The results indicated improvement of the air quality would be better than improving the thermal conditions in a climate like the Northern European. The use of both the thermal BN model and the indoor air quality BN model showed some practical implications that could be useful in the building design phase.

Paper III – "Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions" investigated the practical implications of using the thermal BN model. Building simulations of an office located in Copenhagen, San Francisco, Singapore and Sydney with and without mechanical cooling were conducted to investigate the impact on energy and performance of the building configuration of these locations. The adaptive comfort model stipulates that in buildings without mechanical cooling occupants would judge a given thermal environment as less unacceptable and thus be more comfortable in warmer indoor environments, which would be assessed uncomfortable by occupants who are used to mechanical cooling. Since the thermal BN model was based on the same data used to derive the adaptive comfort model, this difference in thermal sensation based on building configuration was indirectly implemented in the BN model. The results from the simulations and the corresponding performance calculations indicated that even in tropical climate regions, the effects of the indoor thermal conditions on performance were almost negligible in a non-mechanically cooled building compared to a well-conditioned mechanical cooled office building. Results that support the adaptive thermal comfort model.

Paper IV – "Implementation of multivariate linear mixed-effects models in the analysis of indoor climate performance experiments" presented a novel statistical analysis method to be used in the indoor climate research field to investigate the effects on performance of the indoor environment quality. Performance experiments often include the use of several performance tasks simulating office work. Instead of applying tests that measure the same component skills of the subjects, more powerful interpretations of the analyses results could be achieved if fewer tests showed a significant effect every time they were applied. A statistical model called multivariate linear mixed-effect model was applied to data established in three independent experiments as an illustrative example. Multivariate linear mixed-effects modelling was used to estimate in one step the effect on a multi-dimensional response variable of exposure to "good" and "poor" air quality and to provide important additional information describing the correlation between the different dimensions of the variable. The example analyses resulted in a positive correlation between two performance tasks indicating that the two tasks to some extent measured the same dimension of mental performance. The analysis seems superior to conventional univariate analysis and the information provided may be important for the design of performance experiments in general and for the conclusions that can be based on such studies.

Resumé

Nærværende opsummering af Ph.d.-afhandlingen afslutter en periode på tre år, hvor en metodik blev udviklet til at estimere effekterne af indeklimaet på præstationsevnen af kontorarbejde og bygningsmæssige totale økonomiske konsekvenser heraf. Igennem de sidste årtier har flere laboratorier og feltforsøg dokumenteret, at der eksisterer en effekt af indeklimaet på præstationsevnen, men indtil nu er der ikke udviklet en beregnings metodik eller et generelt værktøj, der benytter denne viden.

I den foranliggende projektdokumentering blev der foreslået to modeller baseret på den Bayesiske Netværks teori; en model der estimerer effekten af indendørs temperaturen på den mentale præstationsevne og en model som estimerer effekten af indendørs luft kvalitet på den mentale præstationsevne. Det Bayesiske Netværk kombineret med bygnings simulering og dosis-respons sammenhænge blev brugt til at beregne konsekvenserne på bygnings total økonomien ved at forbedre indeklimaet.

Det Bayesiske Netværk belyser nye muligheder til at udvikle et praktisk værktøj, der kan bruges til at vurdere effekterne af indeklimaet på præstationsevne. Metoden evaluerer blandt andet den naturlige usikkerhed der findes, når man har med mennesker at gøre i indendørsmiljøet. Kontoransatte, der er eksponeret for det samme indeklima, vil i mange tilfælde have forskelligt beklædning på, have forskellige aktivitetsniveauer, opleve forskellige mikromiljøer osv. Faktorer, som alle gør det svært at vurdere en overordnet effekt af indeklimaet på præstationsevnen. Det Bayesiske Netværk udnytter en sandsynlighedsteoretisk indgangsvinkel, hvor en sandsynlighedsfordeling tager hensyn til de forskelle mennesker oplever i indeklimaet.

Resultaterne af de bygnings total økonomiske beregninger indikerer, at afhængig af hvilke indeklima faktorer, der bliver forbedret (temperatur eller luft kvalitet), afhængig af geografisk placering og afhængig af bygnings design, blev en forskel i tilbagebetalingstiderne observeret. I en moderne designet bygning placeret i et tempereret klima, blev det at forbedre luft kvaliteten vurderet til at være mere kost-effektivt end investeringer i mekanisk køling. I varmere klima resulterede investeringer i mekanisk køling i relative korte tilbagebetalingstider.

Der forefindes stadigvæk mange udfordringer før et egentligt værktøj til at vurdere effekten af indeklimaet på præstationsevnen, kan anvendes i byggeprojekter. Men resultaterne fra nærværende Ph.d.-afhandling grundlægger rammerne til et værktøj som med yderligere

forbedringer giver muligheden for at forbedre indeklimaet til gavn for medarbejdere og arbejdsgivere.

Afhandlingen består af en sammenfatning og fire artikler, der er blevet indsendt til internationale videnskabelige tidsskrifter.

Artikel I – "A Bayesian Network approach to the evaluation of building design and its consequences for employee performance and operational cost" introducerer udviklingen af et Bayesisk Netværk, der kombineret med dynamisk bygnings simulering og et dosis-respons forhold, kunne estimerer effekten af temperaturen på præstationsevnen af kontor arbejde. Det udviklede Bayesiske Netværk består af otte forskellige indeklima faktorer der alle er vurderet direkte eller indirekte til at have en indflydelse på præstationsevnen. Sandsynlighedsfordelingerne som er en grundlæggende karakteristisk egenskab ved det Bayesiske Netværk blev baseret på data fra over 12.000 kontoransatte fra forskellige dele af verden. Ved sammenligning mellem seks forskellige bygningsdesign (fire i nord Europa og to i USA) blev det vist, at investeringer i termiske forbedringer kunne retfærdiggøres økonomisk, især i klima hvor det var varmt det meste af året eller hvor bygningsdesign fra begyndelsen var dårligt planlagt, efterladende et stort potentiale for forbedringer. Det foreslået Bayesiske Netværk tilbyder et praktisk og pålideligt udgangspunkt for et værktøj der kan bruges til at vurdere effekten af de termiske forhold på præstationsevnen.

Artikel II – "Feasibility study of indoor air quality upgrades and their effect on occupant performance and total building economy" dokumenterede udviklingen af en Bayesisk Netværks model, som kan blive brugt til at estimere effekten af luft kvalitet på præstationsevnen. Modellen bestod af tre elementer: i) En estimering af forureningsgraden afhængig af bygningstype, ventilations rate, antallet af medarbejdere pr gulv areal osv. ii) Forureningsgrads-afhængige fordelinger af den oplevede luft kvalitet. iii) Et dosis-respons forhold mellem oplevet luftkvalitet og præstationsevne. En tidligere udviklet model blev brugt til at vurdere konsekvenserne af forureningsgraden i det første element; seks uafhængige eksperimenter (med over 700 voteringer fra forsøgspersoner) blev brugt som basis for de oplevede luft kvalitets fordelinger i det andet element, og tre uafhængige eksperimenter (med over 500 voteringer fra forsøgspersoner) blev brugt til at udvikle dosis-respons forholdet mellem oplevet luftkvalitet og præstationsevne i det tredje element. Forskellige bygningsdesign blev sammenlignet for at vurdere de total økonomiske bygnings konsekvenser ved at forbedre (eller forringe) indeklimaet. Resultaterne indikerer, at forbedringerne af luftkvaliteten bedre kunne betale sig økonomisk i et nord europæisk klima end det at forbedre det termiske indeklima. Brugen af både det termisk baseret

Bayesisk Netværks model og den luftkvalitets baseret Bayesisk Netværks model illustrerer fordelene rent praktisk i bygningsdesign fasen.

Artikel III – "Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions" undersøgte den praktiske konsekvens af at bruge den termiske Bayesiske Netværks model. Der blev udført bygnings simuleringer af kontorbygninger placeret i København, San Francisco, Singapore og Sydney med og uden mekanisk køling for at undersøge betydningen af bygningskonfigurationen på energiforbrug og præstationsevne. Den adaptive komfort model stipulerer, at i bygninger uden mekanisk køling vil brugere af bygningen vurdere det termiske indeklima som mindre uacceptable end hvis de var udsat for samme temperaturer i mekanisk kølet bygninger. Da den termiske Bayesiske Netværks model, er udarbejdet på baggrund af de samme data som den adaptive termiske komfort model er denne forskel i termisk perception baseret på bygningskonfiguration indirekte en del af den termiske Bayesiske Netværks model. Resultaterne af simuleringerne viste, at selv i tropiske regioner var effekten af temperaturen på præstationsevnen næsten ubetydelig i ikke mekanisk kølede bygninger sammenlignet med præstationsevnen i velkonditionerede mekanisk kølede bygninger, hvilket er resultater der støtter den adaptive termiske komfort model.

Artikel IV – "Implementation of multivariate linear mixed-effects models in the analysis of indoor climate performance experiments" præsenterede en ny statistisk metode, der viste sig nyttigt i analysen af indeklima forsøg, der undersøger effekten af indeklimaet på præstationsevnen. Præstationsevneforsøg inkluderer ofte brugen af flere test metoder der simulerer kontorarbejde. I stedet for at anvende test, der måler de samme kognitive egenskaber ved forsøgspersonerne, kan mere pålidelige fortolkninger af analyserne opnås ved at reducere antallet af disse test, der måler det samme. En statistisk metode kaldet multivariat lineær mixed-effekt model blev anvendt som et illustrativt eksempel på data fra tre uafhængige eksperimenter. Multivariat lineær mixed-effekt modellering blev brugt i samme udregning til at estimere effekten af en multidimensional respons variable ved eksponering af god eller dårlig luft kvalitet og til at indhente yderligere information der beskriver korrelationen mellem forskellige dimensioner af variablen. Det analyserede eksempel resulterede i en positiv korrelation mellem to præstationsevne opgaver, hvilket indikerede, at de to opgaver til en vis grad målte den samme dimension af mental præstationsevne. Analysemetoden har fordele i forhold til almindelige brugte endimensionale statistiske analysemetoder. Den opnåede viden kan være en vigtig information i designet af fremtidige eksperimenter og de konklusioner, der fremkommer på baggrund af sådanne studier.

Abbreviations

BN: Bayesian Network

BCR: Benefit-to Cost Ratio

CPT: Conditional Probability Table

CPD: Conditional Probability Distribution

HVAC: Heating, Ventilation and Air Conditioning

IAQ: Indoor Air Quality

IEQ: Indoor Environmental Quality

ICIEE: International Centre for Indoor Environment and Energy

PAQ: Perceived Air Quality

PD: Percentage Dissatisfied

PMV: Predicted Mean Vote

PPD: Percent People Dissatisfied

PV: Personal Ventilation

SBS: Sick Building Syndrome

Aim and objective

The main aim of this work was to develop a methodology to estimate the economic consequences of improving the indoor environmental conditions. It had to be practical and easily to implement in existing tools that are typically used when designing buildings.

Specifically for each paper the aims have been the following:

PAPER I   Develop a model which can estimate the effects of temperature on office work performance

PAPER II   Develop a model which can estimate the effects of air quality on office work performance

PAPER III   To show the practical implications of the suggested temperature model used in buildings with and without mechanical cooling

PAPER IV   To suggest a statistical method that enables an evaluation of the correlation between multiple response variables in indoor climate experiments as well as estimating the effects of indoor environmental conditions on performance taking the between and within subject variation into account

INTRODUCTION

"Houses are built to live in, not to look on; therefore, let use be preferred before uniformity, except where both may be had"

- Sir Francis Bacon (1561-1626)
Essays: Of Buildings (1623)

Introduction

The indoor environment influence human beings in many ways. Terms like comfort, health and productivity are commonly used to describe the effects of the indoor environmental quality (IEQ) on humans. National building codes and standards set up guidelines on how to design a comfortable and healthy indoor environment. But no standards, norms, guidelines, calculation method etc. enable in practice the estimation of the effects of the IEQ on productivity. However advertisements from HVAC companies or other companies that offer services to improve the indoor environment explicitly tell their potential clients that by choosing their solution the bottom line will be improved. Which bottom line is then the question?!

This present Ph.d-thesis constitutes the work of a three year study, developing a model which can be used in the building design phase or re-design phase to estimate the effect of temperature and air quality on mental performance in offices. Other indoor parameters like noise and light have also shown to have an effect on performance, but have not been included in this thesis. Most studies that investigated the effects of IEQ on performance have studied the effects of temperature and indoor air quality (IAQ). Since the models used to estimate effects were based on already conducted studies, the amount of data available was not considered sufficient to create models which could estimate the effects of noise and light on performance.

An important point of reference of the Ph.d-thesis was that the framework of the developed model had to be practical. The desire from architects and engineers for a calculation method that can estimate the effect of changing a building design on the total building economy is substantial. In order for a performance model to be accepted and used by practitioners the model has to be realistic and reliable. This is achieved with a strong foundation in valid research results combined with calculation methods that do not assume too much. With too many assumptions the realism is reduced to a limited ideal world, in which results are not that reliable and practical.

The main part of the Ph.d-thesis is four articles of which one is accepted and published online in *"Building and Environment"* and three articles submitted to journals (two articles to *"Indoor Air"* and one to *"Building and Environment"*). An extended summary, containing a literature review, a thorough exposition of selected issues that needs to be elaborated, the results from the articles and a discussion of the findings in general, precedes the four articles.

The effects of IEQ on performance

Historically one of the first reflections of human performance related to exterior conditions came in the end 18th century by the father of modern economics, Adam Smith, who stated that it was unlikely that men would work better when they were ill fed, disheartened and sick compared to well fed, in good spirits and in good health (Smith, 1904). Despite this, the abundance of cheap labour in the early ages of the industrial revolution made it possible for the employers to replace unproductive workforce with new healthy labour. In the beginning of the 20th century some of the first experiments investigating the effects of exterior work conditions on performance where conducted in Chicago in the Hawthorne Works factory complex by psychologist Elton Mayo. The general findings of the experiments on Hawthorne Works was summarized with the term "Hawthorne effect". Basically the Hawthorne effect can be stated to be a short-term improvement in performance caused by observing worker performance and not by improving the environmental conditions. Researchers have afterwards criticized the conduction and the design of the Hawthorne experiments to such extent that the conclusions are not very trustworthy, but nevertheless the Hawthorne effect is a myth which still exists (e.g. Kompier, 2006). This had no doubt a negative influence on the indoor climate vs. performance research field. A few investigations were done after World War II (Viteles and Smith (1946) and Mackworth (1950)) and in the end of the 1960'ies a commonly cited experiment was conducted which investigated the effects of the indoor environment conditions on human performance. Here Pepler and Warner (1968) investigated the leaning performance of university students exposed to six temperature ranges and Wyon (1970) started experiments investigating the effects of temperature on mental performance of school children and later on experiments investigating the effects of temperature on typewriting performance (Wyon, 1974). After the first oil crisis in 1972, energy savings resulted in very poor indoor climate and an era of research in air quality, SBS symptoms and health began. Due to the difficult nature of performance experiments (e.g. the definition of human performance in real-world environments, conducting field performance experiments and the legacy of the Hawthorne effect) performance experiments were very sparse from the mid 70'ties to the 90'ties. From the 1990'ies new performance experiments emerged, both laboratory and field experiments. Table 1 shows an overview of some selected experiments investigating the effects of temperature and air quality on performance from the 90'ties and forward.

Table 1 Overview of selected experiments from 1992-2007 investigating the effects of IEQ on performance

First author	Year	Response	Affected test type (tendens) [1]	Predictor	Exp.	IEQ factor
Kroner et al.	1992	Better performance	Processed insurance files (↑)	Lowering temperature	Field	Temp
Myhrvold et al.	1996	Impaired performance	Three psychological test(↑)	High CO_2	Field	IAQ
Nunes et al.	1993	Impaired performance	Computer performance taks, symbol-digit substitution(↑)	SBS symptoms	Field	IAQ
Wargocki et al.	2000b	Better performance	Addition(↓), Text typing(↑), Stroop (↓) serial addition (↓), Logical (↓), Text typing error(↑)	Pollution source absent	Lab	IAQ
Wargocki et al.	1999	Better performance	Text typing(↑), addition(↑), proof-reading(↑)	Increased vent. rate	Field	IAQ
Milton et al.	2000	Reduced absenteeism	Absenteeism(↑)	Increased vent. rate	Field	IAQ
Lagercrantz et al.	2000	Better performance	Text typing(↑), Accuracy of adding(↑) Proof reading(↑), addition(?), creative think (?),	Pollution source absent	Lab	IAQ
Niemelä et al.	2002	Impaired performance	Talk time(↑)	High temp.	Field	Temp
Tham	2004	Better performance	Talk time(↑)	Lowering temp. Increased vent rate	Field	Temp, IAQ
Bako-Biro et al.	2004	Better performance	Talk time(↑), Speed of talk(↑)	PC absent	Lab	IAQ
Wargocki et al.	2004	Better performance	Text editing (text typing, proofreading) (↑), addition(?), subtraction(?) and multiplication(?)	Replacing filters, increasing vent.	Field	IAQ
Federspiel et al.	2004	No significant effect on IAQ, better performance on temp	Wrap-up time(↑), Speed of talk(↑), Speed of talk(↑) IAQ	Increased vent. rate, low temp.	Field	Temp, IAQ
Wittherseh et al.	2004	Some test better performance, some test worse	Different tests simulating office work	Combined effect	Lab	Temp, IAQ
Kaczmarczyk et al.	2004	at 26 C fewer errors text typing at 23 C no effect	Performance test	PV[2] different IAQ and temp.	Lab	Temp, IAQ
Wargocki et al.	2007a	Better performance	Six different school tests (positive effect on most test)	Lowering temperature	Field	Temp
Wargocki et al.	2007b	Better performance	Six different school tests (positive effect on most test)	Increasing ventilation	Field	IAQ
Balazova et al.	2007	Better performance	Addition(↑)	Combined effect	Lab	Noise, IAQ Temp

[1] Arrow indicating, if significance or tendency direction compared to response was known (e.g. if the response was impaired performance; (↑) indicates the test supported this

[2] PV: Personal ventilation

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In general the experiments from Table 1 can be classified in three types: field experiments in schools, field experiments in call-centers and laboratory experiments. In most of these experiments, the effects of improving temperature or air quality (most represented by increased ventilation rates) had a positive impact on performance. Especially the field experiments in schools and call-centers showed positive performance effects of IEQ improvements, even though only relative small changes were observed in some cases.

In laboratory experiments in controlled environments the results also indicated that improving IEQ would improve performance. However these results were not as clear and uniformly directed as the results of the field experiments. Typically, several different tests simulating office work were performed by the subjects and generally performance is affected differently depending on the test type (e.g. some IEQ conditions effect performance of addition tasks positively, some negatively and some IEQ conditions does not effect performance of addition tasks).

In the following selected studies and reviews regarding the effect of IEQ on mental performance are shortly described.

The effect of air quality on performance
Wyon (2004) summed up the results from seven different experiments investigating the effects of IAQ on performance (Wargocki et al. (1999), Lagercrantz et al. (2000), Wargocki et al. (2000b), Bakó-Biró et al. (2004), Kacmarczyk et al. (2004), Tham (2004), Wargocki et al (2004)). These experiments were mainly laboratory experiments conducted at the International Centre for Indoor and Energy (ICIEE) at the Technical University of Denmark, except one laboratory study in Sweden, one field experiment in Singapore and one field experiment in Denmark. Wyon (2004) concluded inter alia that poor IAQ can reduce the performance of simulated office work by 6-9% and that field experiments demonstrated that performance was reduced more than in laboratory studies.

Seppänen et al. (2006) used some of the same studies mentioned in Wyon (2004) together with four other studies (Heschong Mahone Group (2003), Federspiel et al. (2004), Myhrvold et al. (1997), Tham et al. (2004)) for a meta-analysis analyzing the effect of ventilation on various performance indicators. One of the results of the meta-analysis performed by Seppänen et al. (2006) was a relationship between ventilation rates and relative performance. Figure 1 shows this relationship in relation to two ventilation rate references values.
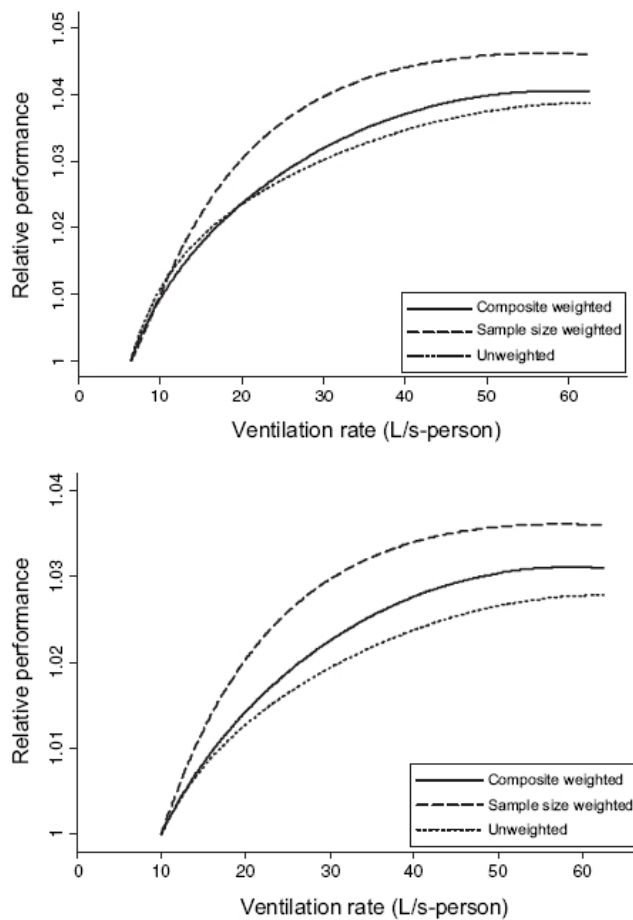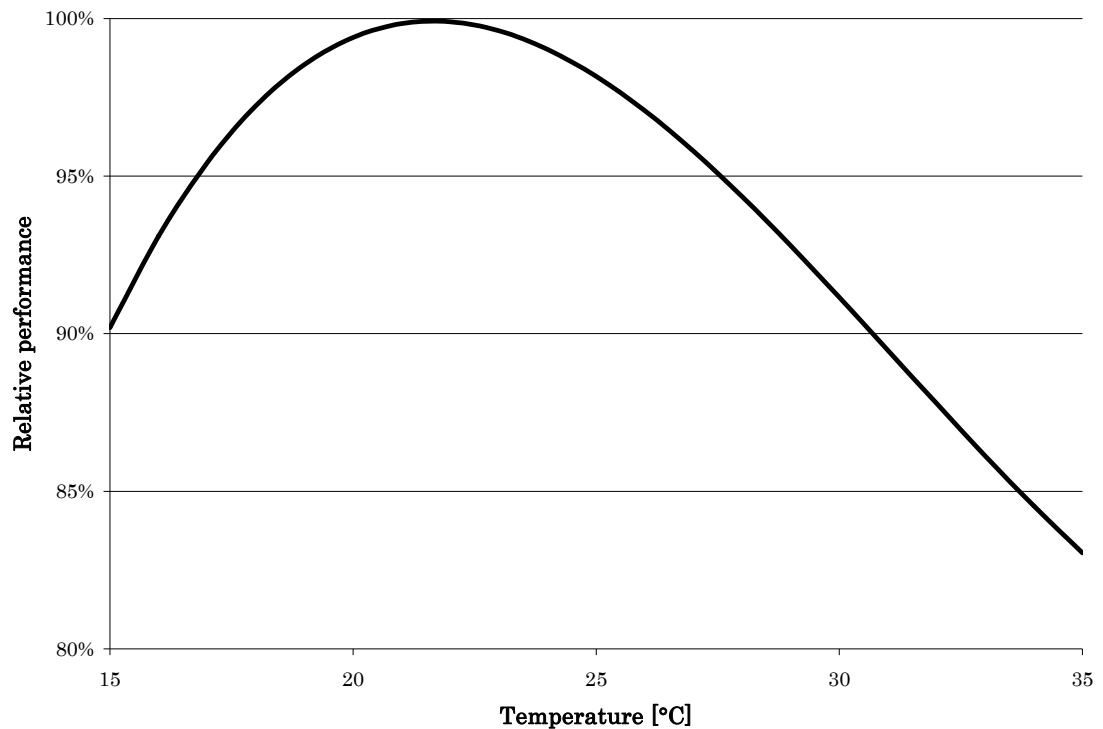
Fig. 1 *Dose-response relationship between ventilation rate and relative performance in the relation to the reference values 6.5 l/s-person (upper figure) and 10 l/s-person (lower) (From Seppänen et al. (2006))*

The effect of temperature on performance

Several studies have investigated the effects of temperature on mental performance (e.g. Wyon (1996), Witterseh (2004)). Recently, more field experiments investigating the effect of temperature on performance have been conducted. Niemelä et al. (2002), Federspiel et al. (2002) and Tham (2004) all have reported field studies where an effect of temperature on performance was observed. In general, warmer temperatures above 24.5-25.4 °C induced a decrement in performance. This effect on school work performed by children in the age from 10-12 years old was also seen by Wargocki et al. (2007a). In a laboratory experiment Witterseh et al. (2004) showed that subjects who felt warm made significantly more errors in an addition task.

Combing the results from laboratory and field experiments, Seppänen et al. (2005) derived a dose-response relationship between air temperature and relative performance. Figure 2 shows this relationship.

Fig. 2 *Dose-response relationship between air temperature and performance (From equation shown in Fisk et al. (2007)).*

Figure 2 shows that optimal performance was achieved at 21.8 °C and that in a range from approximately 21-25°C, temperature only had a modest effect on performance.

Tools to assess performance

A performance tool can be defined as a tool or calculation method that enables an estimation of the effects of the indoor environment on performance. Such a tool can be used in economic calculations of the total building economic impact of improving the IEQ. In its simplest form a performance tool is a dose-response relationship between an IEQ parameter and performance and in a more complex form it could be either a stand-alone software program or an integrated part of a dynamic simulation program that calculates the energy consumption, additional material cost, investment cost of different building designs and compares these design cases with a benchmark case. Figure 3 shows schematically the performance model concept.
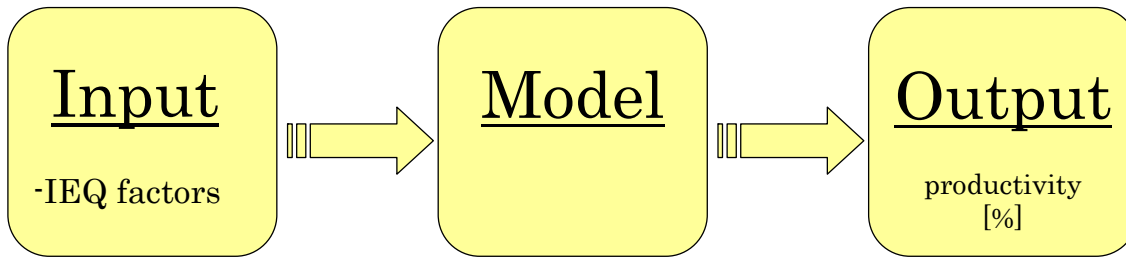
Fig. 3 *Concept of performance models shown schematically*

The model should be time dependent (dynamically) meaning that the modeller decides over how long a time period the calculation is conducted thus incorporating the variation in the indoor environment during the selected time period. Typically, the annual impact of the indoor environment is of interest, but also worst case scenarios (e.g. the hottest period of a year) could in some cases be interesting to investigate.

Existing cost-benefit calculations

It is likely that investments in improving the indoor environment would result in a positive yield. Woods (1989) documented that worker salaries exceed building energy and maintenance costs by a factor of 100, meaning that a doubling of the building energy and maintenance cost is equivalent to a 1% decrease in productivity.

Cost-benefit analysis and other economical estimates of the effects of IEQ on performance have been very sparse. The study of Fisk and Rosenfeld (1997) (updated in Fisk (2001)) indicated that on a national level in the USA the economical consequences of poor indoor thermal conditions, poor air quality, sick days and elevated SBS symptoms, were immense. The study used conservative average estimates of the effects of improving IEQ in a range of 0.5% - 5% increase in performance, which on a national level in the USA corresponded (in 1996) to $20 - $200 billion dollars. Dorgan et al. (2006) studied the effects of poor IAQ on performance and health also on a national level in the USA. The decrement in performance caused by poor IAQ was in the range of 0-6%, depending on the condition of the building (classified by the study team). The study also estimated the cost of improving the IAQ in the buildings and compared this cost with the potential increase in performance, which resulted in a simple payback time of less than 2 years.

Rather than using a macroeconomic approach, the economic consequences of poor IEQ can be estimated on a building/company level by case comparison analysis. This makes the performance tools more practical and with fewer assumptions. Typically, a reference

building or room is compared to a building in which the IEQ is improved, thus improving the performance of the occupants. The cost of improving the IEQ could be e.g. investment in better technical installations, increased energy cost and increased maintenance costs, the sum of which should then be compared with the achieved productivity increase. In the new building design process simulations are commonly conducted to document the energy consumption and the indoor climate in the designed building. Estimating the effects of the IEQ on the total building economy (initial cost and running costs together with the building's impact on occupant performance) building simulations are used to compare energy consumptions between designs as well as the changes in IEQ (e.g. indoor temperature, ventilation rates, CO_2 concentrations etc.). An advantage of using dynamic building simulation is that indoor conditions vary over day and season a variation that is included in the building simulation. Indoor temperatures normally depend on and vary with the outdoor temperature. The same variation is not likely to occur with the air quality. The air quality in mechanically ventilated buildings often depends on e.g., the interior materials, ventilation rate, frequency of changing the ventilation filter etc. These variables are normally less varying than temperature changes.

In studies like Wargocki et al. (2005) and Wargocki et al. (2006) cost-benefit calculation of different cases were compared. Most of the studies used dynamical building simulation to estimate the energy consumption whereas effects of IEQ on performance where not dynamical. The relationship showed that a 1.1% increase in productivity for each 10% decrease in the percent dissatisfied with the air quality upon entering a space. To calculate the energy consumption of twelve different ventilation rates (the supplied ventilation rate to obtain 50%, 40%, 30%, 20%, 15% and 10% percent dissatisfied with the air quality in a non-polluting and a low-polluting office) a building simulation program was used. A life-cycle-cost analysis comparing the initial HVAC cost, energy consumption cost and maintenance cost with the performance of the workers over a 25 year building life time, showed that payback periods of the initial investments were typically below 2 years.

In Wargocki et al. (2006) five different cases were presented; one was the above mentioned case from Wargocki et al. (2005), and one investigated the effects of higher ventilation rates on sick leave and will therefore not be included in this review. Of the other three cases, two are examples of the effects of temperature on performance and one is an example of the effects of air quality on performance. Case 2 in Wargocki et al. (2006) investigated the effects of installing night-cooling to reduce the indoor temperature during the day. The case study used the temperature/performance relationship shown in Figure 2. Restricting the analysis to one day during a hot period and comparing only with the increased energy

consumption, the benefit-to-cost (BCR) results indicated that the economic benefits of running night ventilation exceeded the costs multiple times (BCR ranging from 19-79 depending on the electricity price). Case 3 in Wargocki et al. (2006) used the same dose-response relationship, but instead of estimating the economic consequences of only one day, an hour-by-hour performance comparison was made between a reference case and four thermal improvement designs (adding cooling, increasing operating time, increasing ventilation rate to reduce the temperature and all improvements at once) using building simulation summed up over a year. The result from this case scenario showed that improving the thermal conditions saved money compared to the reference case, regardless of investments, and increased the energy consumption. The result also showed that implementing all IEQ improvements saved three times as much as the thermal improvement which saved the least (adding cooling to the ventilation system). The case investigating the effects of ventilation rate on performance used the dose-response relationship between ventilation rate and performance showed in Figure 1. Increasing the ventilation rate from 6.5 l/s-person to 10 l/s-person and 6.5 l/s-person to 20 l/s-person showed an increase in energy consumption, increased maintenance cost and initial investment of the ventilation system, but the results of the cost-benefit analysis showed, like the other cases, a positive yield indicated by BCRs between 6-9 times return of the investment due to the increased performance of the occupants.

Summing up on the above mentioned cost-benefit analysis, all cases showed an immense economic potential, both on a national level and a company level. Several of the studies used dynamic simulation to estimate the annual energy consumption of a reference case, which then could be compared with an improved IEQ condition case, but only one study used the dynamic simulation to estimate hour-by-hour the effects of IEQ on performance and then summed up the effects for a whole year. All of the studies assumed that people were affected the same way when exposed to the same IEQ conditions.

*Barriers of the implementation of performance calculations in practice*
The two previous sections found an effect of IEQ on mental performance and showed that the economic consequences of the effect, both on macroeconomic and microeconomic level can be immense. Taking this into consideration, why are the effects of IEQ on performance not used in the building design or re-design phase to estimate the total building economy, which again may justify investments in solutions that improve the indoor environment? Below are listed some possible causes why occupant performance calculations are not a standard part of constructing a building;

- Accessibility
- Validity
- Accuracy

The main problem of implementing performance calculations in practice is the accessibility of the calculation methods. It is possible to make performance calculations but one have to have knowledge about research results and how to interpret the findings. If the calculation methods were an integrated part of software programs that designers use anyway (e.g. building simulation programs, life cycle cost programs or financial programs) a more extensive utilization of performance calculations would be seen. The next question is why the commercial or educational facilities have not developed a product that can be used in practice? One answer could be lack of resources to develop such a product. On global scale, the field of indoor climate research is relatively small and the segment of indoor performance research even smaller. Therefore not many people will be able to assist in developing a practical product. There is also the issue of latency of the research done at universities to the results are implemented in practice. The findings of the effects of IEQ on performance are relatively new (the more important scientific studies are less than 10 years old). Companies that could benefit of a performance tool would presumably be software companies and building designers. The software developers could develop a program which can be sold as a stand-alone program or integrated with existing programs and thereby increase the value of these programs. The designers (architects and engineers) would be able to sell an extra service in the building design phase which will increase the turnover. Indirectly particular building owners will benefit from the performance calculations. The calculations will presumably in most cases justify investments in IEQ improvements that increase employee performance and thus the building owner's profit.

Another point is the reliability of the research done so far regarding IEQ effects on performance. If performance increments of 5-10% can be achieved by improving IEQ, there is no economical impediment for not prioritizing the quality of the indoor environment. Figure 4 shows some of the factors affecting performance of a worker.
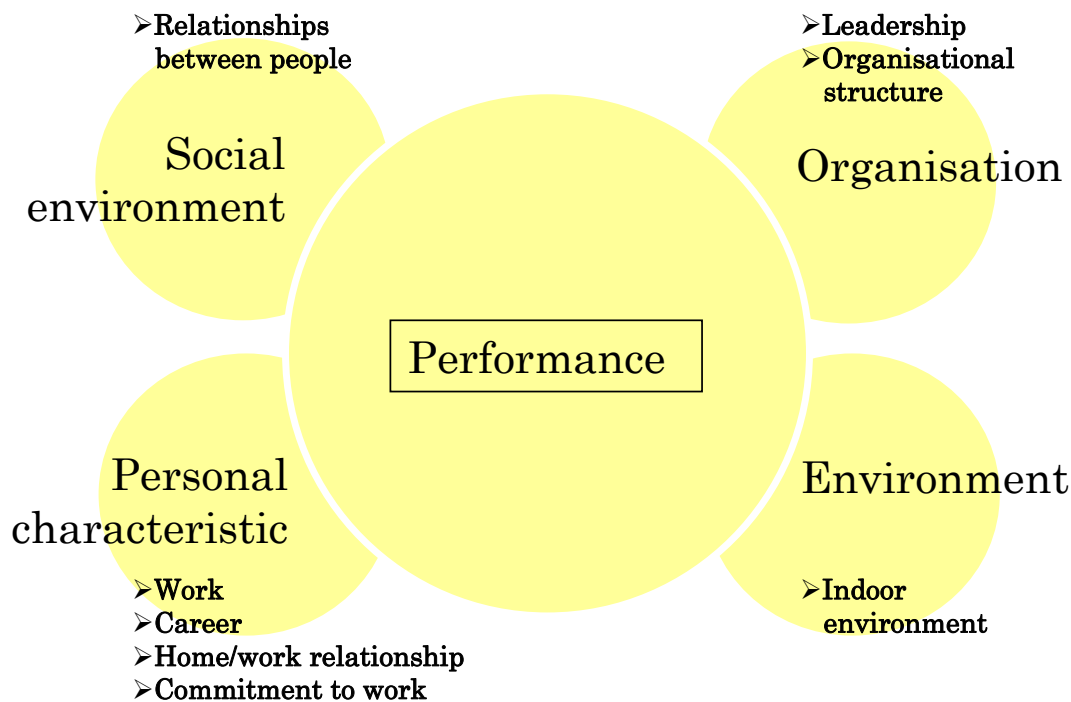
Fig. 4 *Different factors affecting the individual performance (figure created from Wargocki et al. 2006)*

Management, relationship to co-workers, salary, facilities, motivation etc. affects performance and the legacy of the Hawthorne effect probably negligees the magnitude of the effects of IEQ on performance compared to management or psychosocial effects. But these confounding factors are isolated in the performance experiments. Thus, it is up to the designers to convince that a good indoor environment, created already in the design phase, contributes to an increased performance of the employees. However, the interaction of the organizational, psychosocial, personal and IEQ effects are still not thoroughly investigated.

Finally, an additional possible barrier for implementing performance calculations in practice could be the accuracy of the calculations. Due to the economic consequences of even relatively small increases in productivity a short payback time of investment etc. can be expected. This raises the question about the uncertainty in the calculations. Often many, somewhat loose, assumptions have to be taken and, as mentioned earlier, the more assumptions the less realistic and useable estimations of the performance calculation can be expected. Therefore, it is important that uncertainty is evaluated in the performance calculations of a performance tool.

Bayesian performance tool version 0.9

Common for all the above mentioned cost-benefit analyses conducted so far is the linear approach to the inputs of the models. In **Paper I** of the enclosed thesis papers, three important points are suggested in order to develop an effective performance tool. (i) Dynamic calculations for the changes in the indoor environment and energy consumption, (ii) Reliable dose-response relationships between indoor climate parameters and mental performance and (iii) Establishment of a framework that provides an assessment of individual differences and the inherent uncertainties of the empirically derived dose-response relationship.

(i) Dynamic calculations

As previously mentioned dynamic simulations can be useful to document the daily or seasonal variation of the indoor parameters. In a mechanically ventilated building, periods occur when e.g. the installed cooling capacity is insufficient to maintain the temperature in the comfortable range, or in a naturally ventilated building when the ventilation rate is below the necessary value. Instead of calculating the effects of IEQ on performance on the basis of e.g. one or a few temperatures through out a year, an hour-by-hour performance calculation potentially is more accurate, since more variation is included in calculations. Dynamic simulations can also be used to optimize the occupant performance. The periods when performance is reduced the most can be found, and active measures can be suggested during those periods to improve the condition and thus the performance.

(ii)Dose-response relationship

The dose-response relationship between performance and temperature and performance and ventilation shown in Figure 1 and Figure 2, respectively, are relationships using objective IEQ parameters (measured air temperature and ventilation rate). However, objective IEQ parameters *per se* may not be as good a predictor of the effects of IEQ on performance as a subjective assessment of the IEQ. Using objective IEQ parameters as predictors it is assumed that people respond identically to their environmental exposure. Figure 5 shows how different people assess the thermal environment, here at an exposure of 22°C indoor air temperature in a mechanical ventilated building. The distribution was based on data from de Dear (1998).
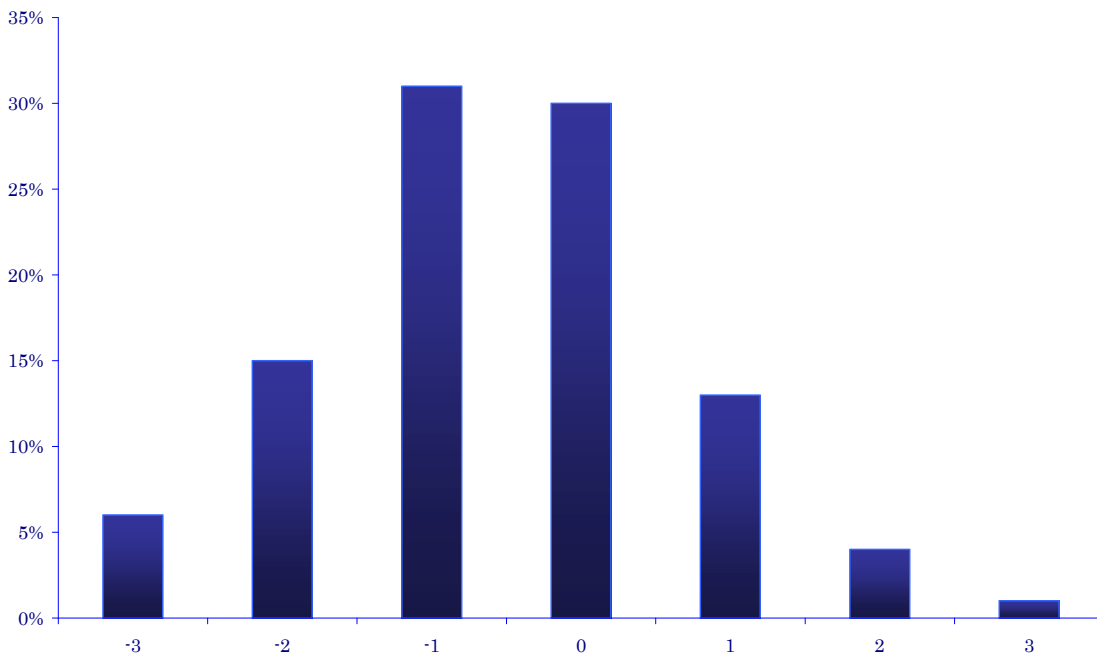
Fig. 5 *Distribution of thermal sensation assessment at 22°C on the seven-point thermal sensation scale*

The dose-response relationship shown in Figure 2, assumes that all people have an optimal performance at approx 22°C. Taking Figure 5 into consideration, this assumption could be too broad and a better predictor of the effects of temperature on performance could be a subjective assessment of the thermal conditions. Witterseh et al. (2004) found a significant correlation between people's thermal sensation and performance, but not between the objective temperature (at three different levels 22°C, 26°C and 30°C) and performance. Wyon et al. (1975) showed no difference in performance for subjects with different clothing levels but thermal neutral exposed to two different temperatures (19°C and 23°C).

When other pollution sources than the occupants are present, ventilation rate per person as a predictor of the effects of IAQ on performance may not necessarily be the best solution. In **Paper II** it was documented that subjects exposed to different pollution loads perceived the air quality very differently. This difference can be seen in Figure 6, showing the perceived air quality distribution of subjects exposed to a high pollution load, normal pollution load and low pollution load (see **Paper II** and the Result section for further details).

14
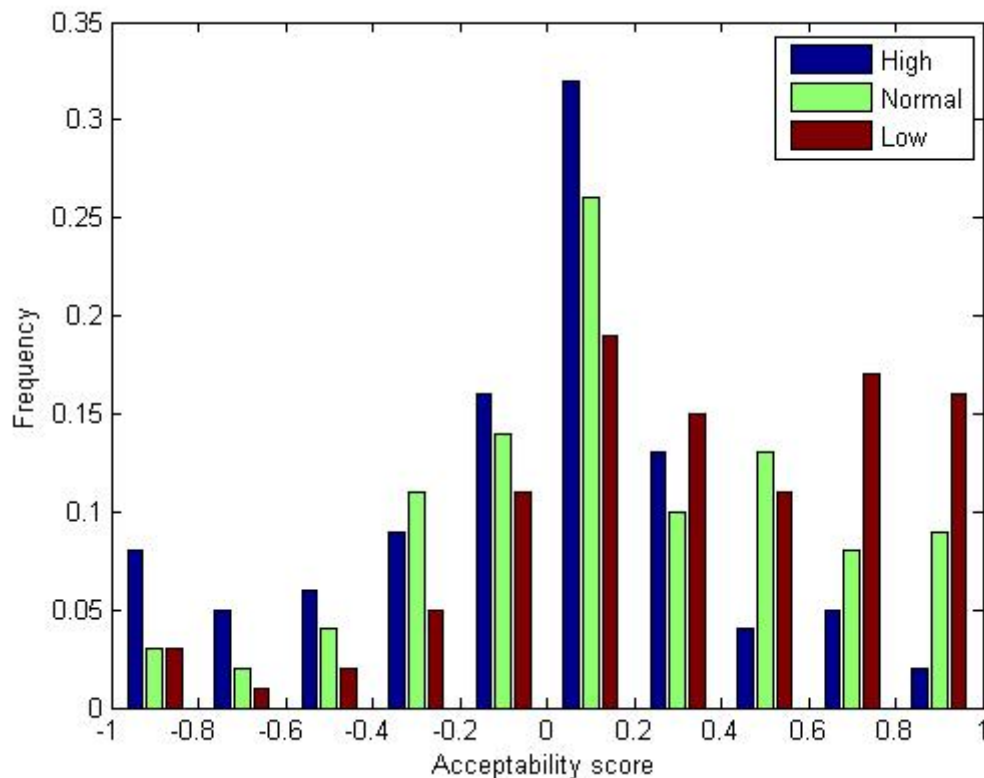
Fig. 6 *Distribution of PAQ votes on the -1 - 1 acceptability scale of subjects exposed to different pollution loads.*

From Figure 6 it is shown that the whole range of acceptability votes of the air quality (from -1 to 1) were covered, which shows that people's acceptance range differs.

Using subjective assessment of the IEQ to evaluate the effects on performance invoke some other and more practical advantages. Including the difference among people is important in the economic calculations evaluating the consequences of IEQ on the total economy of a building design, because a small reduction in performance can influence the total building economy due to the significantly higher costs for salaries compared to e.g. running costs of the ventilation system. Another substantial advantage is that people can be used as measurement tool of performance, which enables easy evaluation of the effects of IEQ on performance, simply by asking people how they perceived the IEQ

The derived dose-response relationships using subjective perception as a predictor of performance can be seen in **Paper I**, **Paper II** and in the result section of this present summary.

(iii) Framework to estimate individual difference and uncertainties in the indoor environment

Placing human beings in the same environment will naturally induce different perceptions of the indoor environment. Some persons have a high metabolic rate; some wear more clothing; some are exposed to higher air velocities; some are female and some are older. These are all factors affecting the thermal sensation (together with the actual temperature) and to some extent affecting each other. There are several approaches to model these uncertainties. Traditionally in the field of indoor climate research a linear, deterministic approach has been taken, seeing the human as an object that exposed to static indoor factors. Fanger's PMV model is a good example of this (Fanger, 1970). From six different variables, a predicted mean vote is estimated. Variability is introduced to this PMV value by calculating the percentage people dissatisfied (PPD), but from a practicality point of view including the variability after all the indoor factors are determined, reduce the realism of the model. In order to include the variability between occupants in a real-world office in the PMV model, many estimates have to be conducted (one for each indoor factor that varies). In practice, this is time consuming and difficult to do, so average assumptions are often applied. A probabilistic model may be a more appropriate and an easier implemented approach.

A probabilistic distribution incorporates the uncertainties of the indoor environment. For example instead of assuming that people are wearing the same clothing, intervals (or states) can be established (A probability of 70% that people wear clothing corresponding to an insulation between 0-0.75 clo; 28% between 0.75-1.2 clo; 2% above 1.2 clo). Such a probability distribution is conditioned by other factors. If it is winter and the indoor temperature is 21 °C, the above distribution could be [20%, 0-0.75 clo; 60%, 0.75-1.2 clo; 20%, above 1.2 clo].

A Bayesian Network (BN) model is useful in calculating probabilistic dependencies between variables. The basic concept in the Bayesian Network is conditional probability. A conditional probability statement can be of the following kind: *"Given the event b, the probability of the event a is x."* (Jensen, 2001). Transferred to the indoor environment: "*Given the temperature is 22°C, the probability that people's thermal sensation is neutral is 60%".* A more thorough review of the theoretical aspects of BN can be read in the method section.

In a performance calculation tool using BN theory in a model enables the estimation of individual differences between occupants by including different probability distributions of

variables in the indoor environment that typically would be considered as uncertain variables (e.g. we don't know the specific insulation of the clothing so we assume that occupants wear clothing corresponding to an insulation level of 1 clo). A BN model can be graphically represented by nodes connected by arcs representing the causal relationship between the variables. Figure 7 shows the BN model used to model the relationship between temperature and performance, described in **Paper I**.
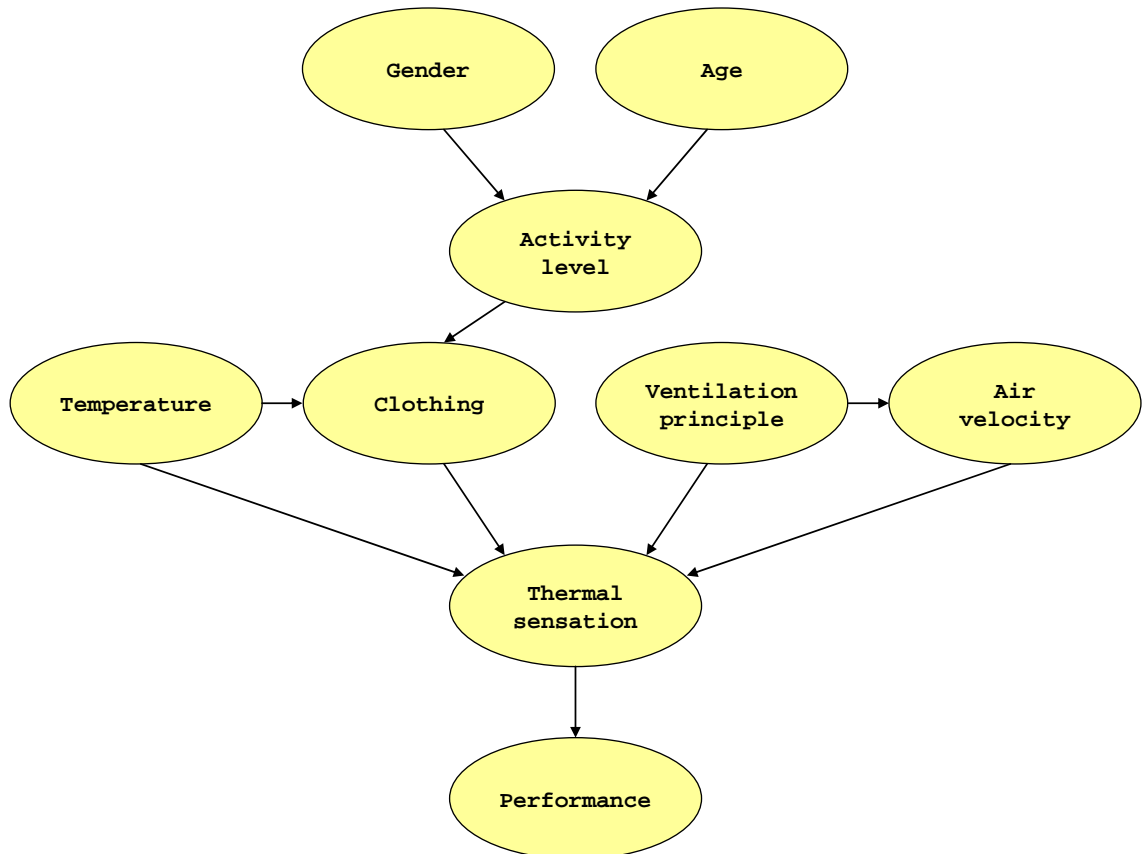
Fig. 7 *Bayesian Network model showing the cause-relationship between different variables in the indoor environment affecting the thermal sensation and performance*

In practice a model is as good as the data that forms the basis of the model. In the BN models in **Paper I** and **Paper II** it was strived to make use of the best data available. A description of the data and the derived dose-response relationships can be seen in the Result section.

In summery, by implementing the three elements 1) Dynamic calculation, 2) Dose-response relationships and 3) a framework that incorporates the individual differences between occupants and the uncertainties of the indoor environment, a performance calculation tool

that is different from what exists today was suggested. Some practical examples of the use of the BN models from **Paper I** and **Paper II** is implemented in **Paper III**.

Statistical analysis of performance experiments

Paper IV addresses the statistical analysis of a number of previous performance experiments. Numerous performance experiments have been carried out in laboratories and in the field; some of them is shown in Table 1. As mentioned earlier, the field experiments showed in most cases a significant effect of the IEQ exposure on mental performance, whereas the same results were not always seen in laboratory experiments.

One reason for the lack of response or the lack of uniform responses in the laboratory experiments could be that the motivation of the subjects concealed the effects of the IEQ. The fact that the subjects participated in experiments of relatively short duration makes them less sensitive than they would normally if they did real office work. Another reason why less consistency was observed in laboratory experiments could be that the IEQ does not affect performance at all, but this is contradicted by the results from the field experiments. Possible effects are relatively small, and therefore the interpretation and conclusion of the statistical analysis in itself could affect the results. Many statistical methods need a full subject dataset in order to perform the analysis. Missing values, which typically occur when conducting repeated experiments with human subjects, can affect the overall result.

In the field of indoor environment research, the same kind of experiments are sometimes analyzed differently making comparison difficult. In **Paper IV** a statistical method called multivariate linear mixed effects modelling is suggested for analyzing experiments investigating the correlation between one or more subjective predictors and mental performance. The method is also valid to analyze the effects on performance of objective predictors (such as air temperature, pollution load etc.).

Traditionally statistical methods such as ANOVA models are fixed effects models, meaning that the predictor (predictors) is deliberately chosen by the examiner. The ANOVA analysis compares the part of the variation in the model that can be accounted for by the predictors with the part accounted for by the residuals (the error term). If most is accounted for by the residuals (depending on chosen significance level) the fixed effects model is not significant. A mixed effect model uses a fixed effect term and a random effect term. Typically, the random effect term is influenced by subjects, since subjects are affected differently when exposed to the same conditions. A random effect is often included in repeated exposure

experiments. By including this possible random effect in the model expression some of the variance can be explained by the random effects and some by the fixed effects leaving less variation to be explained by the error term, and thereby increasing the chance of a significant response of the predictors (Demidenko, 2004).

Gaining information about the nature of the performance tasks applied in the indoor climate research can be relevant and potentially lead to more powerful interpretations and conclusions from the statistical analyses. A multivariate model has the advantage of investigating the correlation between responses. In the field of indoor climate research such information can be used to evaluate e.g. the correlation between different task types. If potential correlation occurs between task types, performance experiments need to apply only one task type, since in such a case the two correlated performance tasks would measure the same component skills of the subjects.

METHODS

*"If man will begin with
certainties, he shall end in
doubts; but if he will content to
begin with doubts he shall end
in certainties"*

- Sir Francis Bacon (1561-1626)

Elaboration of the applied methods

In the enclosed articles a thorough elaboration of the applied methods could not be included. This section provides a more explanatory elaboration of how the Bayesian Network functions, illustrated with a simple example in which the calculations are shown. Also in this section an example of an economic calculation is presented in more detail than in the articles.

Bayesian Network calculations

In the following, an illustrative example will be given to show how the BN will work in context of indoor climate parameters. Data can be applied to a BN either by expert knowledge, who is a person indentifying the causal relationship between some variables by experience, by models or by observations. In the below example, the causal relationship between a few indoor parameters in the BN were estimated by an expert and serves just as an illustrative example.

Figure 8 is an example of a Bayesian Network related to the indoor climate.
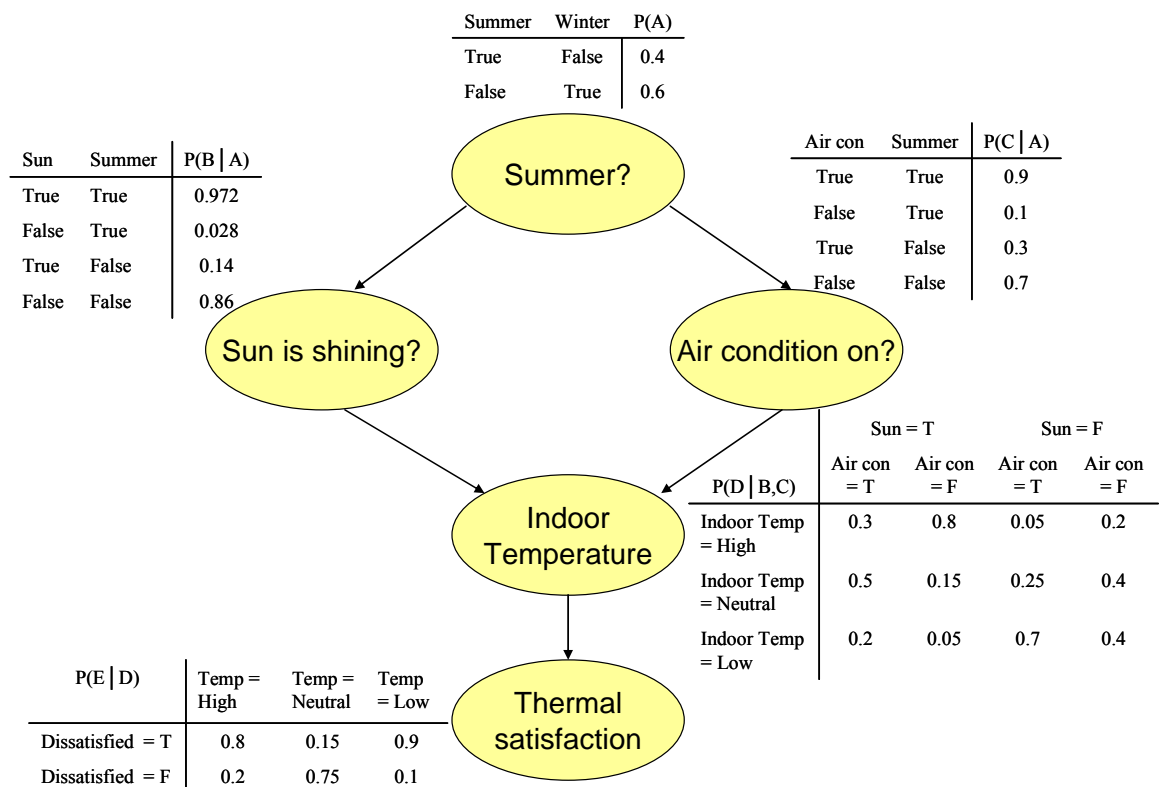
Fig. 8 *A simple Bayesian Network*

Figure 8 shows a graphical representation of a causal network. Each node (balloon) is a variable with a given number of events also called states, clustered around the variables. The states of the variables cause an impact on other variables' states visualized by the arcs. Knowing the states of a variable we can infer something about other variables. In this example 'Summer?' has two states: [True, False]. 'Sun is shining?' and 'Air conditioning on?' also have two states: [True, False]. 'Indoor temperature' has three states: [High, Neutral, Low] and finally 'Thermal satisfaction' has two states: [Satisfied, Dissatisfied]. One of the possible combinations of the network could be that, if it is summer, the sun is shining and the air conditioning is on. This causes the indoor temperature to be neutral, which again affects the thermal satisfaction to be judged as satisfying. The same scenario with the air conditioning turned off, will result in the indoor temperature being high and people will be dissatisfied. The prior probabilities included in the initial development of a Bayesian Network can either come from observations (applied to our case: what are chances of the season being summer based on meteorological data from the last 30 years or how often does the sun shine when it is summer etc.), or the data can come from a model (in our case: in 100 years what are the chances the sun is shining during summertime based on predictive weather models.) or data can come from experts opinions (in our case: Asking a 70 year old farmer what the chances are that the sun is shining during summer) or a combination of real data, models and expert opinions. The strength of the relationships is given by the Conditional Probability Distribution for each variable, which can be shown in a Conditional Probability Table (CPT) (see small tables in Figure 8).

In the above graphical model (also called a directive graphical model) the variable which affects another variable is called a parent and the variable affected is called a 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 A is noted P(B|A). Bayes's theorem describes probabilistic dependencies between A and B in the following way (Jensen, 2001):

$$P(B/A) = P(A/B)P(B) / P(A) \qquad \text{(Eq. 1)}$$

P(A) can also be written as:

$$P(A) = P(A \mid B)P(B) + P(A \mid \overline{B})P(\overline{B}) \qquad \text{(Eq. 2)}$$

where $P(\overline{B})$ is the probability of B not happening.

The network from Figure 8 shows that 'Summer?' is a parent to 'Sun is shining?' and also a parent to 'Air conditioning on?', while 'Sun is shining?' and 'Air condition on?' are parents to 'Indoor temperature' etc. The probabilities can be written as follows: *P(Summer)*, *P(Sun│Summer)* (whether or not the sun is shining is conditioned of whether or not is summer is shown by '│'), P*(Air con│Summer)*, *P(Indoor Temp│Sun, Air con)* and *P(Satisfaction│Indoor Temp)*.

If the Bayesian Network from Figure 8 is simplified an example of the predictive and diagnostic properties of Bayes Theorem can be shown.

Summer	Winter	P(A)
True	False	0.4
False	True	0.6

Sun	Summer	P(B│A)
True	True	0.972
False	True	0.028
True	False	0.14
False	False	0.84
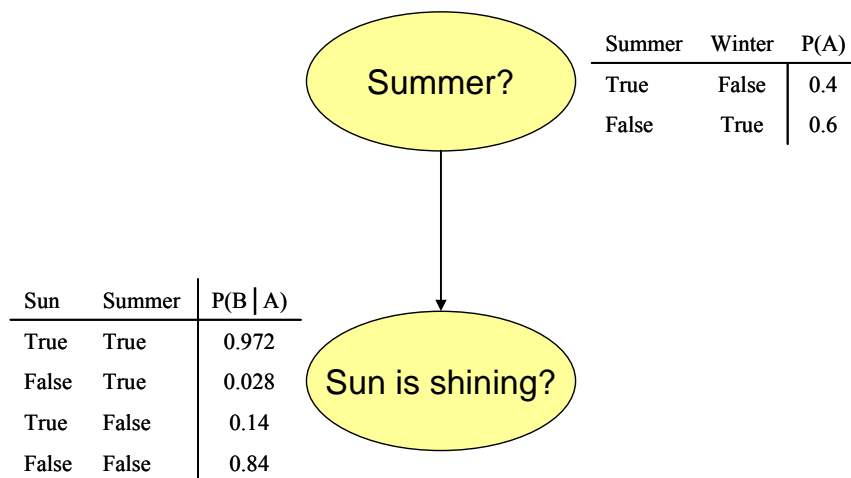
Fig. 9 *Simplified BN model with two nodes*

Figure 9 shows the causal network between the two variables 'Summer?' and 'Sun is shining?' and the their relative strength as given by the Conditional Probability Tables (CPT). The logical reasoning is that the season (summer or winter) affects the probability that the sun is shining. Using Bayes Theorem (Equation 1) we can make a posterior assumption of the season if we observe the state of the sun. It is observed that the sun is shining, which is our evidence and meaning that we are adding knowledge to the network. The Bayes Theorem can be used to calculate the probability of the season being summer based on this new knowledge. *T* indicates that the state is true and *F* indicates that the state is false.

$$P(Summer = T | Sun = T) = \frac{P(Sun = T | Summer = T)P(Summer = T)}{P(Sun)}$$

Where $P(Summer|Sun)$ is the probability of the season being summer if the sun is shining, $P(Sun|Summer)$ is the probability of the sun to shine if it is summer, $P(Summer)$ is the fraction of the year when it is summer, and finally $P(Sun)$ is the fraction of the year when the sun is shining, which also can be written as seen in Equation 2.

$$P(Sun) = P(Sun|Summer = T)P(Summer = T) + P(Sun|Summer = F)P(Summer = F).$$

Thus,

$$P(Summer = T|Sun = T) = \frac{P(Sun = T|Summer = T)P(Summer = T)}{P(Sun = T|Summer = T)P(Summer = T) + P(Sun = T|Summer = F)P(Summer = F)}$$

Now we can input data from the CPTs in Figure 9.

$$P(Summer = T|Sun = T) = \frac{0.972 \cdot 0.4}{0.972 \cdot 04 + 0.14 \cdot 0.6} = 0.822$$

Therefore before knowing the presence of the sun the probability of it being summer was 40%. After observing the sun the probability of it being summer increased to 82.2%. The calculations quickly become more complicated if more variables are added. An example of a slightly more complicated calculation example could be two variables having the same parent as seen in Figure 10. This is also called a diverging connection.

Summer	Winter	P(A)
True	False	0.4
False	True	0.6

Summer?

Sun	Summer	P(B|A)
True	True	0.972
False	True	0.028
True	False	0.14
False	False	0.84

Sun is shining?

Air-con on?

Air con	Summer	P(C|A)
True	True	0.9
False	True	0.1
True	False	0.3
False	False	0.7
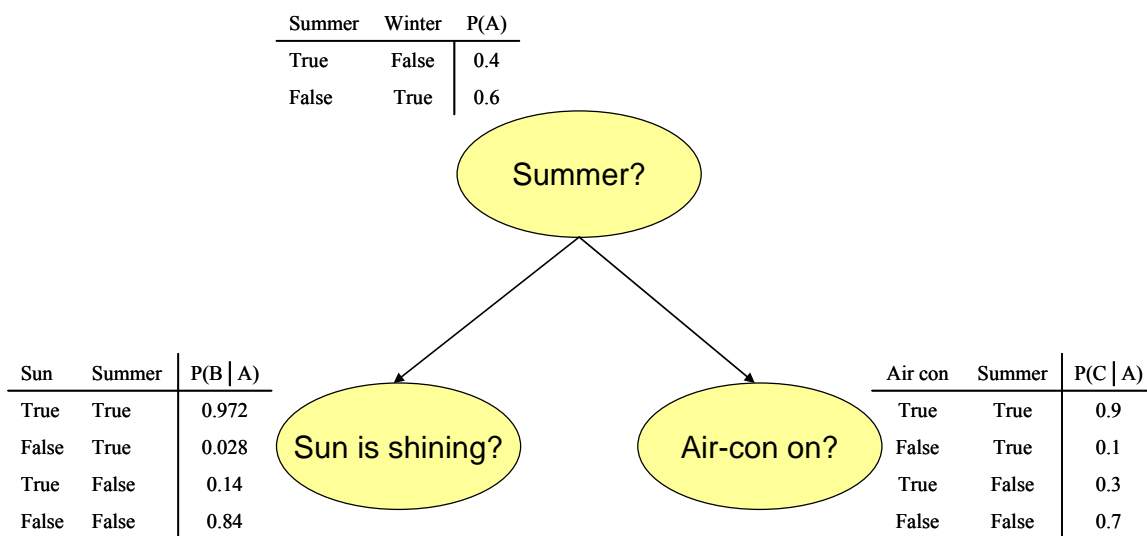
Fig. 10 *Three node BN – diverging connections*

The children of a diverging connection depend of each other as long as the state of the parent is not known. For example if it is observed that the Air-conditioning is on, the probability of it being summer will change thus changing the probability of the sun to shine.

Without prior knowledge of the state of 'Summer?' the probability of the sun is shining can be calculated using data shown in conditional probability tables and following equation:.

P(Sun) = P(Sun|Summer = T)P(Summer=T)+P(Sun|Summer=F)P(Summer=F)

Insetting the values for calculating the probability of the sun is shining *P(Sun =T)*:

P(Sun =T) = 0.972 · 0.4+0.14 ·0.6 = 0.473

With prior knowledge given by the probabilities in the conditional probability tables the probability of the sun is shining is 47.3%. Further if observing that the air-conditioning is turned on. The probability of what time of the year would change, which can be illustrated with following equation, calculating the probability of it being summer observing that the air-conditioning is on:

$$P(Summer = T|Air = T) = \frac{P(Air = T|Summer = T)P(Summer = T)}{P(Air = T|Summer = T)P(Summer = T) + P(Air = T|Summer = F)P(Summer = F)}$$

$P(Summer = T|Air = T) = \frac{0.9 \cdot 0.4}{0.9 \cdot 0.4 + 0.3 \cdot 0.6} = 0.66$, now there is a 66% chance that it will be summer,

thus affecting the chances of the sun is shining, $P(Sun = T) = 0.97 \cdot 0.66 + 0.14 \cdot 0.34 = 0.69$

Due to the observation that the air-conditioning was working, the probability of the sun to shine increased from 47% to 69%.

The above example shows very simple calculations with few nodes and few states. A BN including many nodes with many states is practically impossible deal with manually. This is the major reason why practical application using BN theory progressed slowly until the beginning of the 1980'ies when computational calculations in the field of artificial intelligence research became more frequent. In the BN models used in **Paper I-III** the networks were so complex that a MATLAB routine was implemented to perform the calculations.

Total building economy calculations

The economic evaluation of modifying IEQ is an important part of a performance calculation tool. Through the cost-benefit analysis, the indoor climate has the potential to become an equally important focus area in the design phase as the energy consumption and maybe even the exterior design of a building. There are numerous ways to conduct cost-benefit analyses; the sustainable way is to make a life-cycle-cost analysis, the simple way is to calculate the payback time of the investment in improved IEQ. In Seppänen and Fisk (2006), a detailed conceptual economic IEQ model for owner-occupied buildings was suggested. A similar economic IEQ model focusing on the effects of IEQ on performance and not on health, SBS and complaints was suggested. Figure 11 shows schematically the different steps in the performance calculation and cost-benefit analysis comparing two different building designs.
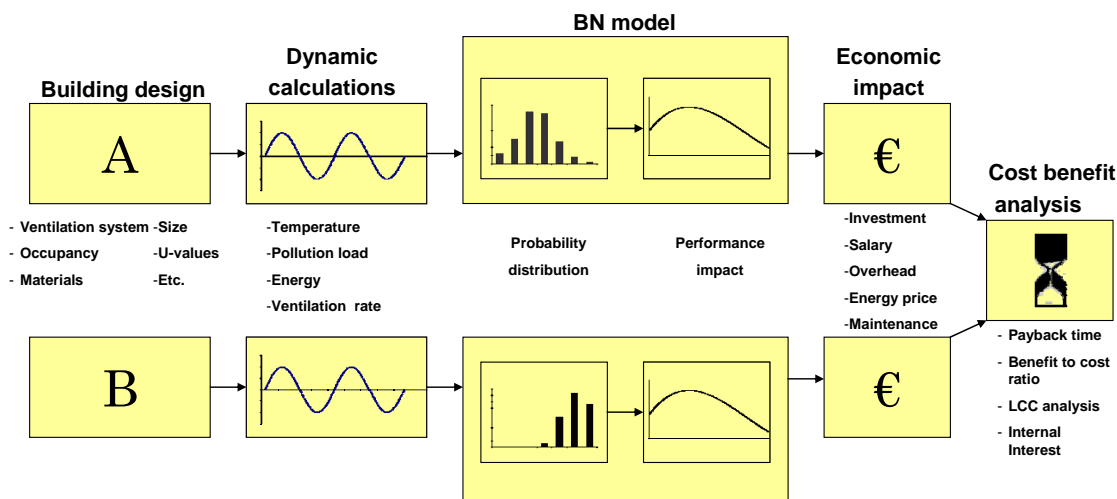
Fig. 11 *Schematically description of the calculation methods from building design to total building economic impact.*

In Figure 11, building design A could be the better case, e.g. where measures have been done to improve the thermal conditions. The impact on indoor temperature and energy consumption was then simulated using a dynamic simulation program. Hour-by-hour results from the simulations were transferred to the BN model, which calculated the differences between occupants and the corresponding effect on performance. Each hour-by-hour calculation was summed up on annual basis to an overall annual performance index, which was used in the economic calculations, where salary, energy price, investment cost etc. were compared with building design case B in a cost-benefit analysis.

Example of an economic calculation

In the following an example of a step by step calculation is shown. The example is a more elaborated version of the renovation example from **Paper II**.

Simple payback time was compared between two different building designs to investigate if the building improvements were economic feasible. Calculation of payback time included the economic impact of energy cost, maintenance cost, investment cost and occupant performance. Table 2 shows the two design scenarios.

Table 2 Different cases used in a renovation scenario

Prior to renovation	Non-low polluting building, low air flow (0.5 l/s m²), CAV ventilation system
After renovation	Very-low-polluting building, increased air flow (3.2 l/s m²), VAV ventilation system

As seen from Table 2, two IAQ parameters were changed: i) Building materials, achieving very-low-polluting building category, ii) Increase of the ventilation rate from a minimum 0.5 l/s m² to 3.2 l/s m². The simulated room was a small office room of 19m² occupied by two persons. Table 3 shows the building characteristics, which serve as input to the dynamic building simulations.

Table 3 Input to the simulations used in the renovation scenario

Floor area	19 m²
No. of occupants	2
Ventilation type	Mechanical
Façade area	5.5 m²
Heat transmission coefficient façade	U_{facade} = 0.27 W/m²K
Window area	5.3 m²
Heat transmission coefficient window (center value)	U_{window} = 2.8 W/m²K
Location	Copenhagen, Denmark

It is seen from Table 3 that the heat transmission coefficients were relatively high compared to present standards. High heat transmission coefficients affect especially the thermal conditions and choosing high values illustrated the effect of a potentially large improvement of the thermal conditions on the total building economy.

After the building simulations (one for each building design) were conducted, the hour-by-hour values (temperature and ventilation rates) were transferred to the BN models to calculate performance indices (one BN model dealing with the temperature and one with air quality - See the Result section on how the specific BN models were developed and how

they function). The performance indices were then used in the economic calculations. The economic assumptions are shown in Table 4:

Table 4 Input for economic calculations

Yearly salary per occupant	€ 50.000
Overhead	1.3
Heating price	0.07 €/kWh
Electricity price	0.25 €/kWh
Investment to install 12 kW cooling[1]	49 €/m²
Investment to increase ventilation by 1 l/s m² [2]	26 €/m²
Investment to increase ventilation by 3.7 l/s m²	96 €/m²
Investment in low-polluting materials[3]	16 €/m²
Increased maintenance due to larger ventilation system[4]	0.5 €/m²
Extra cleaning to keep surfaces low-polluting [5]	0.3 €/m²
[1,2]: Reference: Wargocki et al. (2006) [3]: In Wargocki et al. (2006) the price of the interior was 12% of the construction cost. Construction cost was set at 1300 €/m² resulting in a cost of the interior of 156 €/m². It was also assumed that the price of low-polluting materials was 10% higher than the price of non-low-polluting materials, thus resulting in the investment in low-polluting materials being 16 €/m² [4] Increasing the size of the ventilation system induces increased maintenance cost. It is assumed that 2% of the remedial cost of the ventilation system on an annual basis is the maintenance cost [5] It is assumed that 2% of the remedial cost of the low-polluting materials corresponds to the annual cost for extra cleaning.	

The investments prices were based on prizes shown in cases 3 in Wargocki et al. (2006) normalized by the floor area. The prices were based on renovation of 50 offices. The initial price depended on the area needed to be retrofitted. Renovation of just one single office, however, will be more costly than the initial prices indicated here. Many of the numbers shown in Table 4 can be challenged due to the fact that they are very case-specific and not only depended on which kind of company the simulated offices represented. The numbers are also depended on the nationality of the company. Salary, energy prices etc. were somewhat representative for Danish prices.

Table 5 shows the results from the building simulations and the corresponding performance calculation performed by the BN models.

Table 5 Summary of the output from the building simulations and the resulting performance.

	Prior to renovation	After renovation
Average office temperature [°C]	25.9	22.9
No. of working hours > 26° C per year	1132	50
No of working hours > 27° C per year	943	28
Building pollution type	Non-low-polluting	Very-low-polluting
Specific supply airflow rate [l/s m^2]	0.5	4.2
Heating [kWh/m^2] per year	30	64
Electricity [kWh/m^2] per year	23	38
Total energy [kWh/m^2] per year	53	102
ΔPI_{temp} [%]	0.7	
ΔPI_{iaq} [%]	0.7	

In Table 5 it is seen that the temperature prior to renovation exceeded 26°C during 1100 of the working hours during a year. In Denmark the building code recommend only an exceeding of 100 hours above 26°C. After renovation, the number of hours with a temperature above 26°C is reduced to 50, which also can be seen on the average temperature. The average ventilation rate is 0.5 l/s m^2 prior to the renovation, after the renovation this increased to 4.2 l/s m^2. Table 5 also shows that the total energy consumption was almost doubled, but it is seen that the absolute value of the energy consumption was relatively small even though the building was an older office building. This was due to the simulated room was in the middle of a larger office building. If also the offices in the perimeter of the building were simulated the absolute energy consumption pr m^2, would be larger.

ΔPI_{temp} and ΔPI_{iaq} indicate the performance increment due to the effects of improving the thermal condition and air quality conditions respectively after renovation. As seen, the effects of improving the thermal conditions and the effects of improving the IAQ increased in both cases the performance with 0.7%. In the economic calculations these two separate performance increments were added to a total performance increment after renovation of 1.4%.

Combining economic assumptions shown in Table 4 and the results from the dynamic calculations shown in Table 5 resulted in a total building economy estimate, which is shown in Table 6.

Table 6 Summary of the output from the building simulations and the resulting performance and economic output.

		Prior to renovation	After renovation
1	Income [€/m²]	6594.7	6690.5
2	Energy cost [€/m²]	7.8	13.7
3	Difference in energy cost [€/m²]	5.9	
4	Additional maintenance cost [€/m²]	-	2.2
6	Productivity gain (1.4%) [€/m²]		95.8
7	Total gain [€/m²]		87.7
8	Accumulated cost of investment [€/m²]	0	184.8
9	**Simple pay-back period [years]**	**3**	

The first row in Table 6 represents the financial income per m². It was calculated from the base salary (€50.000) pr occupant divided by the office area: (€50.0000 · 2 occupants) / (19 m²) = €5263/m². The occupants have to earn more than their salary in order to keep the company running. An overhead of 30% was assumed. This resulted in a potential financial income pr m² of: 1.3 · €5263/m² = €6841/m², which corresponds to an optimal 100% relative performance. Prior to the renovation the relative performance due to the effects of temperature was 98.4% (-1.6% reduction) and the effects of IAQ on performance prior to the renovation was 98% (-2% reduction), which resulted in a financial income per office area of €6841/m² · 0.964 = €6594.7/m² at a total of 3.6% performance decrement. After the renovation the effect of the temperature on performance was 99.1%(-0.9% reduction) and 98.7% (-1.3% reduction) of the effects of IAQ on relative performance resulting in a financial income pr m² after renovation of €6841/m² · 0.978 = €6690.5/m² at a total of 2.2% performance decrement.

In the second row the total energy cost was calculated on the basis of the heating and electricity prices shown in Table 4 and the heating and electricity consumptions from Table 5.

In row four the numbers were calculated based on the explanation seen in the footnotes of Table 4. Since the maintenance cost was 2% of the initial investment in a ventilation system, the additional maintenance cost was taken as 2% of the additional investment (2% of €96/m² = €1.9 /m²). Using low polluting materials also induced an increased maintenance cost which was assumed to be 2% of the investment made to install low emitting materials (2% of €16/m² = €0.3 /m²), which resulted in a total cost of €2.2/m².

The productivity gain in row five is the difference between the financial income pr m² in row one. The total gain was the additional energy cost plus maintenance cost subtracted from the accumulated productivity gain (95.8 - 5.9 - 2.2 = €87.7/m²).

The total cost of the investments over a 15 years period paying 7% in interest can be calculated using the annuity factors shown in Wargocki et al. (2006). A 7% interest over 15 years resulted in an annuity factor of 0.11. The annual payment was then $0.11 \cdot €96/m^2$ $+0.11 \cdot €16/m^2 = €12.3/m^2$ and over 15 years this resulted in $15 \cdot €12.3/m^2 = €184.8/m^2$.

The simple payback period was calculated by the ratio of the annual total gain of $€87.7/m^2$ and the cost of the investment of $€184.8/m^2$, which resulted in a payback time of $€184.8/m^2/$ $€87.7/m^2 = 2.1$ years and rounded up into whole year: 3 years.

RESULTS

"To measure is to know"

- Lord Kelvin

Following describes in short the results and the use of the findings from the enclosed papers.

Results from Paper I

The study presented in **Paper I** introduced a BN model which estimated the effects of temperature on mental performance using input from dynamic building simulations. The BN can be seen in Figure 7. The data used to construct the probabilistic distributions in the BN model in **Paper I** were based on a selected proportion of the same data used to develop the ASHRAE adaptive model (de Dear, 1998). The selected dataset consisted of information from over 17.480 occupants in 184 mechanical, natural and hybrid ventilated office buildings from different parts of the world. In the ASHRAE RP-884 Adaptive Model Project the data was classified in three different classes, representing the accuracy of the measurements behind the data. Class I complied 100% with ISO 7730 (1984) and ASHRAE standard 55 (1992) measurement procedures, where Class III were simple measurements of temperature and simple questionnaires. Only Class I and Class II data were included as the basis of the suggested BN model. The selected data formed the basis of the conditional probability tables and thus the conditional probability distribution (the strength of the causal relationships between the indoor variables) also called the prior conditional distribution (prior to any observations or inference done in the BN model). One main advantage of creating a BN model using so much data was not only that the reliability of the model increased but also that different inferences were enabled. In practice this can be used if e.g. the ventilation principle of a building is known (e.g. natural) then the probabilities in the BN model changes so they comply with naturally ventilated buildings. In **Paper III** a description of the effects of the difference in thermal sensation depending on building type on performance was studied.

The nodes shown in Figure 7 consist of different states (e.g. an interval, a categorical label or other classification of the node). For instance the temperature node is divided into sixteen different states representing the temperature from 18°C-33°C. All states can be seen in Table 1 in **Paper I**.

The main function of the BN model was to estimate the distribution of thermal sensation votes. The underlying hypothesis was that people respond differently, and this difference should be included in total economic considerations of IEQ improvement in a building design. By using the thermal sensation vote as a predictor of the effects of temperature on performance, exposure to an identical temperature induces a range of different perceptions.

Compared to the previously derived dose-response relationship (Figure 2), the use of thermal sensation as a predictor prompted the development of a new dose-response relationship between thermal sensation and performance.

This dose-response was derived from four different experiments, investigating the effects of temperature on performance (Toftum et al. 2005, Balazova et al. 2007, Kolarik et al. 2008, Wargocki, 2008). A total of 578 subjective assessments of the thermal conditions together with corresponding performance measures (addition arithmetic) were used to develop the dose-response relationship in Figure 12.

The chart shows a curve with the equation $y = -0.0029x^2 - 0.0034x + 0.999$, with Relative performance on the y-axis (96% to 100%) and Thermal sensation on the x-axis (-3 to 3).
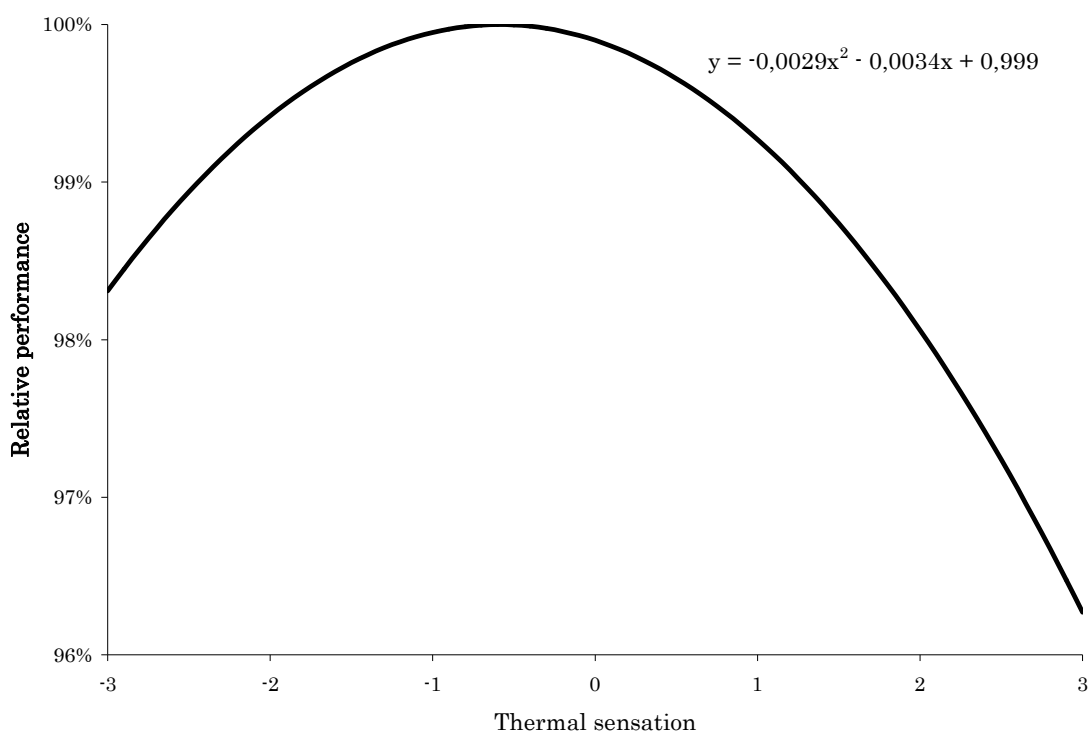
Fig. 12 *Dose-response relationship between thermal sensation and relative performance*

It is seen from Figure 12 that the optimal performance is obtained between -1 and 0 (slightly cool and neutral) (-0.6 to be precise), which indicates that optimal mental performance is obtained when subjects are feeling slightly cool and not when they have a neutral thermal sensation. This finding complies with the findings reported earlier by Pepler and Warner (1968). They found that the conditions for optimal mental performance were different than for optimal thermal comfort. Their subjects performed best at 20°C which, however, was also uncomfortable cold.

Compared to the dose-response relationship derived by Seppänen et al. (2005) (Figure 2), the present dose-response relationship can be considered as conservative with smaller

performance decrements in the extreme end of the relationship, but the two relationships have the same shape. The effects of colder temperature and thermal sensation assessments on the cool side was not as large as the effects of higher temperature and thermal sensation assessments on the warm side.

The BN model presented in **Paper I** was applied in some realistic design scenarios, where the total building economy was established taking the investment cost, energy cost and occupant performance of different design cases into account. These results are presented later in this section together with the economic calculations from **Paper II**.

Results from Paper II

Paper II describes the development of a BN model which can be used to estimate the effects of IAQ on performance. Figure 13 shows the suggested BN.
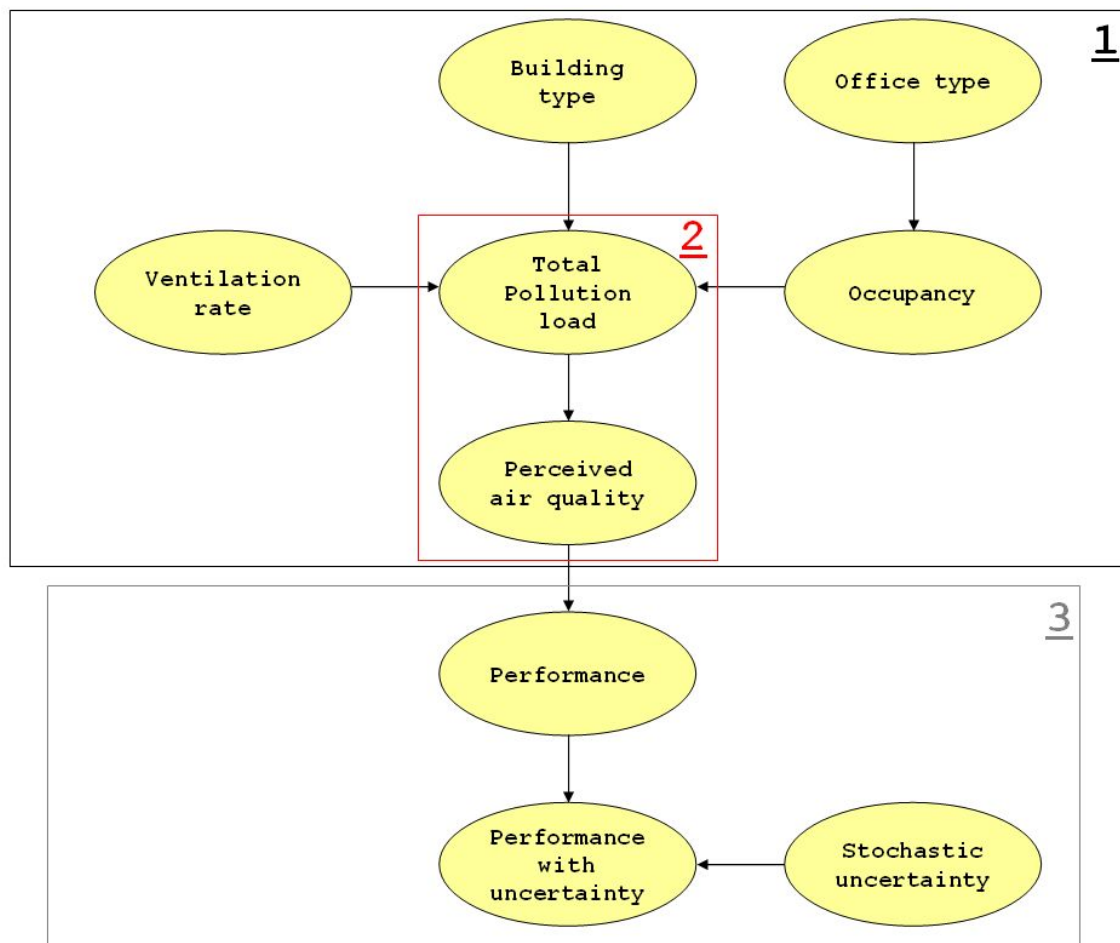
Fig. 13 *The suggested BN model showing the relationship between IAQ variables and performance*

The states of the BN model shown in Figure 13 can be seen in Table 1 in **Paper II**. The model can be divided into three parts: 1) Variables that affect the total pollution load in a given room/building, 2) Calculation of perceived air quality (PAQ) distribution depending on the pollution load of the room/building and 3) Calculation of the effects of IAQ on performance using a dose-response relationship between PAQ and performance.

The data that formed the basis of the conditional probability distributions in the BN model was not as comprehensive as the data in the thermal BN model. As described in the methods section conditional probability distributions in a BN model can be derived from observed data, models or expert knowledge. The first part of the model was the calculation of the total pollution load which was based on a model. The total pollution load depends on the ventilation rate, building type (e.g. low pollution building according to CEN 1752) and the number of occupants. A room could have a pollution load of 0.14 olf/m² with no occupants present and a ventilation rate of 0.5 l/s m². This results in a pollution load of 2.8 decipol (0.14 olf/m² / 0.5 l/s m² = 0.28 olf / l/s = 0.28 pol = 2.8 decipol) according to Fanger (1988). In occupied room the occupant generated pollution load per floor area can be added to the pollution load from the room itself. If the pollution load from the room is 0.14 olf/m² and the ventilation rate is 1.67 l/s m², the occupants in the room contribute with 0.17 olf/m² (six persons of 1 olf in a room of 36 m² results in 6 olf / 36 m² = 0.17 olf/m²). The pollution load is then 0.14 olf/m² + 0.17 olf/m² = 0.31 olf/m². With that particular ventilation rate the pollution load is then 0.31 olf/m² / 1.67 l/s m² = 1.86 decipol. The pollution load is converted to percentage dissatisfied using following equation from Fanger (1988):

$$PD = 395 \cdot \exp(-3.25\ C^{-0.25}) \qquad\qquad (eq.1)$$

where
PD = percentage dissatisfied (%)
C = perceived air pollution (decipol)

Converting the perceived air pollution from the above examples to percent dissatisfied results in 2.8 decipol = 32% PD and 1.86 decipol = 24.4% PD.

In the IAQ BN model three categorical intervals (states) have been suggested: High, for expected total pollution loads > 25% PD, Normal for PD between 15-25% PD and Low for rooms with a PD <15% PD. Frame #2 in Figure 13 considers the distribution of perceived air quality assessments depending on total pollution load category (High, Normal, Low). Six different IAQ laboratory experiments were the data basis of the PAQ distributions

(Wargocki et al. 1999; Wargocki et al. 2000b; Lagercrantz et al. 2000, Wargocki et al. 2002b; Toftum et al. 2008; Balazova et al. 2007). The expected total pollution load in the experiments were calculated (the total pollution load the subjects were exposed to when assessing the PAQ), then the distribution of PAQ scores were derived from subjects exposed to High, Normal and Low total pollution load respectively. A total of 784 subject scores formed the basis of the three PAQ distributions. The distributions were shown in Figure 6. As mentioned earlier the PAQ scores covers the whole voting range from -1 to 1, indicating the importance taking into account individual differences by using the distributions in performance calculations and not just an average value. In Figure 6 it is also seen that the even though subjects were exposed to air qualities with a high pollution load, above 25% score the IAQ as acceptable.

Figure 14 shows the derived dose-response relationship used in the last section of the suggested IAQ BN model. It consisted of data from three laboratory experiments (Wargocki et al. 1999; Wargocki et al. 2000b and Lagercrantz et al. 2000)
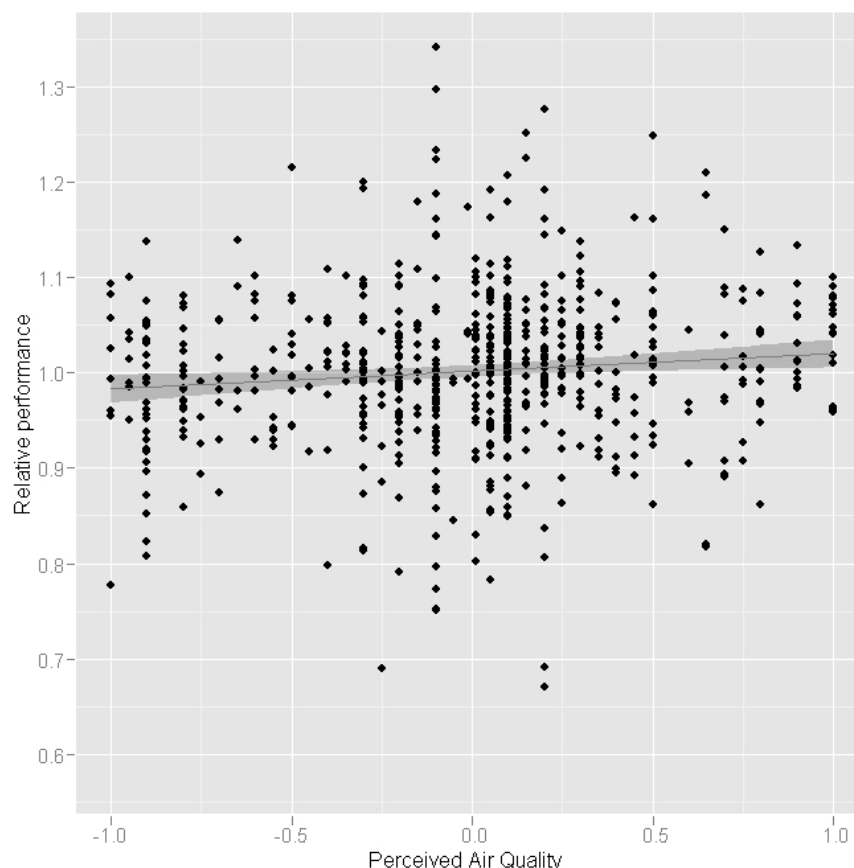
Fig. 14 *Linear regression fit between the percent dissatisfied with the air quality and performance as observed in climate chamber experiments. The relationship was based on experimental results from Wargocki et al. 1999; Wargocki et al. 2000b and Lagercrantz et al. 2000.*

A total of 360 subjective PAQ scores with corresponding performance measures were used to derive the model fit. The model fit after conversion to a maximum performance of 100% can be expressed as follows:

$$RP = 1.81 \cdot PAQ + 98.19 \qquad \text{(eq. 2)}$$

where,
RP is the relative performance and PAQ is the perceived air quality score.

In **Paper II** the consequences for the total building economy of improving the IAQ were also investigated, and these will be presented later in this section.

In summary the results of the IAQ BN model, a practical model that can be used to estimate the effects of the IAQ on performance have been developed. It incorporates the fact that people are affected differently when exposed to the same conditions and combined with a dose-response relationship between PAQ and performance, a realistic model have been developed.

Economic consequences of improving IEQ

In **Paper I** and **Paper II** different economic calculations were performed to document the economical consequences of improving the indoor environment. Table 7 summarizes the results of the calculations. The original calculation method documented in **Paper I** was redone so the same dose-response relationships and the same economic calculation method in both papers were used.

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Table 7: Summary of economic calculation documented in **Paper I** and **Paper II**

Source	Location	Main IEQ change	Payback time [year]	Performance increase		Reference case	Design case
				Temp	*Air*		
Paper I	Denmark	Temp	11.6	+0.2%	0%	Office from 1980-1990 CAV: 2.1 l/sm² Solar shading	+ Cooling + Night ventilation
Paper I	Denmark	Temp	15.5	+0.3%	0%		+ Cooling + Night ventilation + increased vent (3.2 l/sm²)
Paper I	Denmark	Temp IAQ	Infinite	-0.1%	-0.3%		- decreased vent (1.4 l/sm²)
Paper I	LA, USA	Temp	1.0	+1.3%	0%		+ Cooling + Night ventilation
Paper II	Denmark	Temp	7.2	0.1%	0.1%	Modern low energy office VAV: min 1.2 l/sm² Non-low polluting materials	+ Cooling
Paper II	Denmark	IAQ	1.1	0%	0.3%		+ Low polluting materials
Paper II	Denmark	IAQ	2.8	0%	0.3%		+ Increased vent (2.4 l/sm²)
Paper II	Denmark	IAQ	2.4	0.7%	0.7%	Older office, CAV: 0.5 l/sm²	VAV: 3.2 l/sm² Very low polluting materials

Table 7 shows that there seems to be a distinction between cases where the IAQ was improved and cases where the thermal conditions were improved. In a climate like the Northern European (represented by Danish weather conditions) the payback periods of investments in only improved thermal conditions appear to be relatively long (11.6 years, 15.5 years and 7.2 years). Indoor thermal improvements in a climate like the Southern Californian (represented by Los Angeles weather conditions) are on the other hand economic feasible, with a short payback period of only 1 year. In Table 7 it is also seen that the payback time on investments in IAQ improvements were relatively short (1.1 years, 2.8 years and 2.4 years), indicating that with the selected cases in a climate like the Northern European, IAQ improvements were more feasible than thermal improvements. The reason is the longer exposure duration to poor air quality as compared with the duration of exposure to poor thermal conditions in a climate zone like the Danish, but in a hot climate thermal improvements are still feasible due to the longer duration of exposure to poor thermal conditions. Besides the geographical location, building design, investment cost, running cost etc. are also very important and illustrates the importance of dealing with these issues already in the building design phase.

Results from Paper III

Paper III illustrated a practical implementation of the suggested thermal BN model. The model was used to compare the effects of temperature on performance in buildings with and without mechanical cooling. The adaptive comfort model suggested by de Dear and Brager

(1998) allowed occupants to be active in modifying their indoor environment as they preferred. This model was included in the recent version of ASHRAE standard 55 and EN 15251 for buildings with spaces without mechanical cooling, where thermal conditions are controlled primarily by the occupants through opening and closing of windows (ASHRAE 55-2005, CEN EN 15251-2007). Since the thermal BN model was based on the same data used to derive the adaptive comfort model, the distinction between the different thermal sensation perceptions, i.e. whether occupants were located in non-mechanically cooled building or in mechanically cooled buildings, was already incorporated in the conditional probabilities of the BN. Figure 15 shows the difference in the thermal sensation distributions between non mechanically cooled buildings and mechanically cooled buildings.
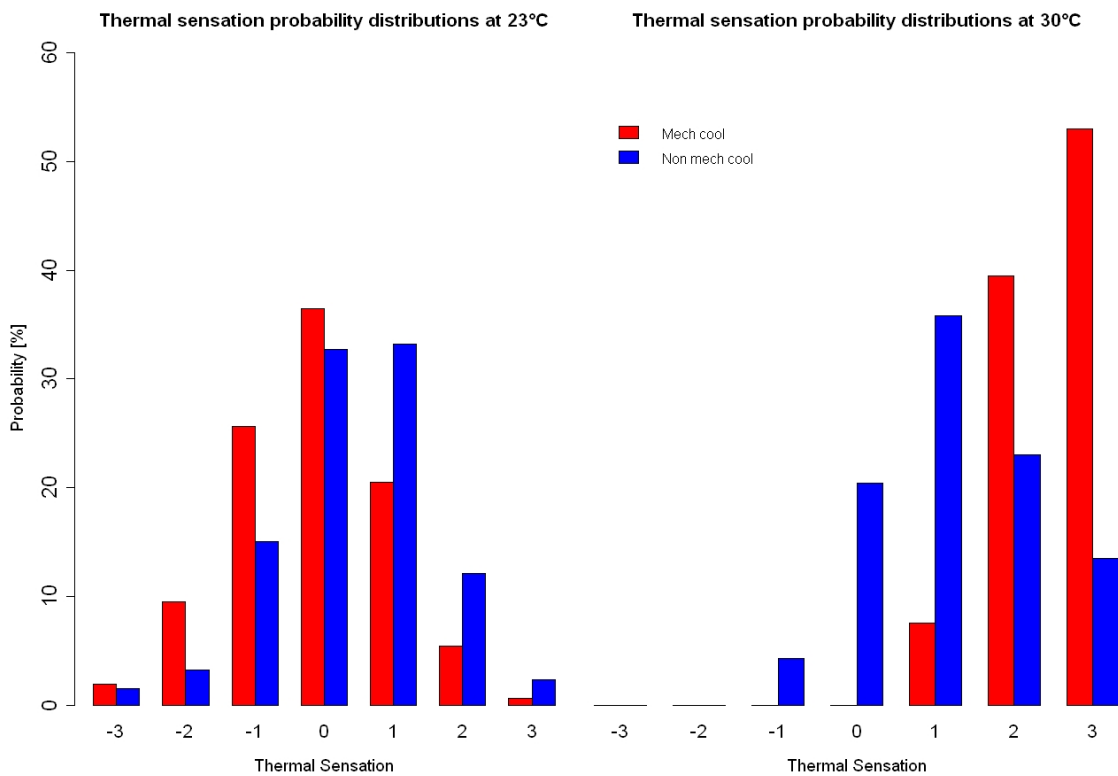
Fig. 15 *Difference in probability distribution between mechanically cooled buildings and non mechanically cooled buildings in two different temperatures (left figure 23°C and right figure 30°C)*

It is seen in Figure 15 in the left figure that the thermal sensation distribution between the two building types was relatively similar at 23°C. The right figure in Figure 15 shows that with higher temperatures, thermal sensation distributions in non-mechanically cooled buildings followed a Gaussian distribution at both temperatures with the mean shifted towards the warmer side. The probability distributions in mechanically cooled buildings shifted from a Gaussian distribution at 23°C to a more exponential distribution at 30°C.

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The result of this distribution difference shows how the thermal conditions may affect differently performance in the two building types. Using the dose-response relationship shown in Figure 12 with the above probability distribution it can be seen that at 23°C the difference in performance between building types was not large, but at 30°C the difference in performance was relatively larger, depending on building type. At 30°C in non-mechanically cooled buildings, occupant performance was not affected as much as the performance of occupants located in mechanical cooled buildings.

The findings from **Paper III** suggested that even though high indoor temperatures where observed in non-mechanically cooled buildings during summer in a temperate climate and all year in the tropics, compared to the thermal effects on performance in a well controlled mechanical cooled building the difference in performance was negligible.

Results from Paper IV

As mentioned earlier, validity was one of the three important factors that could influence the penetration ability of a tool to assess performance. In **Paper IV** a statistical method was suggested to be used for analyzing performance experiments investigating multiple responses at the same time (e.g. the outcome of several simulated office tasks). Since the potential effects of the IEQ on performance could be relatively small, it is important to analyze and interpret the results from statistical methods in the best possible way not to lose information.

The suggested method was based on a multiple linear mixed-effects model which besides the commonly achieved statistical information (estimated mean values, standard errors, T-values, significance etc.) also included information about correlation between responses. Correlation between e.g. two different performance tasks such as addition and text typing within subject level yields no useable information other than the expected (if a subject is performing well in one tasks it is likely that the same subject is performing well in another task and visa versa). On the other hand, if this correlation of tasks occurs between subjects information about the nature of the tasks can be achieved. Between subjects correlation of different tasks indicated that the tasks to some extent were measuring the same component skills of the subjects. Further, the statistical model suggested in **Paper IV**, was a mixed-effects model meaning that the random effects between subjects was included in the model term, making it a slightly more detailed model than just analyzing the effects of a specific predictor on a response.

Data used to form the basis of the statistical analysis in **Paper IV** was based on three experiments documented in Wargocki et al. (1999), Lagercrantz et al. (2000) and Wargocki et al. (2000b). The data was analyzed using a procedure called 'mlmmm' in the statistical software package R. The results showed that the between-subjects correlation between the two performances tasks addition and text typing was observed, indicating that in these experiments addition and text typing reflected some of the same component skills. Thus the paper was just an illustrative paper further analyses have to be done on similar experiments to see if this tendency is consistent. For future performance experiments it is practical to use as few performance tasks measuring the same component skills in order to increase the validity of the results. The probability of obtaining a falsely significant result of the effect of the indoor environmental quality on performance increases with the number of tasks. If, for example, five independent tests are made each with a 5% level of significance, the chance of getting at least one falsely significant result is about 22% in the case when there are no effects. Thus, fewer performance measures investigated with significant effects should indicate stronger results.

DISCUSSION

*"Whenever a theory appears to
you as the only possible one,
take this as a sign that you
have neither understood the
theory nor the problem which
it was intended to solve"*

- Sir Karl Popper (1902-1994)

Discussion

The present Ph.d.-project documents the development of a calculation method to estimate the economic consequences of improving the indoor environment. The method relies on dynamic building simulation and Bayesian Network calculations combined with dose-response relationships between thermal conditions and performance as well as with air quality conditions and performance. The suggested calculation method is still a beta version and should be implemented with this in knowledge.

In the following section a general discussion about the present Ph.d. topic will be presented focusing on future use of the tool to assess performance, future recommendations of the suggested models, limitations and commercial aspects of providing services, which include total building economy estimations using performance tools.

Future recommendations and management of limitations

Are the suggested performance models the correct ones?! The answer to that question is easy: Definitely not! But the models are probably a step in the right direction. Models can be evaluated by others either by validation or by falsification. The models suggested in this thesis are difficult to validate. Validation may imply huge studies with hundreds of subjects investigating the effects of thermal conditions on performance, and similarly with studies investigating the effects of IAQ on performance. Falsification of the presented models is somewhat easier, and documentation and description of the models presented to peers is the first step for others to be able to falsify, which will induce modification of the models. Three elements can be used to evaluate the validity of the BN models: i) Transparency, ii) Uniformity and iii) Verification of the probabilistic modelling (Friis-Hansen, 2008).

Transparency of the suggested BN models was among others achieved by visualising the BN in graphical representations. Figure 7 and Figure 13 show the suggested BN models and the causality can easily be evaluated by third parties. For example, should there be a causal link between gender and clothing in the thermal BN model?! Or are crucial variables missing in the IAQ BN model, which affects the pollution load in a building?

Uniformity deals with the development of the BN. It is important that the same level of detail is consistent throughout the network. If certain parts of the network are more detailed than other, maybe due to better knowledge about some specific causal links, it should be strived to obtain the same level of detail to the other causal relationships in the

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network. The uniformity of the thermal BN model can be considered consistent throughout the network. All variables except the performance variables were a part of the same large dataset provided from the adaptive thermal comfort studies. The same uniformity was not found in the IAQ BN model. Here, a mixture of model estimations and observed data formed the basis of the BN.

The possibility of verifying the probabilistic modelling is also an important evaluation element of the BN models. To some extent, the implementation of evidence in a BN model and the corresponding output should be verifiable in reality. For example, in the thermal BN model the direction of the effects (either positively, negatively or stagnant) of exposure to temperature should be the same in both model and reality. In the present BN models the input of an improved IEQ induces an increment in performance as expected. This observation is not a verification of the entire model, but it advocates for a model estimating something expectable. The unanswered question is then if the magnitude of the effects estimated in the model is similar to reality?!

In the following some selected limitations of the suggested performance calculations are listed. In future development of performance models it is recommended that these limitations be addressed.

The data used to develop the BN models have been the best available. Especially, the temperature BN model was based on thousands of different indoor environment observations. This model shows its flexibility e.g. by distinguishing between naturally ventilated buildings and mechanically ventilated buildings in the distribution of thermal sensation scores. The data material that forms the basis of the IAQ BN model was not as comprehensive, though judged as sufficient to propose and develop the IAQ BN model. In the future, further studies investigating the distribution of PAQ scores dependant on pollution level could be conducted and the results from these experiments implemented in the IAQ BN model.

In **Paper I** and **Paper II** it was mentioned that in order to improve the suggested BN models the dose-response relationships should be investigated in more detail. The applied dose-response relationships can be considered as conservative estimates of the relationship between perceived indoor environment and performance. Compared to the temperature/performance dose-response relationship documented in Seppänen et al. (2005) (shown in Figure 2), where a temperature above 30°C corresponds to a performance decrement of over 10%, a thermal sensation perception at +3 (maximum at the thermal

sensation scale corresponds to the thermal condition perceived as hot) results in a performance decrement at 2.5%. Regarding the IAQ/performance, the dose-response relationship was also more conservative in its estimates of the effects of IAQ on performance compared to previously documented relationships between IAQ and performance (e.g. Wargocki et al. 2006). Here it was reported that per 10% dissatisfied with air quality a 1.1% decrement in performance was observed. Converting the IAQ dose-response relationship derived in **Paper II** to percent dissatisfied results in a 0.3% decrement in performance per 10% increase in percent dissatisfied. Since this effect is linear, a factor 4 difference in performance between the two performance measures in the extreme end of the scale was achieved. A difference of the same magnitude was seen between the two temperature performance relationships. Even though conservative estimates of the effects of IEQ on performance were implemented in the BN models, the economic analyses showed that depending on climatic zones, improvements in IEQ was still economically feasible. But it is recommended that further studies investigate and develop dose-response relationships between IEQ factors and performance. These relationships can then be implemented in modified versions of the BN models.

In conjunction with a development of better dose-response relationships between IEQ and performance, it could be valuable to gain more information about the temporal relations between IEQ exposure and performance. At present time a constant effect of IEQ on performance is assumed, meaning that occupants in the first hour of exposure are equally affected by the IEQ as in the last hour of exposure. It is even likely that the effect of IEQ on performance is not constant, but positively correlated with the exposure time. Further studies investigating this effect are needed to improve future performance models.

Future implementation of tools to assess performance
The present performance calculations from building design to calculation of the total building economic impact of the selected building design consists of several stepwise processes as seen in Figure 11. First dynamic building calculations determine the indoor environment in a selected period (e.g. work hours in a year) which is saved in a text file. Furthermore the text file is then imported into a MATLAB procedure which, based on the two generated BN models (thermal and air quality models), estimates performance indices for both IEQ parameters. These performance indices are for each building design manually transferred to a spreadsheet where the economic calculations are performed. These different procedures are not user friendly and can in practice not be handled by any other than the program developer. An ideal solution would be to integrate all these procedures in one software program handling the dynamic calculations, the BN model calculations and

the economic calculations at once. Figure 16 shows schematically a drawing of such an integrated program.
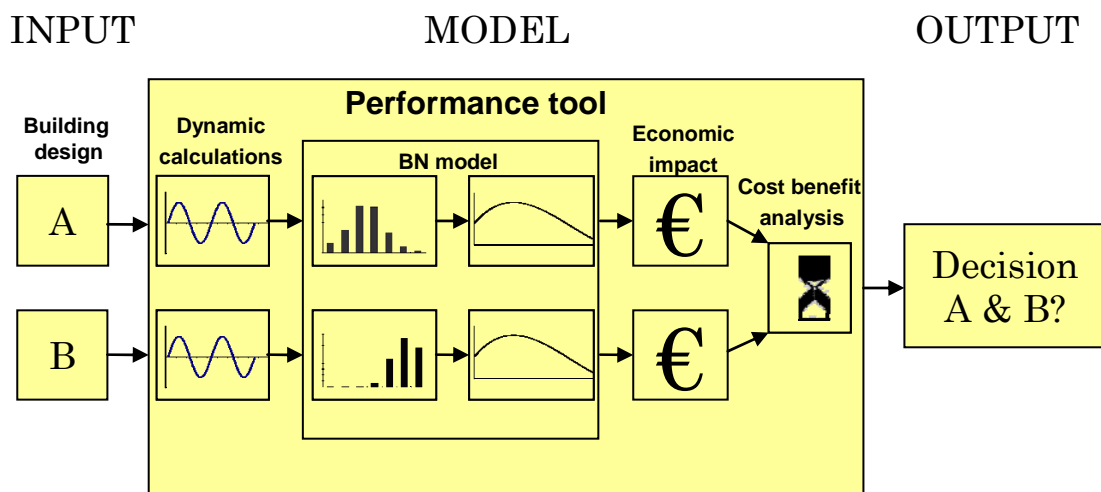
Fig. 16 *Schematically drawing of the integrated tool to assess performance*

The initial steps of integrating the suggested calculation method in an existing program have been done. A program called iDbuild (iDuild, 2008) was developed at the Department of Civil Engineering at the Technical University of Denmark. This program is applicable in the building design phase because it estimates the effects of changes in the building design on indoor temperature, air quality, day light level and energy consumption. It performs simultaneously three building simulations based on parameter variations in the building design (e.g. changing the window from a reference height of 1.2 meter to 1 meter in variation one and to 1.4 meter in variation two). iDbuild is like the BN models written in MATLAB code, which promotes easy integration of the two elements. This was done in a test version of iDuild, and the only step missing in order to have a fully integrated performance tool is the economic calculations. A database needs to be developed with different construction prices (e.g. what is the cost of installing a window that is 1.4 meter high compared to 1.2 meter and what is saved by choosing a smaller window?) and an input module for all the economic assumptions needs to be created (salary, interest rate of loans, energy prices and other running costs etc.).

The performance tool could also be applicable in building life-cycle assessment software programs. In such programs, the impact of different decisions regarding the design of a building are evaluated over the life time of the product. Being able to include the performance of occupants in life-cycle cost calculations would be very useful for both clients and consultants.

Commercial and environmental aspects of the performance tool

The present thesis has not focused much on the ownership of the buildings. Because the majority of the large office buildings are not owner-occupied neither the employers nor the employees have in reality much saying of how a new building is going to be designed or which improvements are going to be made in an existing building. Developers and investors construct large office buildings with the purpose to let out the space. There is a challenge to mastermind the process of describing to the developers that by creating buildings, which are sustainable for the environment and for the occupants, in the end also will increase the value of the building. In today's knowledge society it can be important for the tenants to be able to attract the best employees and to keep good ones. This can be done by offering interesting work assignments, the right means, good co-workers, possibility to evolve and the comfortable and inspiring work conditions. A part of the comfortable and inspiring work conditions can be provided by the building owner typically on the tenants' expenses, by an increased rent. A performance tool could help to decide whether or not tenants will accept an increased rent on behalf of an optimal and productive indoor climate.

Especially if new buildings are going to be constructed, using a performance tool early in the design phase has some economic advantages. But a more profound advantage, of the possibility that the engineers become an active part of designing the buildings, could be the potential environmental impact. Buildings in Europe consume 40% of the total energy consumption, which imply a possible immense energy saving potential, and here a performance tool could work in two directions: It will help control that energy savings do not deteriorated the indoor climate, which happened during the oil crises in the 70'ties and 80'ies, because the saving gained from energy reduction will in many cases be surpassed by the losses due to a decrement in worker performance. On the other hand, if a performance tool can prompt an earlier involvement of the engineers in planned new constructions, substantial energy savings can also be obtained. After 2% of the total construction budget is used, over 80% of the expenses have already been allocated. This implies when the engineers, at a later stage in the design process, are conducting energy calculations, the possible changes are minimal, often leaving room to only sub-optimal design solutions. An integrated design process with early involvement of the engineers together with architects and building owners induces more energy and indoor climate optimal building designs. In the optimal designed building, architecture, economy, energy consumption and indoor climate comes together in a sustainable concept, which hopefully is beneficial to the environment, the employees and the employers.

CONCLUSIONS

"Sometimes I whish I
was a statistician – but
only sometimes"

- Kasper Lynge Jensen

In the present summary of the Ph.d.-thesis "Development of a model to estimate the economic implications of improving the indoor climate" the following can be concluded:

About the economic consequences of changing the indoor climate:

- In the simulated studies following elements were found to influence the total building economy (other elements exists but were not analysed in the present studies):
    - Indoor climate factor (temperature or air quality)
    - New building or renovation
    - Building design
    - Geographically location
- Improvement of the thermal conditions in modern, well-designed low energy buildings located in a Northern European climate seemed not to be economically feasible. (**Paper II**)
- Investment in improving the thermal conditions in buildings located in a hot climate like the Southern Californian may have short pay-back periods and be very feasible. (**Paper I** and **Paper II**)
- Investment in improving the air quality conditions can in most cases be economically justified. (**Paper II**)

About the effects of indoor environment quality on performance:

- In general, the effects on performance of temperature and air quality were relatively small. The derived dose-response relationship between IAQ and performance as well as the dose-response relationship between temperature and performance were more conservative compared to previously derived relationships. (**Paper I**, **Paper II** and **Paper III**)
- Exposure to relatively high temperatures in a non-mechanical cooled building has in most cases a negligible influence on occupants' performance, compared to the effects of comfortable temperatures in a mechanically cooled on performance. (**Paper III**)

About the Bayesian Network models:

- A novel method to link indoor variables with performance has been suggested. The method relies on Bayesian Network theory. (**Paper I** and **Paper II**)

About analysing performance experiments:

- Inclusion of the correlation between multivariate responses could provide valuable information in the interpretation of the statistical analysis. In indoor climate research information about the correlation between different tasks in performance experiments could induce that tasks measuring the same component skills were reduced, so the chance of a falsely effect result was diminished (**Paper IV**).

Concluding remarks: Even though the effects of the IEQ on performance may be relatively small, investment in improving the IEQ were in most of the investigated situations economically justifiable. To avoid increased energy consumption in buildings, it is therefore important that IEQ improvements are thought into a project early in the building design phase, so passive or low energy solutions are implemented in the building, instead of energy demanding suboptimal technical solutions later in the building design phase. Estimation of the economic consequences of improving the indoor climate varies from building to building, and therefore the suggested performance calculations have to be used from case to case.

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Appendix A

The Industrial PhD programme

The student is employed by a company, and timeshares 50/50 between the university and the company. Approximately 50 % of the company's expenses are reimbursed by the Ministry of Science, Technology and Innovation. The student is enrolled in a Ph.d. graduate school at a University, with the same requirements as for an ordinary Ph.d. plus a business course and a business report. The obligations regarding disseminating knowledge are the same as for an ordinary Ph.d., except that the student will do no teaching.

The purpose of the Industrial PhD programme is to educate scientists with an insight in the commercial aspects of R&D, increase R&D and innovative capacity in private companies and to build networks disseminating knowledge between universities and private companies.

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PAPER I

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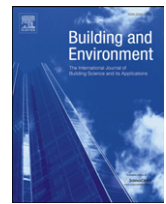
A Bayesian Network approach to the evaluation of building design and its consequences for employee performance and operational costs

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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.

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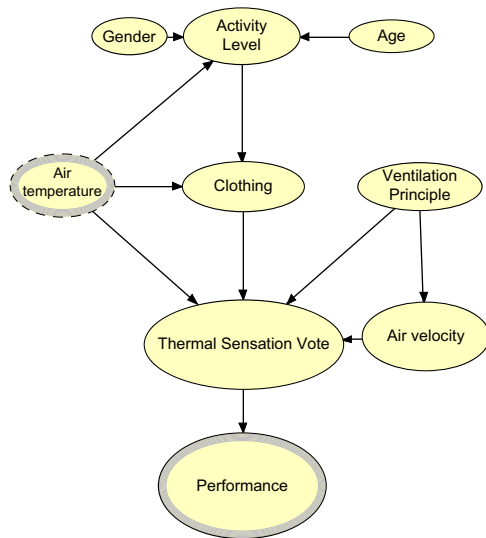
Fig. 1. A Bayesian Network showing the causal relationship between different temperature-related variables and mental performance of office workers.

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:

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

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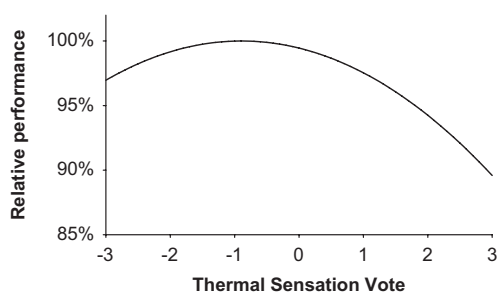
Dose–response relationships between performance and other indoor parameters such as air quality and acoustics in offices have also been developed [2,23,24]. These relationships will not be discussed in this paper.

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	$U_{\text{value-façade}} = 0.28$ W/m^2
Window area	5.3 m^2
Window type	$U_{\text{value-window}} = 2.6$ 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.

Acknowledgements

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PAPER II

Feasibility study of indoor air quality upgrades and their effect on occupant performance and total building economy

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Abstract

Based on the results of building energy and indoor environment simulations, dose-response relationships between two IEQ parameters and performance, and a Bayesian Network representation of the links between relevant building characteristics and performance, this study attempted to quantify the effect on performance and total building economy of improving the indoor air quality and the temperature conditions. Using data from previously published experiments, perceived air quality distributions and a dose-response relationship between perceived air quality and performance were developed. Four different designs of a modern low-energy office and two in an older office building were simulated and the effects of the air quality and the thermal environment on performance were compared and included in the economic evaluation of costs and benefits of investing in improvement of the indoor environment. The shortest pay-back period and the best feasibility of investing in indoor environment upgrades were achieved when non-low-polluting materials were replaced with low-polluting materials. An increase of the ventilation rate also resulted in a relatively short pay-back period, even though this means of upgrading also resulted in higher energy consumption. The analysis of the economic consequences of improving the quality of indoor environment indicated that even though a relatively modest increase in performance was achieved, the investment necessary to improve the air quality could be justified.

Key words

Performance, Model, Air quality, Bayesian Network, Total Building Economic, Productivity

Practical Implications

The present study suggest a calculation method which can estimate the effects of poor air quality on performance using a Bayesian Network model combined with dynamic building simulation and a relationship between perceived air quality and mental performance. The suggested performance model can be used is the design phase of buildings by architects, engineers and developers and has the potential for substantial changes in the importance on the indoor climate is viewed upon, since economics are related to the quality of the indoor environment.

Introduction

Recent studies on indoor climate and occupant performance have focused mostly on assessing effects of temperature or air quality on office or school work (e.g. Federspiel et al. 2004; Wargocki et al. 2004; Wargocki and Wyon 2007). Models to estimate the economic consequences for a corporate organisation of different building design alternatives, uncomfortable indoor temperature or poor air quality are lacking so far, even though the economic potential of such models could be immense. Models enabling the estimation of the feasibility of investment in improved indoor climate, in terms of both energy consumption and occupant performance, would be instrumental in the early design phase in assessing the consequences of a certain building design and promote a better and more qualified design process. Renovation of poorly designed existing buildings is another field where such models could be useful for assessing economically the benefits of indoor environment upgrades.

Jensen et al. (2009) presented a novel method to assess total building economy with different design decisions as input. The method was based on a Bayesian Network approach in combination with building simulation results and a dose-response relationship between indoor temperature and the mental performance of office employees. The study introduced a Performance Index (Π), which was a weighted annual index that compared the impact of different building designs on occupant performance. The method uses a Bayesian Network (BN) approach to simulate individual differences in occupant behaviour and sensation, thus increasing the reality in the estimation of the effects of temperature on mental performance. Until now, no method of this nature has been developed for other indoor climate parameters.

Studies investigating the effects of temperature and air quality on mental performance are scarce. In their literature review, Seppänen et al. (2006) summarized the most important studies regarding the effects of ventilation on performance. These studies included experiments carried out in the laboratory and in field settings. A meta-analysis was performed and a dose-response relationship was determined between ventilation rate and relative performance, indicating that increased ventilation rates may increase occupant performance by up to 3-4 %, depending on the initial ventilation rate.

However, ventilation rate *per se* may not be a good predictor of the indoor air quality when other pollution sources than the occupants are present. Occupants' perceptions may be a far better input to the estimation of performance in indoor environments of different quality. Wargocki et al. (2000a) presented a correlation between the percent of people dissatisfied

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with the air quality (PD) and the relative performance as observed in three different and independent studies. This relationship estimates the relative performance in the range 25-70% PD and was also documented in Wargocki et al. (2006). Figure 1 shows the relationship.
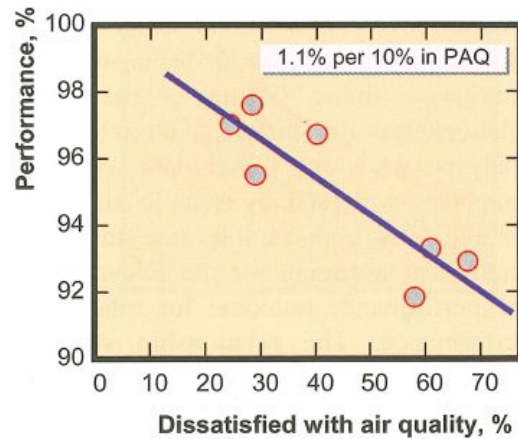
Fig. 1 *Dose-response relationship between percent dissatisfied due to poor air quality and the relative performance of office work (from Wargocki et al., 2006)*

The relative influence on performance of exposure to poor indoor air quality (IAQ) is likely to dominate the exposure to uncomfortable indoor thermal conditions, since the duration of exposure to poor IAQ could be considerably longer, depending on the climate region and building design. Especially in non-tropical regions, where outdoor temperatures vary widely between (and sometimes within) seasons, the exposure duration to hot periods is typically relatively short. The outdoor temperature in Denmark, for example, is only above 26 °C for 1% of the time during typical office hours in an average year. Even though solar radiation, in addition to outdoor temperature, also affects indoor temperatures, the potential risk of overheating may be limited to a very short period. With non-low-polluting building materials and other interior polluting materials, insufficient ventilation, or poor maintenance of the ventilation system, the potential exposure duration to poor IAQ can be up to 50-100% of the occupancy.

If office work performance was significantly affected by the air quality, a potential large effect of poor IAQ on building economy could be expected. Wargocki et al. (2006) described several examples of investment in indoor climate improvements, all demonstrating positive yields. This was mainly due to the fact that the area-specific cost incurred in employee salaries is a factor of 80-100 that of the energy cost, and that investment in indoor climate improvements is normally financed by loans with low interest rates. Thus, the resulting

economic benefit of even a relatively small increase in productivity may be greater than the extra cost.

This study uses the same methodology as described in Jensen et al. (2009), but applied to indoor air quality rather than temperature. The methodology focuses on office buildings with mechanical ventilation. First, a Bayesian Network model to represent and estimate how the indoor environment affects the distribution of occupants' air quality perception is suggested. In combination with a new dose-response relationship that quantifies the effect on performance of perceived air quality, a Performance Index for air quality is calculated. Finally, the relative influence on performance of the thermal conditions and air quality is evaluated and an analysis of the feasibility of investment in indoor environment upgrades is performed.

Method

A Performance Index (Π) is suitable for evaluating the impact on occupant performance of different building designs. Such a Performance Index is described in Jensen et al. (2009) as:

$$\Pi = \sum_i w \cdot BN(E_i)$$

(eq. 1)

in which, i is the time segment for which the performance is calculated (e.g. working hours during a year), w is a weighting factor for each time segment ($w = 1/i$), E_i is the environmental input parameter (e.g. air temperature or air quality) in time segment i, and $BN(E_i)$ is the performance output from the Bayesian Network as a function of E_i.

The duration of the time segment can be chosen to meet the decided accuracy of the calculation. In mechanically ventilated office buildings, temperatures may vary during the day, while changes in the air quality are most likely less frequent.

Perceived Air Quality (PAQ) Performance Index
The performance index for perceived air quality could be expressed from eq. 1 as:

$$\Pi_{PAQ} = \sum_i w \cdot BN(PAQ_i)$$

(eq. 2)

in which PAQ for a given time segment is the perceived acceptability of the air quality voted on the pseudo-continuous acceptability scale that ranges from -1 to 1 with a gap in

the middle (Figure 2) The estimation of the PAQ as input to the estimation of the performance index is described in the following.

How do you assess the air quality?

Pay attention to the dichotomy between acceptable and not acceptable

— Clearly acceptable

— Just acceptable
— Just not acceptable

— Clearly not acceptable
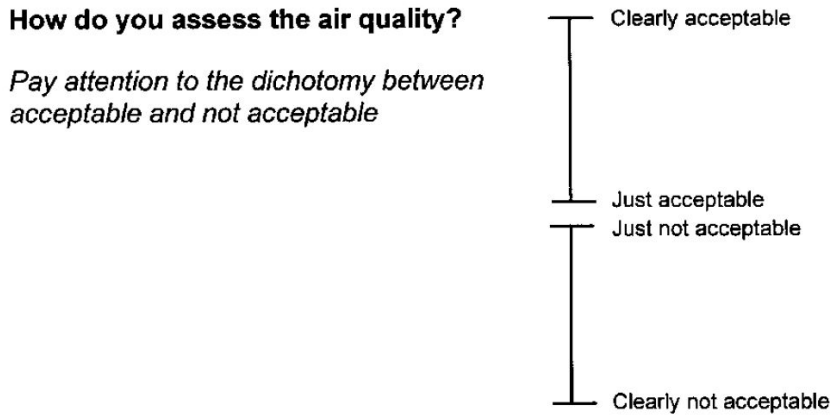
Fig. 2 *Pseudo-continuous acceptability scale to assess the perceived air quality.*

Bayesian Network to estimate perceived air quality

Several studies have shown that temperature and humidity affect people's perception of air quality (Fang et al.1998; Toftum et al. 1998; Fang et al. 2004). To limit disturbing interaction effects between the air quality perception, temperature and humidity, one assumption underlying the developed BN is that the air temperature and relative humidity levels in the particular office environment is restricted to the normal comfort range (22-26 °C and 30-60% RH) (CR-1752, 1998).

The proposed BN model is composed of acyclic relationships between indoor environment variables related to the air quality in a building. The nodes (balloons) represent discrete random variables and the arcs between the nodes represent a probabilistic relationship. Each node has a specific number of discrete states, which are used to condition the probabilistic relationship between nodes. If the state of a node is known, the probabilistic propagation is used to infer the probability of the states of other variables. Models including human decision-making and human influence are subject to many uncertain variables. The BN model is useful for dealing with such uncertainty because it can be modelled by the probabilistic "weight" of the states, making the BN model a good predictor of a realistic world model without the limitations of too many assumptions and constraints. [Jensen, 2001]

A BN model that enables the estimation of perceived air quality and its effect on performance in an office environment is suggested in Figure 3. The BN model consists of three sections: 1) estimation of the total pollution load on the indoor air, 2) estimation of a

PAQ distribution influenced by the estimated pollution load, and 3) a relationship between PAQ and performance.
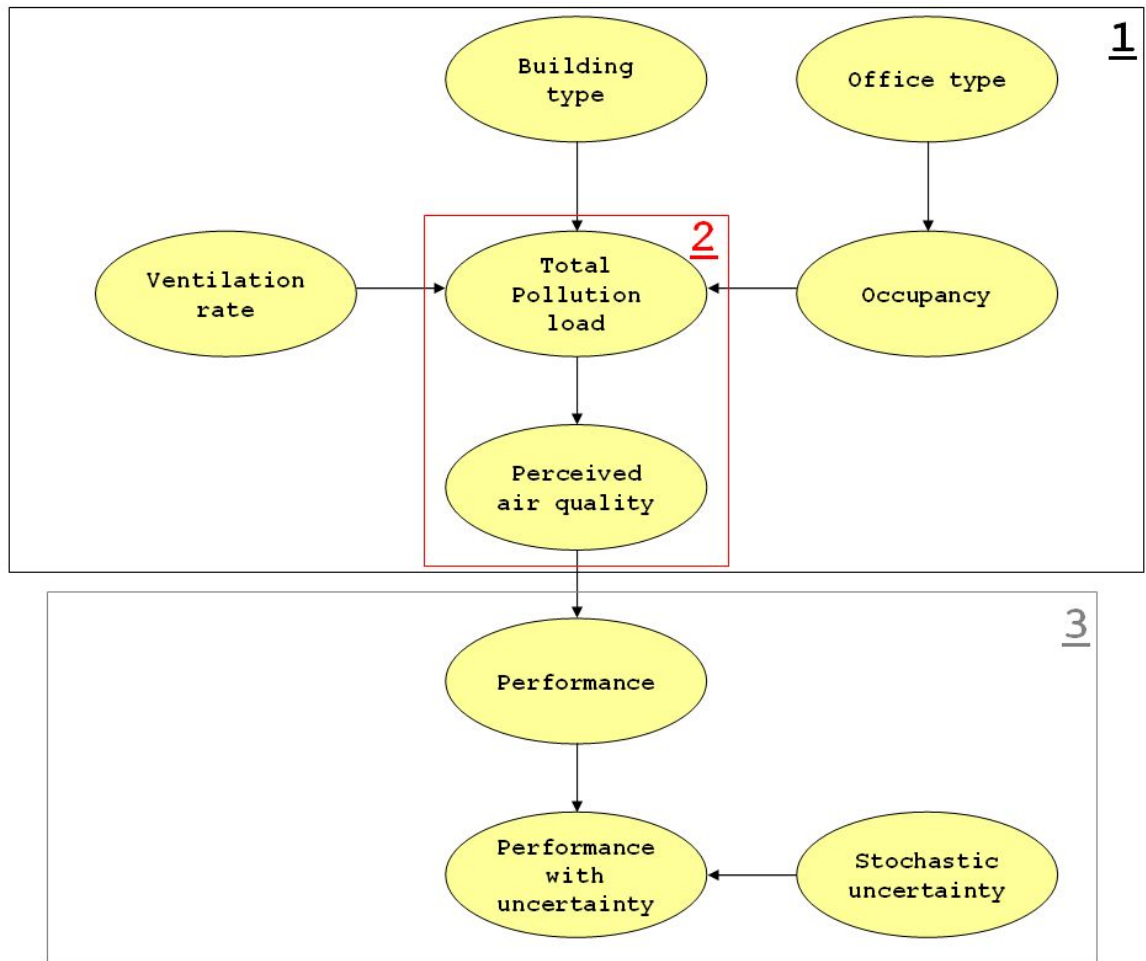
Fig. 3 *Bayesian Network model showing the relationship between different air quality-related variables and the mental performance of office workers.*

The suggested model was constructed so as to be relatively straightforward to implement in practice. A BN model is a dynamic model and variables can be added later if a more detailed or different model is preferred. A description of the nodes and their possible discrete states are shown in Table 1.

Table 1 Nodes and states of the Bayesian Network model

Variable	State	Note
Building type	Very-low-polluting, low-polluting, non-low-polluting, polluting	Type of building according to CEN 15251 and an additional category "polluting" (existing offices)
Occupancy	-inf - 2, 2-4, 4-6...16-18,18-inf	Floor area available to each occupant (m2/person)
Office type	Single office, Open plan office	
Ventilation rate	0-0.5, 0.5-1, 1-1.5, 1.5-2, 2-inf	Ventilation rate in l/s m²
Total Pollution Load	High, Normal, Low	High: > 25% PD, Normal: 15-25% PD, Low < 15% PD
PAQ	-1- -0.8,..0-0.2 ..0.8-1	Interval of PAQ (acceptability) from -1 to 1 in ranges of 0.2
Performance	-inf-94, 95, 96, 97,98,99,100	Relative performance decremented from 100% maximal performance (%)
Stochastic uncertainty	-inf -1,-1--0.75,…0.75-1,1-inf	A normal distribution with mean 0 and variance = 0.1
Performance with uncertainty added	-inf-94, 95, 96, 97,98,99,100	A stochastic error added to the relative performance

The variables included in frame #1 (Figure 3) of the suggested BN model affect the pollution load in a room. These variables differ between buildings (or between simulations of different cases) and should therefore be considered as input to the model and can be decided by the practitioner. The pollution load measured in percent dissatisfied in three categories is affected by the state of three variables: building type (e.g. low-polluting building), occupancy (e.g. m2 floor area available to each occupant) and the ventilation rate. For example, if the building type is non-low-polluting, the ventilation rate low, and the occupancy high, the probability of the pollution load of the building/room being high increases compared with a low-polluting building with high ventilation rate and low occupancy.

The variables included in frame #2 (Figure 3) show the relationship between pollution load and perceived air quality. The perceived air quality distributions for each level of pollution load (High, Normal and Low) are derived from approximately 784 subjects voting in 6 different air quality experiments conducted in climate chambers (Wargocki et al. 1999; Wargocki et al. 2000b; Lagercrantz et al. 2000; Wargocki et al. 2002b; Toftum et al. 2008;

Balazova et al. 2007). In these experiments subjects were exposed to a given pollution load and voted on the acceptability scale shown in Figure 2. Under each exposure in each experiment, the pollution load in the room was estimated with and without polluting materials present and bioeffluents present in the air. The pollution load estimated for the room depended on the materials present and the ventilation rate in the experiment. If the estimated pollution load resulted in more than 25% dissatisfied with the air quality (PD), the condition was labelled as "High", between 15-25% as "Normal" and below 15% as "Low". Figure 4 shows the distribution of perceived air quality votes as a function of the estimated room pollution load. At all three pollution load levels, subjects covered the whole range of acceptability votes, which shows the diversity between individuals and emphasizes the strength of including the distribution of air quality votes in the assessment of how air quality affects performance.
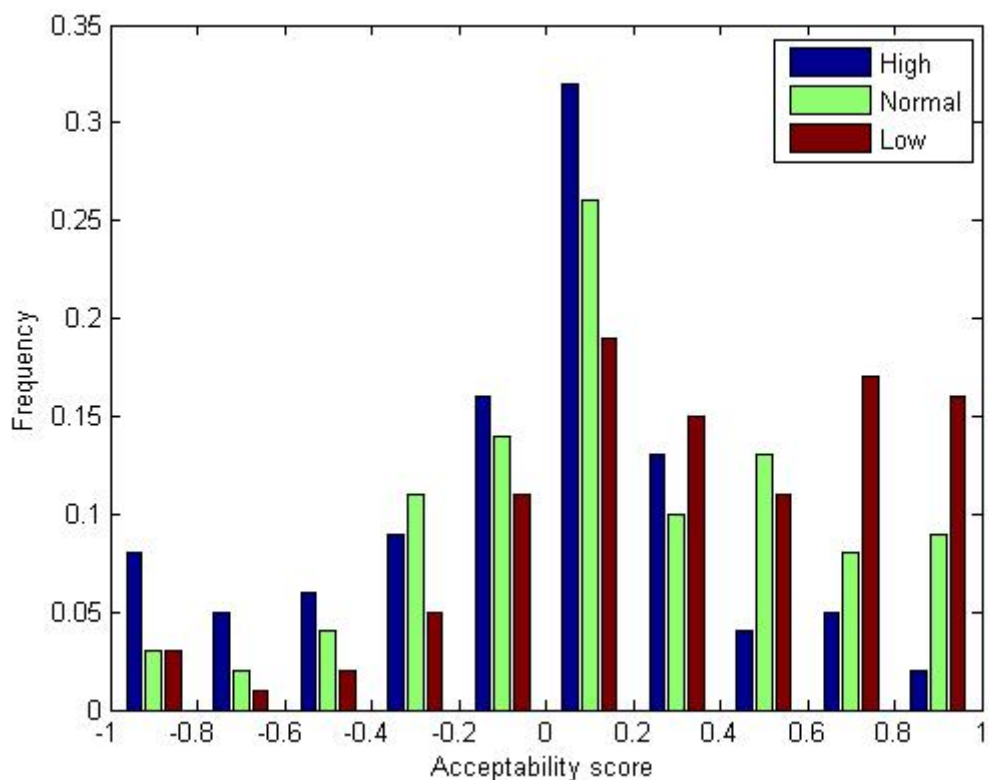
Fig. 4 *Distribution of PAQ votes on the -1 - 1 acceptability scale with the estimated states of the pollution load.*

Frame #3 in Figure 3 shows the relationship between perceived air quality and performance, based on the obtained dose-response relationship. The dose-response relationship was derived from a linear regression model based on data from three experiments (Wargocki et al. 1999; Wargocki et al. 2000b; Lagercrantz et al. 2000)

involving a total of 360 subjective air quality votes and corresponding performance measurements. Each of the three experiments included 30 female subjects exposed to different air quality conditions (either with pollution source absent/present or ventilation rate high/low). The dose-response relationship was derived from two selected performance tests commonly used to measure effects of the indoor environment on the performance of office work, namely addition and text typing (Wargocki et al. 1999). Figure 5 shows the linear regression based on the adopted data and a 95% confidence interval around the estimated model.

The statistical program R was used for the statistical analyses [R core team, 2004].
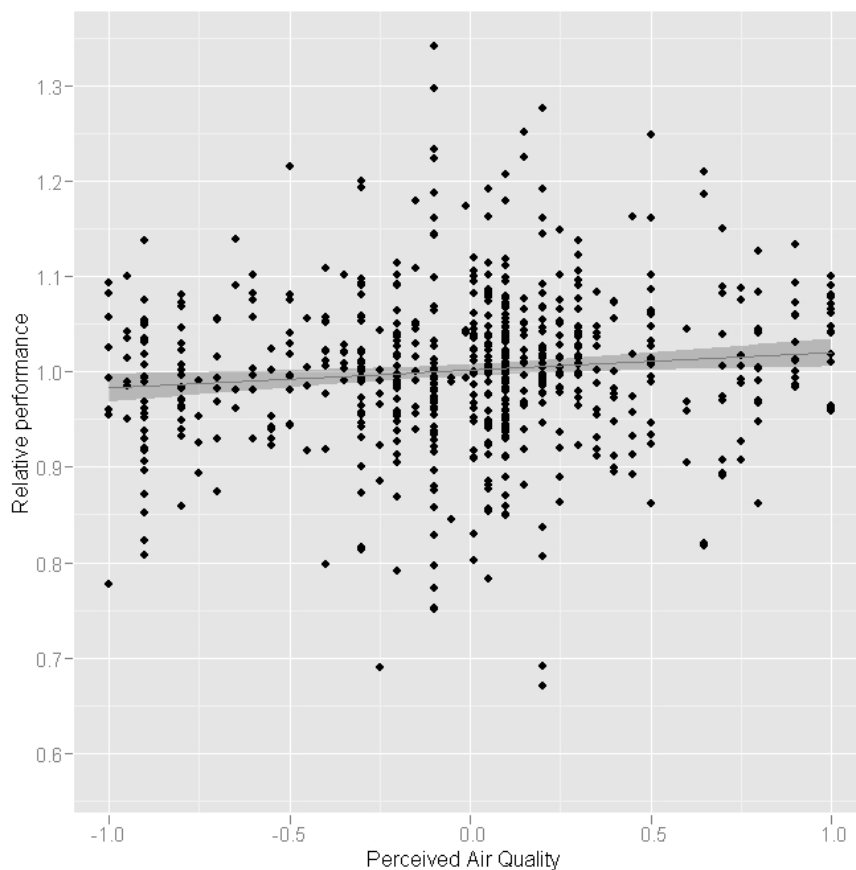
Fig. 5 *Linear regression fit between the percent dissatisfied with the air quality and performance as observed in climate chamber experiments. The relationship was based on experimental results from Wargocki et al. 1999; Wargocki et al. 2000b and Lagercrantz et al. 2000.*

Although the data points were rather scattered, the slope of the regression model was significantly larger than zero ($p < 0.05$). After displacing the model to a maximum performance of 100% at PAQ = 1, the model equation could be written as follows:

$$RP = 1.81 \cdot PAQ + 98.19 \qquad \text{(eq. 3)}$$

where RP is the Relative Performance (optimum is 100%; lower values can be seen as a decrement in performance). PAQ is the perceived air quality voted on the acceptability scale.

Acceptability was converted to percent dissatisfied to compare with the relationship shown in Figure 1 using the following equation [Clausen, 2000]:

$$PD = \frac{e^{-0.18-5.28 \cdot ACC}}{1+e^{-0.18-5.28 \cdot ACC}} \cdot 100 \qquad \text{(eq. 4)}$$

where PD is the percent dissatisfied with the air quality and ACC is the vote on the pseudo-continuous acceptability scale (Figure 2).

The linear dose-response model resulted in a decrement of performance of 0.3% for an increase of 10% dissatisfied due to poor air quality, which was a more modest influence of PAQ on performance than that observed by Wargocki et al. (2006).

The two final nodes in the BN model in frame #3 in Figure 3 indicate that a stochastic uncertainty was added to the dose-response relationship between PAQ and the relative mental performance. The uncertainty term was added to compensate for the deterministic nature of the dose-response model. The uncertainty term followed a normal distribution with $\mu=0$ and $\sigma^2 = 0.1$.

Input to the Bayesian Network model
The purpose of the suggested methodology of using a Bayesian Network model combined with a dose-response relationship between PAQ and mental performance, was to compare the impact on total building economy of different design scenarios. Normally dynamic building simulation programs are used to estimate the indoor environment end energy consumption with different building designs. At this stage in the design process, easy changes in the construction or materials used in the building can be made and the impact on the thermal and air quality conditions can be re-estimated along with the energy use of the building.

In the current study, the input to the BN model was output from the building simulation program BSim 2002 (Wittchen et al. 2005). Additional inputs may be building-specific and

their effects are not simulated (e.g. frequency of filter changes). For the sake of evaluating the relative influence of the thermal and PAQ performance indices, an office scenario was simulated. The specification (geometry, materials, etc.) of the office was imported into the building simulation program and the output then exported to a MATLAB routine which incorporates the BN model.

Next, to estimate the economic consequences of investing in improved IAQ, a reference and several modified building designs were compared in terms of their effect on the building economy.

IAQ Performance Indices were used to estimate the total building economy of the different designs by comparing the energy consumption, the expenses incurred in improved air quality and the income resulting from higher occupant performance.

Modification of the Thermal Performance Index

The BN model to calculate the thermal performance index has been described in detail in Jensen et al. (2009). The BN model used in this study was somewhat modified compared to that described in the earlier study. One important modification was a revised dose-response relationship between thermal sensation and relative mental performance. The modified dose-response relationship was suggested after additional data from recent experiments were available. The experiment was a laboratory experiment in which 32 female subjects were exposed to four different thermal conditions (from 23.5 °C to 29°C) (Wargocki, 2008). They performed different tasks simulating office work, of which addition was selected to be used in the current study in accordance with the results included from other studies. Altogether, 578 subjective votes of thermal sensation and the corresponding performance measurement form the basis of the adjusted dose-response model. The relationship can be described as follows:

$$RP = -0.0029 \cdot tsv^2 - 0.0034 \cdot tsv + 0.999 \qquad \text{(eq. 5)}$$

where RP is the *Relative performance* (optimum is 100%; lower values can be seen as a decrement in performance), and tsv is the *thermal sensation vote* (-3 to +3 on the seven-point thermal sensation scale).

In accordance with the suggested air quality BN model, a stochastic uncertainty term was also added to the thermal BN model.

Simulation scenarios

In this study, two different scenarios were simulated. The scenarios investigated the relative influence of the thermal and air quality conditions on performance by evaluating the two performance indices and the corresponding economic consequences with differing indoor environment designs. The first scenario, a design scenario, focused on the thermal and air quality conditions in a modern office building with and without mechanical cooling. The second scenario was a renovation scenario, which investigated the effect of improving the air quality. The output from the dynamic simulation program included hourly values of temperature, energy consumption and ventilation rate during the simulated period (one year). The energy consumption was used in the economic calculations, the ventilation rate in the air quality BN model, and the temperature in the modified thermal BN model.

Design scenario

In the design scenario an office in a modern, low-energy building was simulated. The office was a corner office with windows facing south and west. It had a floor area of 44 m² and was occupied by six employees. Table 2 shows the specific building characteristics.

Table 2 Building characteristics input for the simulated office.

Floor area	44 m²
No. of occupants	6
Ventilation Type	Mechanical (VAV)
Façade area	25.2 m²
Heat transmission coefficient façade	$U_{facade} = 0.14$ W/m²K
Window area	18 m²
Heat transmission coefficient window	$U_{window} = 1.14$ W/m²K
Location	Copenhagen, Denmark

Three different cases were compared with a reference to study the effect on performance of the temperature or the air quality. Table 3 shows the reference and the different cases.

Table 3 Overview of the different simulated cases.

Reference	Non-low-polluting building
Case 1	Cooling
Case 2	Low-polluting materials
Case 3	Increased ventilation

In the reference situation, the mechanical ventilation system was a variable air volume (VAV) system, which supplied a minimum ventilation rate of 1.2 l/s m² and a maximum ventilation rate of 3.6 l/s m² (corresponding to an air change rate of 1.9 h⁻¹ and 5.7 h⁻¹). In order for the ventilation system to supply more outdoor air, the indoor air temperature had to be above the temperature set-point of 21 °C during winter and 25 °C during summer. Otherwise, the system would sustain the minimum ventilation rate during the working

hours. In all simulations, the system had a heat recovery unit with an efficiency of 85% installed. A cooling coil of 12 kW was installed in the ventilation system and included in the simulation of case 1. In case 2 all interior surfaces (building components, furniture, paints, carpets etc.) were selected to be low-polluting, thus decreasing the pollution load and resulting in a conversion of the building type from a non-low-polluting to a very-low-polluting building according to CEN EN 15251 (2007). In case 3, the ventilation rate of the VAV system was increased from a minimum of 1.2 l/(s m²) to 2.4 l/(s m²) and the maximum ventilation rate from 3.6 l/(s m²) to 7.2 l/(s m²) with similar temperature set-points.

Total building economy was compared between cases to determine whether the applied indoor environment improvements could be justified. Table 4 shows the input used for the building economy calculations.

Table 4 Input to economic calculations

Yearly salary per occupant	€ 50.000
Overhead	1.3
Heating price	0.07 €/kWh
Electricity price	0.25 €/kWh
Investment to install 12 kW cooling[1]	49 €/m²
Investment to increase ventilation by 1 l/s m² [2]	26 €/m²
Investment in low-polluting materials[3]	16 €/m²
Increased maintenance due to larger ventilation system[4]	0.5 €/m²
Extra cleaning to keep surfaces low-polluting [5]	0.3 €/m²
[1,2]: Reference: Wargocki et al., (2006) [3]: In Wargocki et al., (2006) the price of the interior was 12% of the construction cost. Construction cost was set at 1300 €/m² resulting in a cost of the interior of 156 €/m². It was also assumed that the price of low-polluting materials was 10% higher than the price of non-low-polluting materials, thus resulting in the investment in low-polluting materials being 16 €/m² [4] Increasing the size of the ventilation system induces increased maintenance cost. It is assumed that 2% of the remedial cost of the ventilation system on an annual basis is the maintenance cost [5] It is assumed that 2% of the remedial cost of the low-polluting materials corresponds to the annual cost for extra cleaning.	

To evaluate the total economic consequences of improving the indoor air quality, the financial income of the employer was calculated based on the office workers' yearly salary and an overhead indicating the ratio of employee turnover to employee salary. All economic calculations were standardized to the floor area of the office. When better IAQ was obtained at the expense of higher energy consumption and necessary investment in e.g. ventilation system upgrades, the additional energy and investment costs had to be subtracted from the income increment that resulted from higher performance. Simple pay-back time was used

to estimate the feasibility of investment in improvement of the indoor environment (Abdelhalim and Kirkham, 2004).

Renovation scenario

A renovation scenario was simulated in order to investigate the effect of improving the air quality in a "poorly" designed existing building prior to and after renovation. The simulated office was a south facing office shared between two occupants. It had a 19 m^2 floor area and an insufficient constant air volume (CAV) ventilation system supplying 0.5 l/s m^2 outdoor air (0.6 h^{-1}). The heat transmission coefficients for windows and façade were higher than present standard values. The floor was covered by an old carpet and the building could be classified as being non-low-polluting. The building characteristics can be seen in Table 5.

Table 5 Input to the simulations used in the renovation scenario

Floor area	19 m^2
No. of occupants	2
Ventilation type	Mechanical (CAV)
Façade area	5.5 m^2
Heat transmission coefficient façade	U_{facade} = 0.27 W/m^2K
Window area	5.3 m^2
Heat transmission coefficient window (center value)	U_{window} = 2.8 W/m^2K
Location	Copenhagen, Denmark

The indoor environment in the office and its effect on performance was compared between the cases prior to and after renovation. The renovation comprised replacement of the constant air volume (CAV) system with a larger VAV system, which increased the ventilation rate from 0.5 l/(s m^2) to 3.2 l/(s m^2) (maximum ventilation rate 9.5 l/(s m^2)). The set-point for the VAV system was 21 °C during winter and 25 °C during summer and the efficiency of the heat recovery unit was increased from 60% in the CAV system to 85% in the VAV system. Also, the polluting materials inside the office were removed and replaced with low-polluting materials, thus changing the building type to very-low-polluting. Table 6 shows the two different cases prior to and after renovation.

Table 6 Different cases used in the renovation scenario

Prior to renovation	Non-low polluting building, low air flow (0.5 l/s m^2) , CAV ventilation system
After renovation	Very-low-polluting building, increased air flow (3.2 l/s m^2), VAV ventilation system

In the calculations of the economic consequences of improving the IAQ, the input values from Table 4 were used.

Results

Design scenario

Table 7 summarizes the results of comparing the relative influence of the thermal and the air quality performance indices during the working hours and the corresponding economic analysis. Each of the three cases was compared with the reference situation.

Table 7 Summary of the output from the building simulations and the resulting performance and economy analysis in the design scenario.

	Reference case	Case 1	Case 2	Case 3
Average office temperature [°C]	23.2	23.0	23.2	23.1
No. of occupied hours > 26°C	121	37	121	93
No of occupied hours > 27°C	46	2	46	24
Building pollution type	Non-low-polluting	Non-low-polluting	Very-low-polluting	Non-low-polluting
Average supply airflow rate [l/s m²]	1.6	1.4	1.6	2.8
Heating [kWh/m²]	54	56	54	65
Electricity [kWh/m²]	44	55	44	56
Total energy [kWh/m²]	99	111	99	121
ΔPI_{temp}[1] [%]	-	0.1	0	0
ΔPI_{iaq}[2] [%]	-	0.1	0.3	0.3
Income [€/m²]	8695	8704	8722	8722
Energy cost [€/m²]	-	2.6	0	3.5
Additional maintenance cost [€/m²]	-	-	0.3	0.7
Productivity gain [€/m²]	-	17.8	26.6	26.6
Total gain [€/m²]		6.3	26.3	22.4
Accumulated cost of investment [€/m²][3]	-	80.6	26.2	56.6
Simple pay-back period [years]	-	**6**	**1**	**3**

[1] ΔPI_{temp} is the difference in the thermal performance index between the reference situation and the cases.
[2] ΔPI_{iaq} is the difference in the air quality performance index between the reference situation and the cases.
[3] All investments (see Table 4) were discounted over 15 years with 7% interest. The accumulated cost was the sum of annuity payments during 15 years (the total investment cost with interest)

In the simulated scenarios, improvement of the thermal conditions (reference → case 1) did result in a small increase in performance due to the improved thermal conditions by installation of cooling. However, no change of the thermal performance index between the reference situation and cases 2 and 3 was observed. Improvement of the air quality

(reference → cases 2 and 3) did increase the air quality performance index, although the increase was fairly modest (0.3%).

The outcomes of this analysis naturally depend on the input to the building simulations and the applied dose-response relationships. Nevertheless, the effects on performance of implementing the suggested improvements (cases) are so modest that a significantly different dose-response relationship, which was not justified by the underlying experimental results, is needed to change the findings.

The economic analysis indicated that even though only modest increases in performance due to improved air quality were seen, short pay-back periods occurred for both cases 2 and 3. In particular in case 2, the investment pay-back time was as short as one year, since there was no increase in the energy consumption and only a modest increment in the maintenance cost compared with the productivity gain of the employees. The investment in low-polluting materials resulted in a better air quality during the full occupancy duration, indicating that the duration when the improvement may affect the occupants should be accounted for when selecting a strategy for indoor environment upgrades. In case 3 with increasing ventilation rate, the associated higher energy consumption was compensated for economically by the productivity gain resulting in a pay-back time of three years.

Renovation scenario
To examine the economic feasibility of investing in IAQ improvements in a poorly designed office building, results of two simulated cases were compared. The scenarios illustrated the potential use of the performance model in a renovation case, where an office was renovated by changing the building materials and increasing the ventilation rate with the aim of improving the IAQ. The building characteristics and the simulation cases can be seen in Tables 5 and 6. Table 8 summarizes the results of the performance modelling, dynamic building simulation and total building economy calculations.

Table 8 Summary of the output from the building simulations and the resulting performance and economic output.

	Prior to renovation	After renovation
Average office temperature [°C]	25.9	22.9
No. of working hours > 26° C	1132	50
No of working hours > 27° C	943	28
Building	Non-low-polluting	Very-low-polluting
Specific supply airflow rate [l/s m^2]	0.5	4.2
Heating [kWh/m^2]	30	64
Electricity [kWh/m^2]	57	94
Total energy [kWh/m^2]	88	158
ΔPI_{temp} [%]	0.7	
ΔPI_{iaq} [%]	0.7	
Income [€/m^2] [1]	6705	6753
Energy cost [€/m^2]	-	11.4
Additional maintenance cost [€/m^2]	-	2.1
Productivity gain [€/m^2]	-	47.9
Total gain [€/m^2]		68.6
Accumulated cost of investment [€/m^2]	0	175.2
Simple pay-back period [years]	3	
[1] The increase in income resulted from added benefits of improved air quality and temperature conditions		

Table 8 shows that the pay-back period of the investments in renovation of the office building was determined to be three years, which indicated that the investment in a larger ventilation system could be feasible. The annual performance increment due to improved IAQ was calculated to be 0.7%, the same as the increase in the thermal performance index, and the trade-off between this increase and the additional required investment was thus sufficient to justify the renovation. If, however, improved air quality by other means could be obtained without increasing simultaneously the energy consumption, the pay-back time would be even shorter.

No method has yet been suggested to combine performance outcomes of modifying simultaneously several indoor climate parameters, accounting for synergistic, antagonistic or no interaction effects. In this study we chose to evaluate separately the two performance indices, assuming no interaction between employee performance and the thermal environment or the air quality, thus adding the performance benefits estimated from better air quality and temperature control.

Discussion

Although modest, the predicted annual benefits of indoor environment upgrades were in most scenarios sufficient to justify the necessary investment. Especially in the design

scenario, the replacement of non-low-polluting materials with low-polluting materials yielded a very short pay-back period (pay-back period equal to one year). The calculated pay-back period was of similar magnitude as that determined in other studies for equivalent upgrades (e.g. Wargocki et al., 2006; Wargocki and Djukaniciv, 2005; Kelly, 1999 and Dorgan et al. 1998). The result was achieved even though the applied dose-response relationship between perceived air quality and performance was very conservative in terms of the effect on performance of modifying the air quality. In contrast to the studies mentioned the present performance model includes not only dynamic calculations of the indoor environment and the associated effect on performance (including possible daily and seasonal variation) but allows also uncertainties in indoor parameters to be incorporated in the BN model.

Installation of cooling in the design scenario resulted in the longest pay-back period observed in the study (six years). Thus, improvement of the thermal conditions alone was less feasible than improvement of the air quality by replacing polluting materials or improving both air quality and thermal environment by increasing the ventilation rate, even in spite of the increased energy consumption. In the simulated scenarios, with the building located in a temperate climate in Scandinavia, the duration of the occupants being exposed to poor air quality was reduced during all the occupied hours, whereas the effect on performance affected by temperature through introducing mechanical cooling was in this climate zone in comparison rather modest. Similar studies conducted in other climate zones may result in different findings.

It was assumed that improving the indoor environment in an older building with a poor ventilation rate compared to present standards would result in larger increments of performance. In the renovation scenario this was investigated and the results indicated that a larger performance increment occurred but with significantly greater energy consumption. This affected the pay-back period, which was calculated to three years.

It has long been a challenge to indoor air researchers to model sensory responses to material emissions and thus predict the perceived indoor air quality in a space at the design stage (e.g. Fernandes et al. 1999; Knudsen et al. 1999; Sakr et al. 2006; Fang et al. 1999; Weschler and Shields, 2000). How to deal with combinations of materials tested individually, chemical reactions occurring in the air and on surfaces, sorption and other effects influencing emissions and VOC concentrations in the air, interaction with the thermal conditions, and individual differences between human sensory responses are just some of the complications researchers have faced. We have attempted to meet this problem

of accurately predicting the air quality by using crude, discrete levels of the pollution load on the air (low, normal, high) as input to the estimation of the expected distribution of perceived air quality votes (Figure 4). With the current state-of-the-art we believe this approach to be the most suitable for this study and the one that associates best with the BN model that builds on conditional probabilities.

The reason for not using the dose-response relationship between the percent dissatisfied with the air quality and performance as initially suggested by Wargocki et al. (2000a) was that the operable range from 25%-70% dissatisfied corresponded to a perceived air quality range on the acceptability scale of -0.20 to 0.24. This range did not take into account the extremes of the scale, which definitely were covered by the estimated distribution of perceived air quality votes and where the potentially largest effects of poor air quality on performance occurred.

In the suggested performance model estimating the effects of IAQ on the performance of office workers, two factors in particular influence the performance index: the distribution of PAQ votes and the dose-response relationship between PAQ and performance. In this study, both factors were based on laboratory experiments and thus represent an extrapolation of occupant perceptions in real office environments. Also, the tasks used to quantify subject performance in the climate chamber studies were merely simulated representations of real office work, although they build on some of the same component skills as those used in real office environments. However, no relevant knowledge from field studies was available, limiting us to the use of climate chamber data.

The perception of air quality is influenced by temperature and humidity. In this study we limited the ranges of these parameters so their variability and its effect on the perceived air quality were assumed negligible. Instead, the effect on performance of temperature was handled by the temperature performance model.

Conclusions

The shortest pay-back period and the best feasibility of investing in indoor environment upgrades were achieved when non-low-polluting materials were replaced with low-polluting materials. An increase of the ventilation rate also resulted in a relatively short pay-back period, even though this means of upgrading also resulted in higher energy consumption. The analysis of the economic consequences of improving the quality of the indoor environment indicated that even though a relatively modest increase in performance was achieved, the investment necessary to improve the air quality could be justified.

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Based on the results of building energy and indoor environment simulations, dose-response relationships between two indoor environment parameters and performance, and a Bayesian Network representation of the links between relevant building characteristics and performance, this study attempted to quantify the effect on performance and total building economy of improving the indoor air quality and the temperature conditions. In the future, such models may become important tools in the design of buildings and their indoor environments.

Acknowledgements

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PAPER III

Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions

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Abstract

Based on building energy and indoor environment simulations, this study uses a recently developed method relying on Bayesian Network theory to estimate and compare the consequences for occupant performance and energy consumption of applying temperature criteria set according to the adaptive model of thermal comfort and the more conventional PMV model. Simulations were carried out for an example building with two configurations (with and without mechanical cooling) located in tropical, subtropical, and temperate climate regions. Even though indoor temperatures differed significantly between building configurations, especially in the tropical climate, the estimated performance differed only modestly between configurations.

However, the energy consumption was always lower in buildings without mechanical cooling and in particular so in the tropical climate. The findings of this study indicated that determining acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of occupants.

Introduction

Conventional methods of determining acceptable indoor thermal conditions have been based mostly on human heat transfer models coupled with the estimation of psycho-physical, group-average indices of thermal sensation and comfort (e.g. iso 7730-2005, CEN/TR 1752-1998, ASHRAE 55-2004). Probably, the best known and most widely used model is the PMV-model, which was developed with human subjects exposed to well-controlled environments in climate chambers (Fanger 1970). The PMV model has been validated in a wide range of studies in the field, probably most comprehensively in ASHRAE's worldwide research in buildings with HVAC systems that were situated in cold, temperate and warm climates and were studied during both summer and winter (Cena et al. 1998; Donini et al. 1996; de Dear and Fountain 1994; Schiller et al. 1988).

de Dear and Brager (1998) argued that the PMV model inadequately treated the occupants as passive recipients of their indoor environment exposure and suggested that occupants should be allowed to be active in modifying their indoor environment as they preferred. They proposed an optional method to determine acceptable indoor thermal conditions, also

known as the adaptive model of thermal comfort, which is a regression equation that relates the neutral temperature indoors to the monthly average temperature outdoors. The adaptive model has been included in recent versions of ASHRAE Standard 55 and EN 15251 for buildings with spaces without mechanical cooling, where the thermal conditions are controlled primarily by the occupants through opening and closing of windows (ASHRAE 55-2004, CEN EN 15251-2007).

Application of the adaptive model of thermal comfort in warm climate regions may result in relaxed temperature criteria and may therefore provide a potential means to reduce the consumption of energy used to cool buildings. One of the main themes of the discussion that rose at the introduction of the adaptive model was if it would also provide an acceptable degree of occupant satisfaction in spaces without mechanical cooling. It is likely that occupants in such spaces are used to larger temperature variation and therefore have lower expectations and would judge a given warm environment as less severe and less unacceptable than would people who are used to stricter climate control (Fanger and Toftum 2002). In the discussion, however, the effect of relaxed temperature criteria on occupant performance was inferior, possibly because no obvious approach was available to estimate the effects on occupant performance of indoor temperatures.

Jensen et al. (2009) proposed such an approach developed to assess the effects of the thermal indoor environment on the mental performance of office employees and to compare the economic consequences of different building designs based on occupant performance and energy use. The approach combines Bayesian network theory with dynamic simulation of the indoor environment and of the energy consumption as well as with dose-response relationships between indoor climate parameters and mental performance. The Bayesian network is based on the compilation of subjective thermal sensation data and the associated objective thermal measurements from 10.700 occupants of climate controlled buildings and 6.400 equivalent data records from buildings without mechanical cooling located in different parts of the world (de Dear 1998). In the current study the approach is used to estimate and compare the consequences for occupant performance and energy consumption of applying temperature criteria set according to the conventional method and the adaptive model in an example building with and without mechanical cooling located in tropical, subtropical, and temperate climate regions.

Methods

Input to the assessment of employee performance was hourly values of operative temperature simulated for a space in a building with and without mechanical cooling,

located in Singapore (tropical – latitude 1° 14' N), Sydney (subtropical – latitude 34° 0' S), San Francisco (temperate – latitude 37° 47' N), and Copenhagen (temperate – latitude 55° 40' N). Based on observations recorded in thermal comfort field studies in the two building configurations, a Bayesian network was used to infer the probability of the occupants being satisfied with the thermal conditions (Jensen et al. 2009). Since occupants in non-mechanically cooled buildings may be more forgiving of a warm environment than would people who are used to air-conditioning, different thermal sensation distributions would result from identical temperatures in the two building configurations. This is illustrated in Figure 1, which is based on data from de Dear (1998).
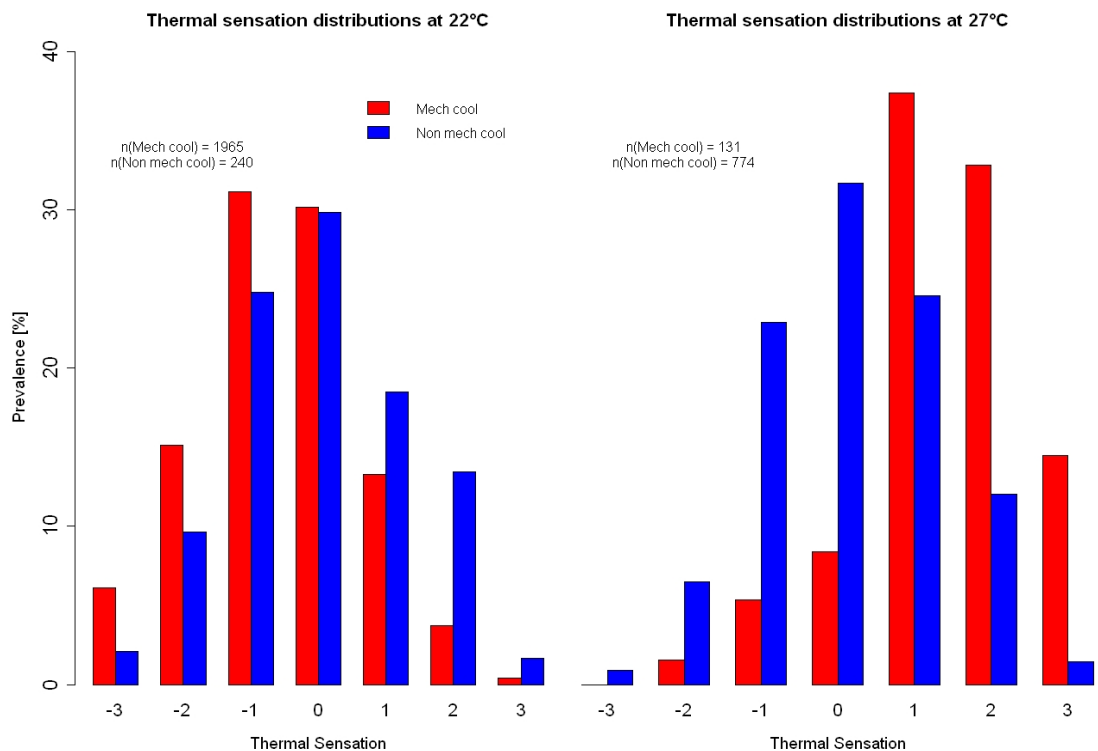
Fig. 1 *Distribution of thermal sensation votes cast in buildings with and without mechanical cooling at recorded temperatures 22 °C and 27 °C. Data adopted from de Dear (1998).*

The distributions of thermal sensation votes cast by occupants in buildings with and without mechanical cooling at 22 °C follow an almost perfect Gaussian distribution, although without mechanical cooling the prevalence of warmer votes was somewhat higher. At 27 °C the distribution in HVAC was left-skewed and almost 50% of the occupants in HVAC buildings voted warm or hot, whereas more than 80% of the occupants in buildings without mechanical cooling at the same temperature voted slightly cool, neutral or warm.

As suggested in several earlier studies, thermal sensation for people in near thermal comfort conditions is more likely to influence performance than temperature per se (e.g.

Wyon et al. 1975; Witterseh et al. 2004). Using thermal sensation to quantify effects on performance of the thermal climate, the different distributions of thermal sensation votes will affect the outcome, whereas temperature as input would yield identical performance estimates at identical temperature levels.

Simulated hourly temperatures were thus used to estimate the thermal sensation distribution with and without mechanical cooling and, for both populations, to subsequently estimate mental performance by weighting the performance decrement according to the associated distribution of thermal sensation votes, using the dose-response relationship between thermal sensation and performance shown in Figure 2.
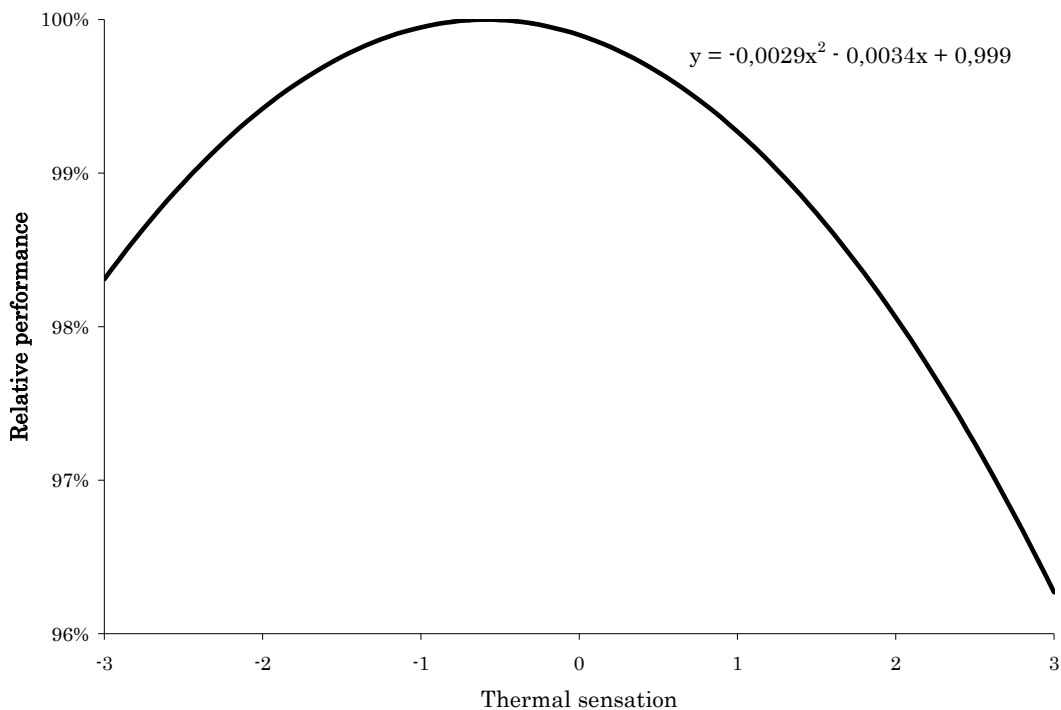
The curve is labelled $y = -0{,}0029x^2 - 0{,}0034x + 0{,}999$

Fig. 2 *Dose-response relationship between thermal sensation and mental performance.*

The dose-response relationship in Figure 2 is a modification of the dose-response relationship suggested in Jensen et al. (2009).

An alternative means of off-setting elevated temperatures may be to raise local air velocity to increase the cooling effect and maintain thermal comfort. This may result in reduced consumption of energy by the central air conditioning, but currently requires individual control of the local air velocity by each occupant (ASHRAE 55-2004). However, this study focused on low air velocities, which also were most prevalent in the ASHRAE field studies

(< ~0.1m/s). The matrix of conditions of this study compares temperature criteria determined according to the ASHRAE Standard 55 comfort envelope (-0.5 < PMV < 0.5) and according to the adaptive model of thermal comfort.

For the selected geographical locations, Table 1 illustrates monthly average outdoor temperature and the outdoor temperature at 6 a.m. averaged for each month during a normal year.

Table 1 Monthly 24 hr average temperature at Singapore Paya Lebar Airport, Sydney Int'l Airport, San Francisco Int'l Airport, Copenhagen Kastrup Airport and the temperature at 6 a.m. averaged for each month in Singapore, Sydney, San Francisco, and Copenhagen. Monthly averages adopted from www.worldclimate.com and values at 6 a.m. from IWEC 1.1 (2001).

Month	Singapore		Sydney		San Francisco		Copenhagen	
	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)	Monthly average (°C)	Monthly average at 6 a.m. (°C)
Jan	26.2	27.8	22.1	19.3	9.2	5.7	0.1	1.4
Feb	26.9	26.9	22.0	20.6	11.2	8.5	0.1	-0.6
Mar	27.3	28,3	20.9	18.5	11.8	8.1	2.3	1.7
April	27.7	29,2	18.3	15.0	13.1	8.9	6.5	4.6
May	27.7	28,8	15.2	12.9	14.5	10.2	11.6	9.9
June	27.5	28,6	12.8	10.1	16.3	12.2	15.2	13.0
July	27.2	26,9	11.8	8.7	17.0	13.3	16.8	15.0
Aug.	27.1	29,0	13.0	9.2	17.6	12.6	16.3	15.3
Sep.	27.1	27,3	15.2	11.7	18.0	13.1	13.3	11.0
Oct.	27.2	29.9	17.6	14.8	16.1	12.3	10.0	8.6
Nov.	26.8	25.8	19.4	16.7	12.6	9.7	5.3	4.5
Dec.	26.3	25.4	21.2	18.5	9.6	7.3	1.4	1.0

The transition in clothing insulation from winter to summer and vice versa is naturally integrated in the adaptive model, but the conventional comfort envelope encompasses only two levels of clothing insulation corresponding to a distinct winter and summer situation (1.0 clo and 0.5 clo, respectively). The operative temperature limits for intermediate values of clothing insulation may be determined by linear interpolation between the limits for 0.5 clo and 1.0 clo, according to the following relationships (ASHRAE 55-2004):

$$t_{min,I_{cl}} = [(I_{cl} - 0.5\ clo)\ t_{min,1clo} + (1.0\ clo - I_{cl})\ t_{min,0.5\ clo}]/0.5\ clo \qquad (°C) \qquad eq.\ 1$$

$$t_{max,I_{cl}} = [(I_{cl} - 0.5\ clo)\ t_{max,1clo} + (1.0\ clo - I_{cl})\ t_{max,0.5\ clo}]/0.5\ clo \qquad (°C) \qquad eq.\ 2$$

In which

$t_{max,\ I_{cl}}$ = upper operative temperature limit for clothing insulation I_{cl}

$t_{min,\ I_{cl}}$ = lower operative temperature limit for clothing insulation I_{cl}

I_{cl} = thermal insulation of the clothing in question (clo)

From the comfort envelopes specified in ASHRAE standard 55 Figure 5.2.1.1 (ASHRAE 55-2004), the following temperature limits for 0.5 clo and 1 clo were obtained, corresponding to PMV = ± 0.5 and PPD = 10%:

$t_{min, 1\ clo}$ = 20 °C

$t_{max, 1\ clo}$ = 24 °C

$t_{min, 0.5\ clo}$ = 23 °C

$t_{max, 0.5\ clo}$ = 26 °C

These values are within the comfort envelope and are also in agreement with temperature limits specified in ISO 7730-2005 and EN 15251-2007 for winter (1.0 clo) and summer conditions (0.5 clo).

With data from the same database that was used to develop the adaptive comfort model, de Carli et al. (2007) analyzed matching observations of clothing insulation and external temperature and identified the outdoor temperature at 6 a.m. to be the variable that correlated best with clothing insulation in buildings without mechanical cooling (among the four tested variables). In buildings with mechanical cooling, the correlation did not differ between the outdoor temperature at 6 a.m., mean daily temperature or mean monthly temperature. The study by de Carli et al. (2007) suggested a set of regression equations to estimate mean occupant clothing insulation based on the outdoor temperature at 6 a.m.:

With mechanical cooling: $\quad I_{cl} = 0.766 - 0.01\ t_{outdoor,\ 6\ a.m.}$(clo) $\qquad$ eq. 3

Without mechanical cooling: $I_{cl} = 0.980 - 0.02\ t_{outdoor,\ 6\ a.m.}$(clo) $\qquad$ eq. 4

In the current study, equation 3 applying to buildings with mechanical cooling was used to estimate the average clothing insulation during the year in such buildings.

In buildings without mechanical cooling, comfort temperature and upper and lower temperature limits corresponding to 90% satisfied were determined from the monthly average temperature with the equations (de Dear and Brager 1):

$T_{lower} = 15.3 + 0.31\ t_{outdoor,\ monthly\ average}$

$T_{comfort} = 17.8 + 0.31\ t_{outdoor,\ monthly\ average}$

$T_{upper} = 20.3 + 0.31\ t_{outdoor,\ monthly\ average}$

Based on the monthly average temperature recorded at 6 a.m., equation 3 was first used to determine the monthly average clothing insulation and then equations 1 and 2 were used to determine the upper and lower limit of the temperature comfort envelope. Next, the comfort temperature adjusted for the seasonal variation in clothing insulation was determined as the average of the upper and lower temperature limit. For each studied location, Figure 3 compares comfort temperature determined according to the conventional method, adjusted for the variation in clothing insulation due to outdoor temperature, with comfort temperature determined according to the adaptive model.
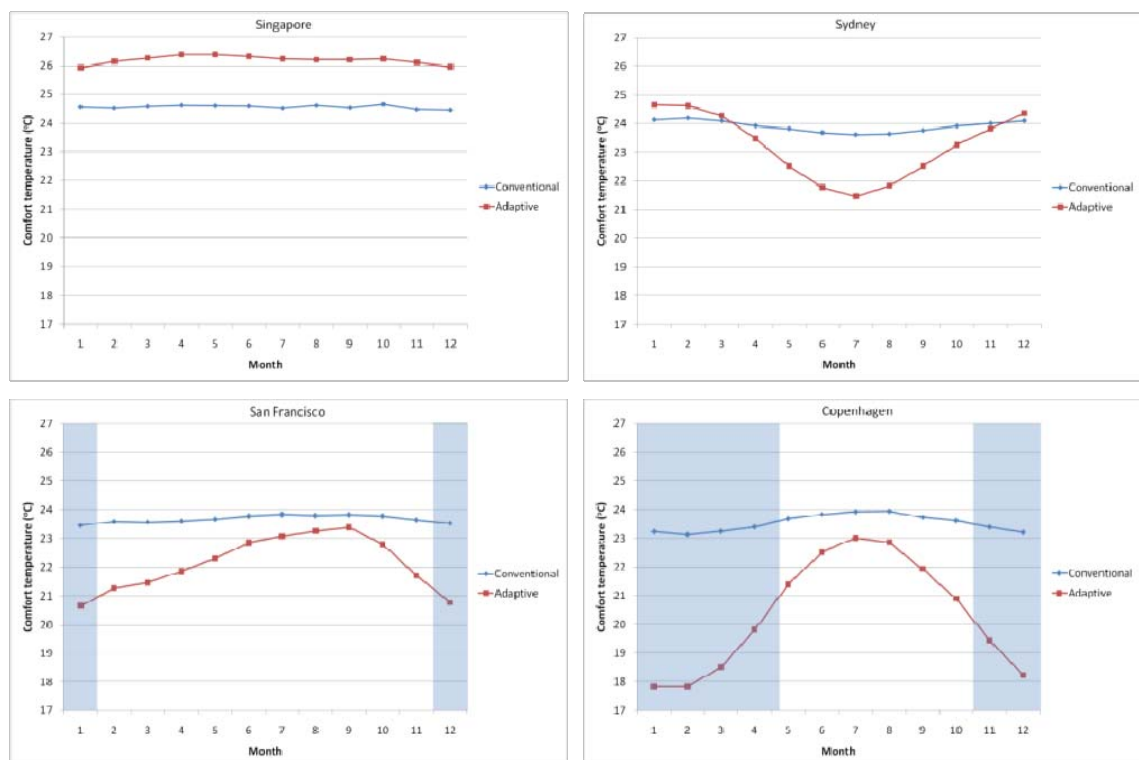
Fig. 3 *Comparison of comfort temperatures determined according to the conventional method, adjusted for seasonal variation in clothing insulation, and the adaptive model at the four studied locations. Shaded regions show when the monthly average outdoor temperature was below 10 °C.*

In ASHRAE 55, the adaptive model has a lower outdoor cut-off temperature at 10 °C, below which the allowable operative temperature limit should not be used and where no indoor temperature for naturally conditioned buildings is specified (ASHRAE 55-2004). In Copenhagen, the monthly average outdoor temperature was below this cut-off temperature from November to April and in San Francisco in December and January. During these periods, a comfort temperature corresponding to an outdoor temperature of 10 °C was used ($t_{comfort}$ = 20.9 °C).

Indoor climate and energy simulations

In order to estimate hourly indoor temperatures and energy data, simulations were carried out using the software IDA ICE version 3.0 build 16 (IDA, 2008). The same building setup was used at all four locations with only minor changes between locations. A single room of 120 m² occupied by 10 persons was simulated with the specifications listed in Table 2.

Table 2 Specifications of the simulated building

Internal heat gain from equipment	1200 W
Number of occupants	10
U value of external wall	0.708 W/(m² · K)
Type of windows	2-layer window with 15 mm air gap and wooden frame (10 % of window area)
Center U-value of glazing in window	2.8 W/(m² · K)
Solar heat gain coefficient of window	0.76
U-value of window frame	2.0 W/(m² · K)
Size of window	1.25 m X 1.20 m
Number of windows	6
Dimensions of the room	10 m X 12 m

The simulated office was adjacent to other rooms with identical thermal conditions, i.e. the three internal walls were adiabatic. Also, the temperature conditions above and below the office were symmetrical resulting in the heat being transmitted through the ceiling was re-transmitted through the floor. Thus, the ceiling of the simulated office acted as the floor of the office located on the level above and the floor of the simulated office acted as the ceiling of the office below. Heating was provided by waterborne radiators. Figure 4 shows a sketch of the office.
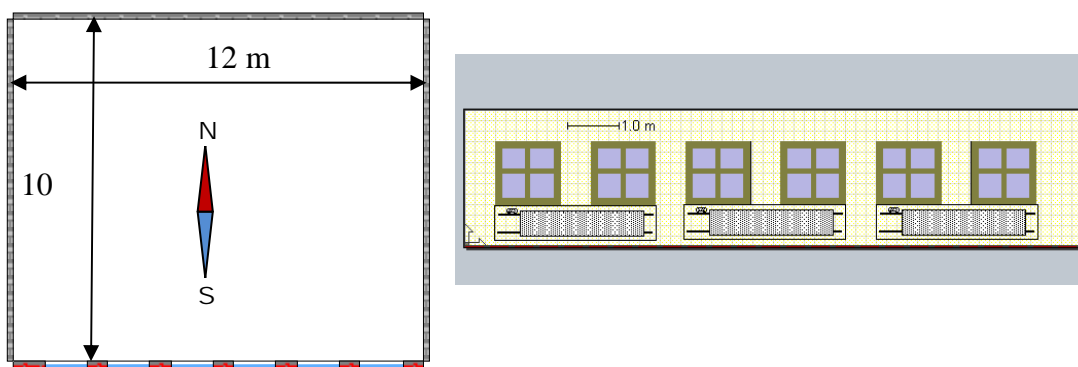
Fig. 4 *The office seen from above (left) and the external wall seen from the inside (right). The external wall was facing south when the building was located in the northern hemisphere and facing north in the southern hemisphere.*

The internal heat gain from electrical equipment (PCs, etc.) was 50% of the total gain (Table 2) from midnight to 7 a.m. and from 6 p.m. to midnight. During office hours from 9

a.m. to 4 p.m. it was 100% and from 7 a.m. to 9 a.m. and again from 4 p.m. to 6 p.m. it was linearly increased and decreased, respectively, between 50% and 100%. The occupant load was 100% from 9 a.m. to 11 a.m. and again from 1 p.m. to 4 p.m. From 6 p.m. to 7 a.m. it was 0% and was increased linearly from7 a.m. to 9 a.m. and decreased from 4 p.m. to 6 p.m. During lunch (11 a.m. to 1 p.m.), the occupancy was decreased linearly to 50% at 12 p.m. and then increased again. The lighting was controlled automatically to be on when a desktop in the middle of the office was lit by daylight at 100 lux or less and off when the daylight illumination exceeded 10,000 lux.

All windows were equipped with a stationary overhang of 0.75 m tilted approximately 35o from horizontal and located approximately 0.3 m above the upper edge of the window. In San Francisco the overhang was extended to 1 m width.

Simulated temperature control

In the naturally ventilated building, the occupants by behavioural means attempted to maintain the temperature within the upper and lower temperature limits and the temperature was controlled by adjusting the window opening and the radiators. The windows were opened when the indoor temperature exceeded the upper temperature limit and they were closed again when the temperature was below the lower temperature limit. The total aerodynamic opening area with all windows 100 % open was set to 4.5 m². The opening area was set at the time of the window opening event and did not change until the windows were closed again. If the outdoor temperature at the time of the opening exceeded 25 °C, the windows were opened 100 %. If the outdoor temperature at the time of the opening event was lower than 5 °C, the windows were opened only 20 %. Between 5 °C and 20°C, linear interpolation was used to determine the opening area of the windows.

Leaks and cracks in the building envelope were positioned in all four external walls in the building and connected to the room. The size and position of the leaks were adjusted so that the annual average infiltration rate was 0.1 h^{-1}.

The flow of water through the radiator was regulated with a p-controller. If the indoor temperature dropped more than 1 °C below the limit, the flow through the heater was 100 %. The supply temperature of the water varied with the outdoor temperature.

In the mechanically ventilated buildings, the indoor temperature set-point was determined by the clothing insulation value according to equations 1 and 2. The temperature was adjusted by the heating and cooling coils in the ventilation system and by a waterborne

radiator, which was controlled as described for the naturally ventilated buildings. The supply air temperature was regulated in the range of 8 °C and 1 °C below the indoor temperature.

In order to save energy, the fan speed was reduced to 20% after working hours and the outdoor air supply rate was decreased during the cold periods of the year as shown in Table 3.

Table 3 Settings and schedule for operation of the ventilation system in the buildings with mechanical cooling.

Location	Singapore	Sydney	San Francisco	Copenhagen
Fan running at reduced speed	Weekends and workdays between 6 p.m. and 2 a.m.	Weekends and workdays between 6 p.m. and 5 a.m.	Weekends and workdays between 6 p.m. and 2 a.m. from October to May	Weekends and workdays between 6 p.m. and 5 a.m. from October to May
Recirculation/heat recovery	Modulated between 0 l/s and 400 l/s recirculation.	Modulated between 0 l/s and 400 l/s recirculation.	Heat recovery unit. Efficiency between 0 % and 60 %	Heat recovery unit. Efficiency between 0 % and 60 %
Outdoor air supply rate	70 l/s	70 l/s	200 l/s from May to September. 400 l/s rest of year	200 l/s from May to November. 300 l/s rest of year
Cooling coil max power output	5400 W	4000 W	2500 W	750 W

At all locations, the maximum power output of the cooling coil was adjusted so the annual number of hours with indoor temperatures higher than the upper limit was between 90 and 110 hours during occupancy.

Performance calculations

To calculate the effects on performance of the temperature exposure, the hourly temperatures simulated in IDA for each location and building configuration were imported into a MATLAB procedure, which implemented the Bayesian Network (BN) model suggested by Jensen et al. (2009). The BN is a graphical model that represents the links between indoor climate variables and characterizes their correlation. In the present model, temperature and building configuration were input to the BN. The indoor temperature affects multiple variables at the same time, including activity, clothing level, and thermal sensation, while the building configuration affects for example air velocity and thermal sensation. Most of these indoor climate variables are inter-correlated and therefore difficult to estimate in a deterministic model.

The BN handles such correlation by using probability distributions in the calculations. Each variable is divided into intervals (states), which are attributed a probability (e.g. the variable clothing has three states: Light, normal and heavy clothing. Given that the temperature is high, the probability of the occupants wearing light clothing is higher than them wearing heavy clothing).

The data underlying the conditional probabilities were adopted from de Dear (1998). Knowledge of the state of a variable (e.g. the temperature is 30 °C in a building with mechanical cooling) enables the BN to infer the states of other variables by the probabilistic calculations. This yields a probability distribution of the states (e.g. probability of occupants wearing light clothing: 90%, probability of people wearing normal clothing: 8% and probability of people wearing heavy clothing 2%) and adds an uncertainty to the model estimate (we are not 100% sure that all people will wear light clothing, we are 90% sure), which can be considered to be a better representation of the real world situation.

In real offices, the occupants are affected differently when exposed to the same IEQ conditions as illustrated in Figure 1. The suggested performance model uses the BN to estimate the difference between people's thermal sensation, which not only depends on the temperature exposure, but also on the building configuration. With the dose-response relationship shown in Figure 2, the model estimated a performance index indicating an accumulated relative performance measure, where 100% was considered to be optimal performance and e.g. 98% corresponded to a 2% decrement in performance due to the thermal conditions during the period in question. Mathematically, the calculation of the relative performance can be expressed as shown in the equation below:

$$\Pi = \sum_i w \cdot BN(temp_i) \quad for\ i = 1,2,\ldots,n$$

in which, Π is the performance index in percent, i is the time segment for which the performance is calculated (e.g. working hours during a year), w is a weighting factor for each time segment (w = 1/i), tempi is the temperature in time segment i, and BN(tempi) is the performance output from the Bayesian Network as a function of tempi.

Results

For the two climatic extremes included in this study (Singapore and Copenhagen), Figure 5 shows the simulated indoor temperature profiles during a year in the two building

configurations and the corresponding temperature comfort ranges, determined according to the adaptive model and the PMV model with adjustments for clothing.
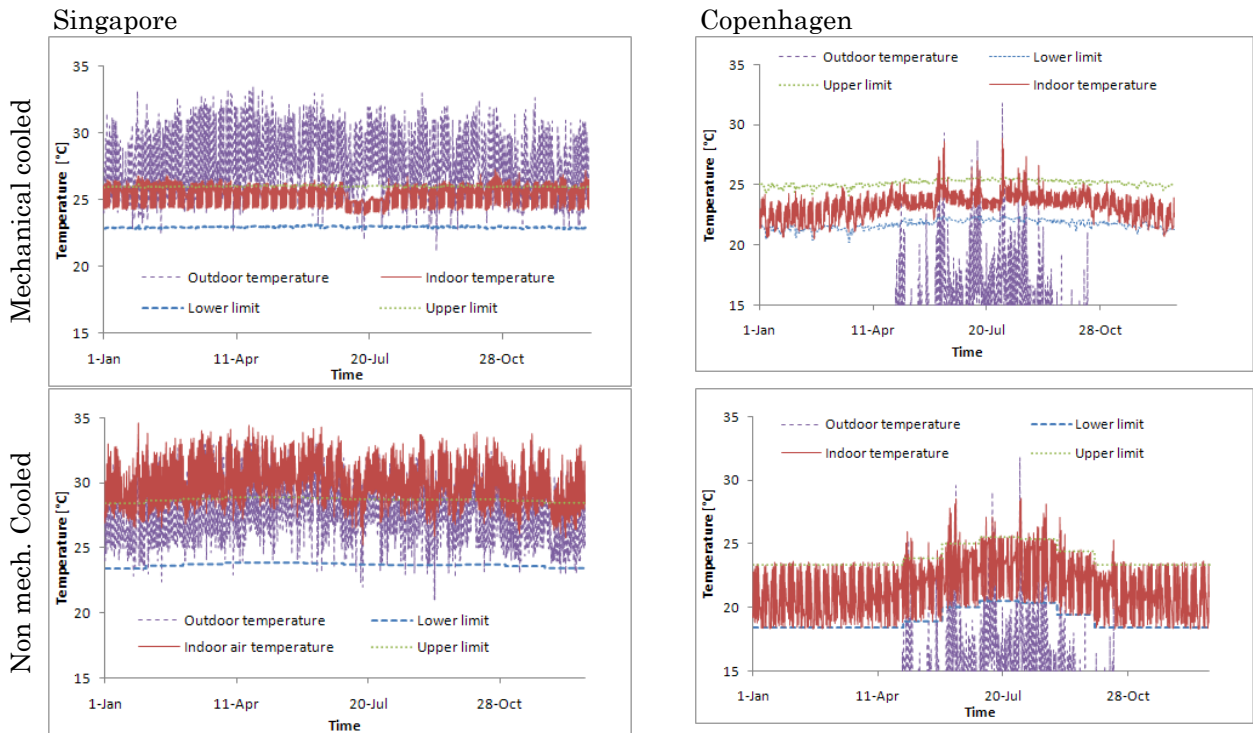
Fig. 5 *Simulated indoor temperature profile, outdoor temperature and upper and lower comfort temperature limits in the buildings in Singapore and Copenhagen. Upper figures: With mechanical cooling; lower figures: Without mechanical cooling.*

In the building without mechanical cooling located in Singapore, the indoor temperature during most of the simulated period was well above the upper comfort temperature, even though the adaptive model yielded far more relaxed temperature criteria as compared with the PMV model used in the buildings with mechanical cooling. In the building with mechanical cooling in Singapore, the temperature rose during the day and exceeded by a small amount the upper comfort temperature almost daily. In Copenhagen, this exceedence was limited to a few extreme days per year.

Table 4 summarizes the accumulated number of occupied hours during the simulated year when the indoor temperature exceeded the upper comfort temperature.

Table 4 Accumulated number of hours when the indoor temperature exceeded the upper comfort limit and percent of the occupied hours when the temperature fell in the ranges < 22°C, 22-26°C, and > 26°C.

		Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling	Accumulated hours (hrs) [1]	2169	756	250	232
	% of hours with t < 22°C [2]	0	12.6	30.2	41.6
	% of hours with t $\in 22 - 26$°C [2]	0	52.1	62.7	53.6
	% of hours with t > 26°C [2]	100	35.3	7.1	4.8
With mechanical cooling	Accumulated hours (hrs) [1]	103	93	99	98
	% of hours with t < 22°C [2]	0	0	0	0.8
	% of hours with t $\in 22 - 26$°C [2]	87.6	95.2	97.1	96.1
	% of hours with t > 26°C [2]	12.4	4.8	2.9	3.1

[1] Accumulated number of hours during occupancy with temperatures above the upper comfort limit.
[2] Percent of the occupied hours when the temperature fell in the given range.

In correspondence with Figure 5, the building without mechanical cooling in Singapore stood out with nearly 100% of the hours during occupancy above the temperature limit. However, also in Sydney, San Francisco, and Copenhagen the indoor temperature in the buildings without mechanical cooling periodically was too high. In the buildings with mechanical cooling, the simulations were tuned to yield exceedence of comparable magnitude, around 100 hours per year.

Table 5 shows the energy consumption resulting from the simulations, distributed on heating, cooling and electrical consumption.

Table 5 Energy output from the indoor climate and energy simulations.

Location	Singapore		Sydney		San Francisco		Copenhagen	
Ventilation	With mech. cooling	Without mech. cooling	With mech. cooling	Without mech. cooling	With mech. cooling	Without mech. cooling	With mech. cooling	Without mech. cooling
Heating [kWh]	0	0	984	6	2115	17	5521	86
Cooling [kWh]	31226	0	6033	0	772	0	301	0
Electrical [kWh]	9752	8279	9755	8236	10957	8259	10395	8291

Cooling and heating contributions are consumption of cooling and heating in the coils in the HVAC system and the radiators, not primary energy consumption. In the mechanically cooled buildings, the electrical contribution includes the fan energy consumption in addition to lighting, circulation pumps and equipment. Not surprisingly, the energy penalty for maintaining the temperature within the comfort range was very high in Singapore, and to a much lesser degree in Sydney, whereas in San Francisco and Copenhagen application of the mechanical cooling rarely was necessary. However, in the two latter cities, the heating energy consumption was significantly higher than with mechanical cooling (HVAC system) due to the higher air exchange rate also during the winter season. As reflected in the low heating energy consumption without mechanical cooling, the simulated building configuration resulted in low transmission heat loss due to the adiabatic internal walls and the small area of the well-insulated external wall. At all simulated locations, the energy consumption was significantly lower in buildings without mechanical cooling.

With the simulated temperature profiles as input, the BN was used to determine annual average performance indices at all locations and in both building configurations. The resulting indices are shown in Table 6.

Table 6 Performance indices determined from one-year simulations of indoor temperature.

	Performance index (%)			
	Singapore	Sydney	San Francisco	Copenhagen
Without mechanical cooling	98.1	98.8	99.0	99.0
With mechanical cooling	98.9	99.0	99.1	99.1

In general, the annual performance index varied only little across location and building configuration, despite the considerable differences in the simulated indoor temperatures. Perhaps most surprising was the result from Singapore, where the simulated temperature without mechanical cooling continuously was higher than even the relaxed temperature criteria determined with the adaptive model, but where the performance index was 98.9 and 98.1 in buildings with and without mechanical cooling, respectively. Yet, of all the simulated locations the lowest performance was observed in Singapore in the building without mechanical cooling. In Sydney, San Francisco and Copenhagen there was only negligible difference between the performance indices with the two building configurations. Also, the mean temperature differed much less between building configurations at these locations than in Singapore.

Discussion

It was a surprise that the rather extreme difference in temperature between buildings with and without mechanical cooling resulted in so modest differences in the performance estimates. Especially in Singapore, where the difference in mean temperature between the two building configurations during the occupied hours was as high as 5.9°C, the decrement in the estimated performance was only 0.9 %-points. Several factors contributed to this result: One important influencing factor was the two different thermal sensation distributions that were used in the BN to estimate performance, one for buildings with mechanical cooling and one for buildings without. As was the basis for the adaptive model to recommend relaxed temperature criteria, occupants in buildings without mechanical cooling, who were not used to strict climate control, were more forgiving of their thermal exposure and cast less extreme votes on the thermal sensation scale at high temperatures as is also illustrated in Figure 1 (de Dear and Brager 1998; Fanger and Toftum 2002). Thus, when thermal sensation, rather than temperature, is used as input to the estimation of performance, the effect of high temperatures is moderated because the proportion of occupants who feel neutral or slightly warm rather than warm or hot will be much higher in buildings without mechanical cooling, despite the high temperatures. The difference in thermal sensation distributions at identical temperature exposures between the populations of the two building configurations was crucial to the development of the adaptive model as it was to the initiation of the current study. As it turned out, this difference, at least partly, also explained why the difference in performance was smaller than anticipated with the considerable differences in environmental exposure.

Another influencing factor was the applied dose-response relationship (Figure 2), which was developed by combining the results of several laboratory studies on thermal exposure and mental performance (studies listed in Jensen and Toftum 2009). Most of the exposures in these studies focused on the in- and near-comfort temperature ranges and no exposure took place at temperatures above 28°C, probably resulting in a "flatter" dose-response relationship than could be expected with more extreme experimental temperature exposures. Nevertheless, even though total building economy was considered beyond the scope of this study, expenses incurred in occupant salaries exceed by several magnitudes building operation and maintenance costs, and investment in improved indoor environment, resulting in even small improvements in performance, has been shown to be economically justifiable (Jensen et al. 2009; Jensen and Toftum 2009). Thus, the basis of assessing thermal environment effects on performance should be extended to temperatures above 28oC and incorporated in the does-response relationship to fully address the exposures that resulted from the simulations.

Whereas the estimated performance index differed only modestly between building configurations, the energy consumption was always lower in buildings without mechanical cooling, especially in Singapore where the omission of mechanical cooling yielded a substantial reduction of the energy consumption. Based on the results of this simulation study it thus appears that determining acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of occupants who are more attentive to their thermoregulatory options and do not have high expectations to their indoor environment. In San Francisco and Copenhagen, inclusion of mechanical cooling had only negligible effect on the cooling energy consumption indicating that the periods when the cooling system was active were short. The number of hours when the temperature was below 22°C in these two cities was much higher without than with mechanical cooling indicating a lower mean temperature in this building configuration during the heating season, although heating with both building configurations was controlled according to identical set-points.

Inarguably, an infinite number of scenarios could have been simulated, each with different energy and performance outcomes and each representing a compromise that restricts the generalisation of the study results. This study applied a rather crude approach with limited local modification and building features considered to be representative of a universal configuration with or without mechanical cooling and in which as many control and other input parameters as possible remained constant between cities. Indeed, the major difference in the simulated building configuration was the inclusion of an HVAC system. Nevertheless, to reach to a different conclusion as regards the performance index estimated in the two building configurations would require a radically different building configuration or that the building control system was specified and set up completely differently.

de Dear and Brager (1998) pointed out that occupants in buildings without mechanical cooling to a higher degree rely on their behavioural opportunities to maintain an acceptable indoor environment than occupants who are used to automatic control systems. State-of-the-art of building simulation software allows only a rather mechanistic approach to the simulation of occupant control, e.g. windows are opened when the simulated temperature reaches a specified set-point rather than as a response to occupant perceptions. Indeed, Andersen et al. (2007) showed that occupant behaviour could influence the consumption of energy to climatise a building by as much as 330%. The realism of a simulation study as this could be enhanced by the inclusion of probabilistic knowledge of occupant behaviour and subjective decisions in response to environmental exposures.

Conclusions

As a consequence of the different thermal sensation distributions observed in buildings with and without mechanical cooling, occupant performance was only slightly lower without mechanical cooling when thermal sensation was used as input to the estimation of performance, even in a tropical climate where simulated indoor temperatures were much higher than in buildings with mechanical cooling. However, consumption of energy to climatise the buildings without mechanical cooling was considerably lower without mechanical cooling indicating that determination of acceptable thermal conditions with the adaptive model may result in significant energy savings and at the same time will not have large consequences for the mental performance of the occupants

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PAPER IV

Implementation of multivariate linear mixed-effects models in the analysis of indoor climate performance experiments

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Abstract

The aim of the current study was to apply multivariate mixed-effects modelling to analyse experimental data on the relation between air quality and the performance of office work. The method estimates in one step the effect of the exposure on a multi-dimensional response variable and yields important information on the correlation between the different dimensions of the response variable, which in this study was composed of both subjective perceptions and a two-dimensional performance task outcome. Such correlation is typically not included in the ouput from univariate analysis methods. Data originated in three different series of experiments investigating the effects of air quality on performance. The example analyses resulted in a significant and positive correlation between two performance tasks indicating that the two tasks to some extent measured the same dimension of mental performance. The analysis seems superior to conventional univariate statistics and the information provided may be important for the design of performance experiments in general and for the conclusions that can be based on such studies.

Keywords

Practical implications

This study introduces a statistical method known as multivariate linear mixed-effects modelling, which, when applied on subject experiments with more than one response variable, as is often the case in indoor environment studies, has several advantages over conventional univariate statistical methods. The method estimates in one step the effect on a multi-dimensional response variable of the exposure and yields additional important information on the correlation between the different dimensions of the variable.

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Introduction

Recent years, indoor environment effects on the performance of office work have been studied quite extensively, often with sequences of simulated office tasks that repeatedly were presented to subjects during controlled environment exposures (e.g. Wargocki et al. 1999, Wargocki et al. 2000b, Bako-Biró et al. 2004, Witterseh et al. 2004, Kolarik et al. 2008, Toftum et al. 2008). Common office work typically comprises different component skills ranging from simple repetitive tasks to more complex tasks that require a higher degree of mental effort. Some tasks are common to most office work, while other differ diversely between job functioning. The results of some of the studies cited above documented that high indoor air quality had a positive impact on occupant performance (e.g. Wargocki et al. 1999, Wargocki et al. 2000b, Bako-Biró et al. 2004). In these rather similar experiments, the task sequences simulated common elements of typical (clerical) office work and included text-typing, arithmetical tasks, proof-reading, short-term memory tasks, and creative thinking. The task outcomes have generally been defined in terms of speed and accuracy, e.g. rate of characters typed and an error rate for text-typing or rate of correct additions or multiplications solved and a corresponding error rate. One or several such outcomes were obtained for each subject for each experimental exposure. In addition to objective performance measures, a range of subjective scales have been used to assess such factors as perceived air quality, thermal sensation and other environmental perceptions, the intensity of symptoms (e.g. headache, lethargy, mucous membrane irritation, skin irritation) and self-estimated performance.

Conventional statistical analysis of the experimental results has focused on comparing performance measurements between conditions as a response, and a treatment, e.g. high or low pollution load, as explanatory variable (e.g. Wargocki et al. 1999). The analysis was thus able to prove or disprove relations between exposure and task performance, whereas little or no information on correlations between the performance of the applied tasks or between task performance and monitored subjective measures was obtained. Such information is important in the search for causality between indoor environment exposure and occupant performance and to the design and outcome of performance experiments in general.

Other studies have applied mixed-effects modelling in their analysis of the experimental results (Kolarik et al. 2008, Toftum et al. 2008). Mixed-effects analysis is commonly used in longitudinal repeated measures experimental designs, common among medical studies (Demidenko, 2004). In such experiments it is not uncommon that subject drop-outs occur,

which may be a challenge also to indoor climate experiments. If missing values occur in performance experiments, the use of conventional statistical analysis traditionally requires that the data for the subject in question is omitted entirely. This results in loss of information which, due to the potentially relatively small effects of the indoor environment on performance, can be crucial for the outcome of the analysis.

Recent studies have investigated the relation between performance and subjective assessments of specific indoor climate parameters (e.g. thermal sensation or perceived air quality) (Wargocki et al. 2005; Jensen et al., 2009; Jensen and Toftum, 2009). Such relations introduce new issues in the analyses of the data due to the sometimes complex covariance structure between subjective assessments of the indoor environment and subject performance. A multivariate linear mixed-effects model can be used to explore this covariance structure and the correlations between the response variables (Shafer et al, 2002). Like the univariate mixed-effects model, the multivariate model has been used in the field of medicine in longitudinal studies (Shah et al. 1997, Thiébaut et al. 2002).

The aim of the current study was to apply multivariate mixed-effects modelling to evaluate correlations between the outcome of different tasks used to study the performance of office work and the correlation between the applied tasks and selected subjective responses. The analysis was based on a multidimensional response variable composed of both subjective perceptions and a two-dimensional performance task outcome.

Method

Various statistical software procedures can perform multivariate mixed-effects analysis. The present investigation was carried out using the package *'mlmmm'* which is included in the R statistical program (R team 2004). The SAS statistical software has a similar tool called proc MIXED (Tiébaut et al. 2002).

To run the *'mlmmm'* routine data need to be arranged in columns; one for each response and each predictor variable. The specific code for running the *'mlmmm'* routine has been included in Appendix 1 of the present paper. The output from the *'mlmmm'* procedure, in addition to the usual estimates of the fixed effects (i.e. effects controlled by the experimenter, such as the level of air quality), were matrices of variance-covariance estimates of the between and within-subjects random variation, which enable calculation of the correlations between the individual responses in the multidimensional response variable.

Description of experiments

The data set was accumulated by the results of three different series of experiments investigating the effects of air quality on performance (Wargocki et al. 1999; Lagercrantz et al. 2000 and Wargocki et al 2000). All three experiments were conducted in office spaces in which the indoor environment could be controlled. The experiments were carried out in a balanced, randomized design in which the subjects were exposed to a pollution source (old carpet equal to the floor area of the office). One of the experiments was conducted in Sweden, the other two in Denmark. In two studies the indoor air quality was modified by removing a pollution source, while in the third study the ventilation rate was significantly increased. In all three studies the pollution source was a carpet, which had been in use during 20 years in an office building with a long history of indoor environment complaints. In the cases with the pollution source absent or the source present with increased ventilation rate, the air quality was labelled as "good" and as "poor" when the source was present and the ventilation rate low.

 A total of 90 female subjects participated in the experiments and they were exposed for approximately 4.6 hours under each condition. During the exposure, the subjects performed different performance tasks, which simulated office work. Among others, the performance tasks included addition tests and text typing tests (two other tests were also presented to the subjects, but were not included in the present analysis).

In the addition task, five two-digit numbers, random but excluding zeros, were printed in columns and the subjects had to add the numbers by performing mental arithmetic. The number of correct additions per hour was used as a measure of their performance. In the text typing task, the subjects retyped a printed text shown to them on a computer screen. Each subject typed during 47 minutes and the number of characters per minute was used as a measure of their performance. The subjects were presented to the performance tasks two times during the total exposure. Subjective assessments of the air quality were made before and after exposure using the continuous acceptability scale ranging from -1 to 1 with a distinction between acceptable and unacceptable (Gunnarsen et al. 1992). Figure 1 shows the scale.
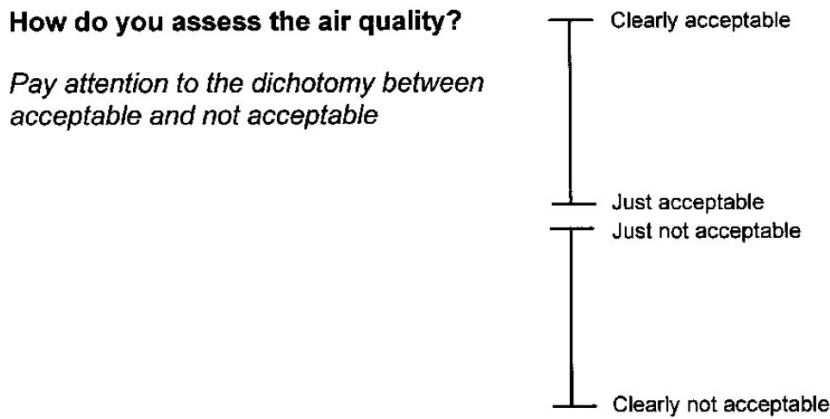
Fig. 1 Pseudo-continuous acceptability scale used to assess the perceived air quality

In addition to the pollution source (the carpet), assessments of the perceived air quality after the 4.6 hrs exposure included also bioeffluents from the subjects. It was this assessment after the exposure that was used to represent the perceived air quality.

Description of the dataset

Each of the 90 subjects was exposed to two different air quality conditions. During each exposure they two times performed two performance tasks. Table 1 shows the variables in the dataset and the first twelve rows of data.

Table 1: First twelve rows of the dataset composed of the experimental results. subj is the subject id, paq the perceived air quality vote, text the text typing task performance, addition the addition task performance, pred.int a variable related with the model intercept (constant value of 1), and pred.airq a variable indicating the experimental exposure.

subj	paq	Text	addition	pred.int	pred.airq
1	-0.097	147	238	1	1
1	-0.109	142	240	1	1
1	-0.098	131	178	1	0
1	-0.102	115	163	1	0
2	-0.014	89	194	1	1
2	-0.020	85	242	1	1
2	-0.947	81	252	1	0
2	-0.950	87	276	1	0
3	-0.202	159	228	1	1
3	-0.199	155	252	1	1
3	-0.702	139	223	1	0
3	-0.697	145	233	1	0

The air quality is characterized by pred.airq, where 1 indicates exposure to good air quality and 0 indicates exposure to poor air quality. The variable pred.int is a constant index variable of the value 1 related with the intercept of the model. The performance variables

text and addition are the response variables indicating the characters typed per minute and the addition units completed per hour. Another response variable is paq indicating the subjective assessment of the air quality from -1 to 1 on the continuous acceptability scale.

Since the perceived air quality (PAQ) was assessed only once after each condition, the same vote was repeated in the dataset, one repetition for each time a performance task was performed within an experimental condition. Therefore, to circumvent numerical errors, a very small random variation was added to the original PAQ score, so the two PAQ scores under the same condition were not completely identical. The error followed a normal distribution with $\mu = 0$ and $\sigma^2 = 0.005$. This is illustrated in Table 1 for subject 3, where the two first and two last PAQ scores differed little within experimental exposure. It is also seen from Table 1 that subject 1 voted the same score under both air quality conditions, but due to the addition of the random error, slightly different scores were applied in the analysis.

Statistical analysis

The multivariate linear mixed-effects model and its assumptions will be introduced in some detail. The model used in the present study was formulated and served as the statistical model known to the *'mlmmm'* procedure: Let one three-dimensional observation, Y_{ij}, consist of the three responses which in the present case were the responses for 'paq', 'text' and 'addition'. Index 'i' represents the subject and the index 'j' indicates the j'th test made on the i'th subject. The data had a common three-dimensional mean, μ, and for each observation there was (in this study) one explaining independent variable (predictor), X_{ij}, namely the air quality (good or poor) chosen by the experimenter for the observation (i, j).

Each subject had her/his own three-dimensional deviation from the common mean and it was denoted by $P_i = \{P_1, P_2, P_3\}_i$. Thus, P_i represents the between-subjects variation, which was assumed to be normally distributed with a variance-covariance matrix $Var\{P\} = G$. Finally $\varepsilon_{ij} = \{\varepsilon_1, \varepsilon_2, \varepsilon_3\}_{ij}$ is the three dimensional vector of random deviations and it represents the residual (including within-subject) variation. ε_{ij} is assumed to be normally distributed with variance-covariance matrix $Var\{\varepsilon\} = \Sigma$. The model for the j'th observation for subject i is then

$$Y_{ij} = \mu + X_{ij}\beta + P_i + \varepsilon_{ij} \qquad\qquad \text{Eq. 1}$$

where $\beta = \{ \beta_1, \beta_2, \beta_3 \}$ is the three dimensional vector of effect estimates corresponding to the independent variable X_{ij}. In the general case X_{ij} can be a vector of predictors in which case β is a matrix.

With reference to Table 1, for example, we can write:

$$Y_{22} = \begin{bmatrix} -0.02 \\ 85 \\ 242 \end{bmatrix} \quad \text{and} \quad X_{22} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

And for this observation

$$\begin{bmatrix} -0.02 \\ 85 \\ 242 \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} + \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix}_2 + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix}_{22}$$

The aim is to estimate $\{\mu_1, \mu_2, \mu_3\}$, $\{\beta_1, \beta_2, \beta_3\}$ and the matrices $Var\{P\} = G$ and $Var\{\varepsilon\} = \Sigma$.

Correlation matrices

The diagonal of the matrix G contains the between subjects-variance for each of the three responses, and the diagonal of Σ contains the residual and within-subject variance for each of the three responses.

From the matrices G and Σ the corresponding correlation matrices were computed and the resulting correlation coefficients describe to which degree the three simultaneous responses, 'paq', 'text' and 'addition' were correlated between and within subjects. Equation 2 shows how the correlation coefficients were calculated.

$$\rho_{ij} = \frac{G_{ij}}{\sqrt{G_{ii}G_{jj}}}, \textit{for } i = 1,2,\ldots,r \textit{ and } j = 1,2,\ldots,r \qquad\qquad \text{Eq. 2}$$

r is the number of subjects in the study. Similar expressions apply for the within-subject covariance matrix Σ.

The conditional correlation represents the correlation between the components of P after removal of the common influence from component m. The conditional correlation between the ith *and* jth component of P, conditioned on component m, can be calculated from Eq. 3.

$$\rho_{ij|m} = \frac{\rho_{ij} - \rho_{im}\rho_{jm}}{\sqrt{\left(1 - \rho_{im}^2\right)\left(1 - \rho_{jm}^2\right)}} \qquad \text{Eq. 3}$$

These conditional correlations represent the correlation between two responses in the case when the third response has a fixed value, and they are computed both for the between and the within subject variances, G and Σ.

Results

Since the applied data set was combined from the results of three studies, a separate analysis was performed for each experiment in order to investigate if the variances could be assumed to be identical across experiments. This analysis indicated that the experiments differed somewhat in this respect, but since the general purpose of this paper was to illustrate the methodology and the differences were not dramatic, data from all three experiments were included in the present analysis.

A common problem in performance experiments has been to isolate from the effect of the environmental exposure the effect of learning due to subjects increased familiarity with the tasks. The current data set was based on experiments conducted in a balanced design, which to some extent moderates the effect of learning, and therefore data was not adjusted for learning.

Implementation and analysis of the proposed model

The initial R commands used to run the *'mlmmm'* routine are shown in Appendix 1a. The outcome of running the routine included a 2x3 matrix of the coefficients of the fixed effects, a 3x3 matrix of the variance-covariance coefficients of the random effects and a 3x3 matrix of the variance-covariance coefficients of the residuals. The commands to achieve this outcome can be seen in Appendix 1b. In the following, the results are further analyzed for statistical significance and correlation between responses.

Table 2 shows the parameter estimates for each response. The first row for each of the responses in Table 2 represents the general mean $\{\mu_1, \mu_2, \mu_3\}$ and the second row represents the estimate of the effect of modifying the air quality $\{\beta_1, \beta_2, \beta_3\}$. The test statistic T was calculated with 90 degrees of freedom, corresponding to the number of subjects in the experiments.

Table 2: Parameter estimates for the three-dimensional response.

	Variable	Estimate	Std error	T stat	Prob > T
Text typing	Intercept (μ_1)	141.67	4.17	33.97	
	good air quality (β_1)	2.13	1.03	2.07	0.04
Addition	Intercept (μ_2)	236.28	6.55	36.07	
	good air quality (β_2)	-4.47	2.68	-1.67	0.10
Perceived air quality	Intercept (μ_3)	-0.0613	0.0435	-1.41	
	good air quality (β_3)	0.1051	0.0279	3.77	0.00001

It is seen from Table 2 that exposing subjects to good air quality (removing pollution sources or increasing ventilation rates) will increase the subjects' performance in the text typing task with 2.13 char/min from 141.7 to 141.7 + 2.13 = 143.8 char/min or approximately 1.5%. On the other hand, exposing subjects to good air quality seemed to decrease their performance of the addition task with 1.9%. There was a significant relationship between text typing and air quality as well as between the assessed perceived air quality and the classification "good" air quality (p=0.04 and p <0.01, respectively). The relationship between addition and air quality was not statistically significant at the 0.05 level, but with a slightly relaxed significance criterion would indicate an effect, although it would be in the opposite direction of the text typing response.

Table 3 shows the estimates of the between-subjects random effects and Table 4 shows the estimates of the within-subject random effects. The diagonal shows the variance components and the covariance components are represented by the adjacent numbers.

Table 3: Estimate of the matrix G representing the between-subjects random variability.

	text typing	addition	paq
text typing	92.0	81.4	0.532
addition	81.4	619.2	0.208
paq	0.532	0.208	0.067

Table 4: Estimate of the matrix Σ representing the residual within-subject variability.

	text typing	addition	paq
text typing	1506.5	949.3	0.063
addition	949.3	3512.2	-0.413
paq	0.063	-0.413	0.135

The magnitude of the variances of the responses (text-typing and addition outcomes and perceived air quality) depended on the scale used to measure the response, and the variances were thus not directly comparable in terms of magnitude. The paq estimates in Table 4 (in grey shading) result from the artificial repetition of paq (inducing a small normal distribution with $\mu= 0$ and $\sigma^2 = 0.005^2$ on the PAQ scores) for each subject. These estimates were not related to the experiments and will not be dealt with.

With the fixed effects estimates, separate model expressions can be written for text typing, addition and perceived air quality in accordance with the general model expression shown in equation 1. Equation 4 shows the model expression for text typing for good air quality:

$$Y_{text,ij} = 141.7 + [1] \cdot 2.13 + P_i + \varepsilon_{ij} \quad with \quad \begin{cases} \varepsilon_{ij} \sim N(0,39^2) \\ P_i \sim N(0,9.6^2) \end{cases} for\ i = 1,2,\ldots,n \quad and\ j = 1,2,\ldots,n \qquad Eq.4$$

and for poor air quality

$$Y_{text,ij} = 141.7 + [0] \cdot 2.13 + P_i + \varepsilon_{ij} \quad with \quad \begin{cases} \varepsilon_{ij} \sim N(0,39^2) \\ P_i \sim N(0,9.6^2) \end{cases} for\ i = 1,2,\ldots,n \quad and\ j = 1,2,\ldots,n \qquad Eq.5$$

where Y_{text} is the performance measurement for text typing (characters per minute). P_i is the between-subjects variation. The between-subjects variation is assumed to follow a normal distribution with mean $\mu= 0$ and variance $\sigma^2 = 9.6^2$. ε_{ij} is the residual variation with mean $\mu= 0$ and variance $\sigma^2 = 39^2$. The difference between the within-subject effect and between-subjects effect indicated that most of the variance in the model was explained by the within-subject residual variation. The effect on text typing performance of improving the air quality was significant, since p = 0.04.

The model expression for addition for good air quality is shown in Equation 6.

$$Y_{add,ij} = 236.3 + [1] \cdot -4.17 + P_i + \varepsilon_{ij} \quad with \quad \begin{cases} \varepsilon_{ij} \sim N(0,59^2) \\ P_i \sim N(0,25^2) \end{cases} for\ i = 1,2,\ldots,n \quad and\ j = 1,2,\ldots,n \qquad Eq.6$$

and for poor air quality

$$Y_{add,ij} = 236.3 + [1] \cdot -4.17 + P_i + \varepsilon_{ij} \quad with \quad \begin{cases} \varepsilon_{ij} \sim N(0,59^2) \\ P_i \sim N(0,25^2) \end{cases} for\ i = 1,2,\ldots,n \quad and\ j = 1,2,\ldots,n \qquad Eq.7$$

where Y_{add} is the number of additions per hour. This relationship was not significant (p = 0.10). Again P_i was the normally distributed between-subjects variation with mean $\mu = 0$ and variance $\sigma^2 = 25^2$. ε_{ij} represents the within-subject residual variation with mean $\mu = 0$ and variance $\sigma^2 = 59^2$. The difference between the variances indicated again that most of the variance in this model was explained by the within- subject residual variation.

Finally, equation 8 expresses the perceived air quality under the "good" air quality condition

$$Y_{paq,ij} = -0.062 + [1] \cdot 0.105 + P_i + \varepsilon_{ij} \quad with \quad \{P_i + \varepsilon_i\} \sim N(0, 0.25^2)$$
$$for\ i = 1,2,\dots,n \quad and \quad j = 1,2,\dots,n$$

Eq.8

and equation 9 under the "poor" air quality condition.

$$Y_{paq,ij} = -0.062 + [0] \cdot 0.105 + P_i + \varepsilon_{ij} \quad with \quad \{P_i + \varepsilon_i\} \sim N(0, 0.25^2)$$
$$for\ i = 1,2,\dots,n \quad and \quad j = 1,2,\dots,n$$

Eq.9

where Y_{paq} is the subjective assessment of the air quality on the continuous acceptability scale ranging from -1 to 1. For "good" air quality 0.105 was added to the mean acceptability obtained under the "poor" air quality conditions. The between and within-subject variation cannot be separated in this model due to the data used to model the estimates. The combined variation is assumed to be normally distributed with mean $\mu = 0$ and variance $\sigma^2 = 0.25^2$.

Correlation between responses
One main advantage of the multivariate mixed-effects model is that it enables assessment of the correlations between the responses. This can indicate whether or not the applied tasks measured similar component skills. In order to analyze the results from the estimates of the random effects variation, a correlation matrix between the responses was determined with Equation 2. Table 5 shows the matrix of correlations between the applied performance tasks and the perceived air quality.

Table 5: Matrix of correlations between the applied performance tasks and the perceived air quality

	text typing	addition	paq
text typing	1	0.34[*]	0.21[*]
addition	0.34[*]	1	0.03
paq	0.21[*]	0.03	1
Note [*]: Significant relationship. Calculated using the 95% confidence interval (CI) for each correlation coefficient and evaluating if the CI includes zero. If so no significant correlation coefficient. CI = $\mu \pm 1.96/90^{-0.5}$			

Table 5 shows a significant and positive correlation between the perceived air quality and the text typing outcome, indicating that if the air quality was perceived as being good, occupants performed better. The correlation between the addition task outcome and the perceived air quality was not significant.

As seen from Table 5 the correlation between the two tasks was 0.34 indicating that when subjects performed better in one task it was also likely that they performed better in the other task, i.e. subjects who were good at mental arithmetic were also good at text typing. To investigate if this correlation depended on the perceived air quality, the conditional correlation was calculated with Equation 3:

$$\rho_{12|3} = \frac{\rho_{12} - \rho_{13}\rho_{23}}{\sqrt{\left(1-\rho_{13}^2\right)\left(1-\rho_{23}^2\right)}}$$

Eq. 10

Insertion of numerical values gives

$$\rho_{12|3} = \frac{0.34 - 0.21 \cdot 0.03}{\sqrt{\left(1-0.21^2\right)\left(1-0.03^2\right)}} = 0.34$$

Eq. 11

The result shows that the correlation between the two task types was independent of the perceived air quality since ρ_{12} was practically equal to $\rho_{12|3}$. Thus the better performing subjects scored high in both tests regardless of the air quality exposure.

Analysis of the within-subject residual variation was used to assess whether the performance of different tasks presented to a subject were correlated. Table 6 shows the correlation coefficients of the within-subject variation between the text typing and addition tasks.

Table 6: Correlation matrix of the residual

	text typing	Addition
text typing	1	0.41*
addition	0.41*	1
Note*: Significant relationship. Calculated using the 95% confidence interval (CI) for each correlation coefficient and evaluating if the CI includes zero. If so no significant correlation coefficient. CI $= \mu \pm 1.96/90^{-0.5}$		

The correlation between text typing variation and addition variation within a subject was found to be 0.41, which again was highly significant. The result indicated that with

repeated testing of one subject, the text typing and addition results were positively correlated which supported the findings of the other analyses conducted.

Discussion

In the initial stages of this study, perceived air quality was anticipated as being the dose variable in the development of dose-response relationships between text typing performance and perceived air quality and between addition performance and perceived air quality. However, in itself perceived air quality was a subjective response variable subjected to both within-subject and between-subjects variability and as such would not be the obvious dose variable choice (in contrast to objectively measurable parameters, e.g. temperature). Researchers and professionals within sensometrics commonly deal with this challenge and have addressed it by using advanced multivariate statistical methods, such as the multivariate mixed-effects analysis. One of the main advantages of this method is that the analysis includes in the same run several response variables and that correlation between the variables is revealed, as it was done in this study for the outcome of the text typing and addition performances. A disadvantage is that the interpretation of the analysis output may not be equally intuitive or as straightforward as the more conventional analyses, such as linear regression analysis, t-test or ANOVA. Nevertheless, as with the conventional ANOVA, the multivariate linear mixed-effects model provides information also on the estimated mean effect of the experimental exposure and with the handling of the between- and within-subject variance may offer a more robust method of analysing experiments that include mental performance as a response to indoor environment exposures. In most such experiments, the magnitude of the difference in performance outcome between exposures is small compared with the between and within-subject variability, and therefore statistical methods that appropriately deal with this variability should be explored. Primarily, the presented study was of a methodological nature and the results were only illustrative examples of how similar data could be analyzed. The results indicated that there was a significant relationship ($p < 0.05$) between the perceived air quality and text typing performance, indicating that when the air quality was good, subjects performed 1.5 % better than when the air quality was poor. Furthermore, subjects perceived the air quality as being better when the pollution source was absent or the ventilation rate increased. The effects of the perceived air quality on the addition task indicated that when the air quality was good subjects performed worse. However, this unexpected relationship was not significant. Depending on how each task cognitively works, the results could be interpreted as indicating that people work faster (more characters

written) in good air quality, whereas the effect on the addition performance of altering the air quality was not conclusive.

The analyses resulted in a positive correlation between the addition task and the text typing task with a correlation coefficient of 0.34. This indicated that the two tasks to some extent measured the same dimension of mental performance. Such information may be valuable in the design of future performance experiments. The probability of interpreting falsely a significant result of the effect on performance of the indoor environmental quality increases with the number of tasks. If, for example, five independent tests are carried out, each with a 5% significance level, the chance of interpreting the effect of the exposure to be significant in at least one task is about 22% when actually no effect occurred. Thus, inclusion of fewer performance tasks may be a means of reducing the risk of making type I errors in univariate analyses of performance experiments. Thus, prior to setting up the experimental performance test ensemble, the desired underlying component skills to test and the correlation between the actual tests that address these skills, should be clear to enable optimisation of the experimental design. Alternatively, multivariate statistical analyses of the results may be used.

The correlation between text typing and addition may be influenced by the level of the perceived air quality, but as indicated by the correlation coefficient between text typing and addition, conditioned on the perceived air quality, this influence had only negligible effect on the correlation estimate. If the perceived air quality influenced the correlation between the two tasks, the interpretation of the correlation would be more difficult. In this case, for example, with poor air quality no correlation would indicate that the two tasks did not measure the same component skills, but if the correlation was significant with good air quality, that the two tasks would measure similar component skills.. With the data included in this analysis, the correlation between text typing and addition was not influenced by the perceived air quality, indicating that regardless of the air quality the two tasks to some extent were measuring the same dimensions of office performance.

Conclusion

Multivariate linear mixed-effects modelling was used to estimate in one step the effect on a multi-dimensional response variable of exposure to "good" and "poor" air quality and to provide important additional information describing the correlation between the different dimensions of the variable. The example analyses resulted in a positive correlation between two performance tasks indicating that the two tasks to some extent measured the same dimension of mental performance. The analysis seems superior to conventional univariate

analysis and the information provided may be important for the design of performance experiments in general and for the conclusions that can be based on such studies.

Acknowledgment

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Appendix 1

The present appendix describes the 'mlmmm' routine available in the statistical package R. R is an open source freeware program that can be downloaded from http://www.r-project.org/.

a)

```
> #Initializing the mlmmm library
> library(mlmmm)
> #Reading data
> data <- read.table("mlmmmdata.csv", header=T, sep=";")
> attach(data)
> #Adding a small error to the paq
> n <- nrow(data)
> dev <- rnorm(n,0,0.005)
> data$paq <- data$paq + dev
> #Prepaping data to be run with the mlmmm routine
> y <- as.matrix(cbind(data$text,data$addition,data$paq))
> subj <- data$subj
> pred <- cbind(data$pred.int,data$pred.airq)
> xcol <- 1:2
> zcol <- 1
> #Running mlmmm
> result.data <- mlmmm.em(y,subj,pred,xcol,zcol,maxits=200,eps=0.0001)
 ###  performing mle for mlmm with NA values ###
```

b)

The fixed effects estimates:
```
> fixed <- result.data$beta
```

The variance-covariance matrix of the within-subject residual variance:
```
> random <- result.data$sigma
```

The variance-covariance matrix of the within-subject residual variance:
```
> residual <- result.data$psi
```