A Procedure to Estimate the Cost Effectiveness of the Indoor Environment Improvements in Office Work

Olli Seppänen

Abstract

Deteriorated indoor climate is commonly related to increases in sick building syndrome symptoms, respiratory illnesses, sick leave, reduced comfort and losses in productivity. The cost of deteriorated indoor climate for the society is high. Some calculations show that the cost is higher than the heating energy costs of the buildings. Also building-level calculations have shown that many measures taken to improve indoor air quality and climate are cost-effective when the potential monetary savings resulting from an improved indoor climate are included as benefits gained. As a step towards systemizing these building level calculations a procedure has been developed to estimate the cost-effectiveness of various measures. The model shows the links between the improvements in the indoor environment and the following potential financial benefits: reduced medical care cost, reduced sick leave, better performance of work, lower turn over of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality and climate. The pathways to these potential benefits from changes in building technology and practices go via several human responses to the indoor environment such as infectious diseases, allergies and asthma, sick building syndrome symptoms, perceived air quality, and thermal environment. The procedure also includes the annual cost of investments, operation costs, and cost savings of improved indoor climate. The model illustrates how various factors are linked to each other.

The paper presents the conceptual model between indoor environment and human responses, summarizes the existing information on the links, and demonstrates the use of those links in the engineering work.

Introduction

The evidence that indoor environmental quality (IEQ) substantially influences health and productivity is becoming strong. Some calculations show that the cost of deteriorated indoor environments is higher than building heating costs [Seppänen 1999]. Macro-economic estimates indicate that large economic benefits are possible from improved IEQ [Fisk 2000, Mendell et al. 2002]. Building professionals should quantify the costs and benefits of measures that improve IEQ; however, as suitable models are not available, only initial costs and energy and maintenance costs are typically considered in economic calculations. However, a few sample calculations have shown that measures to improve IEQ are very cost-effective when the financial value of health and productivity benefits are considered [Djukanovic et al. 2002, Hansen 1997, von Kempski 2003, Seppänen et al. 2000, Smolander et al. 2003, Tuomainen et al. 2003, Wargocki et al. 2003]. Thus, there is an obvious need for tools and models that enable economic outcomes of health and productivity to be integrated with initial, energy and maintenance costs in cost benefit calculations.

The conceptual model on indoor environment and productivity

A conceptual model [Seppänen and Fisk 2003] for estimating the cost-effectiveness of changes in building design or operation that affect IEQ is illustrated in Figure 1. It shows the multiple pathways between measures that improve IEQ and the financial gains resulting from better health and productivity. In the model, a design or retrofit measure leads to an improvement in one or more IEQ conditions (e.g. pollutant concentration), which in turn influences one or more human responses (Boxes #3-9), such as a health condition or complaint frequency. Human responses are linked to benefit categories (Boxes #10-14) such as the health care cost or sick leave days. Finally, changes in the outcomes in boxes #10-14, lead to economic gains (boxes #15-19). The arrows between boxes represent quantitative mathematical functions that link conditions or outcomes in the two boxes.

Human responses

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

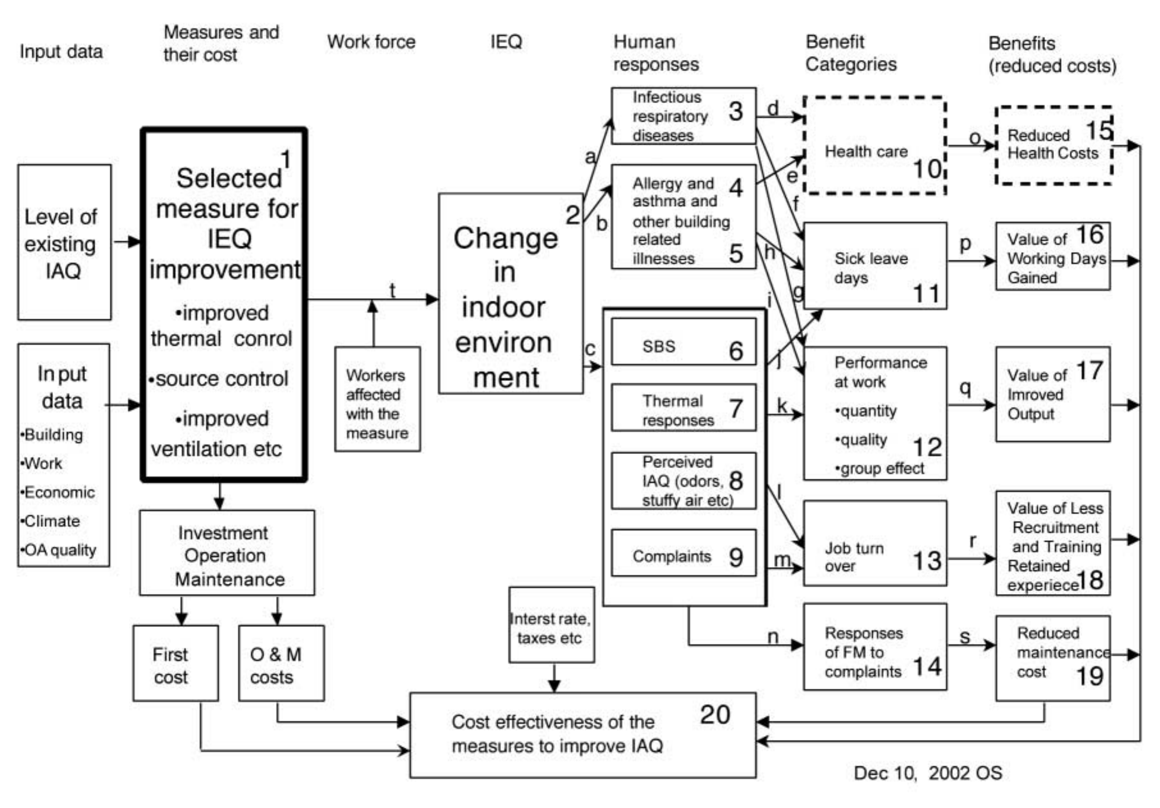


Figure 1: Conceptual economic model to calculate the cost effectiveness of indoor environmental improvements in owner-occupied buildings [Seppänen and Fisk 2003].

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

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

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

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

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

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

Linkages between building features, IEQ and human responses

To use the model, we normally require quantitative estimates of how a building design or operational change influences IEQ conditions and, in turn, quantitative estimates (indicated by functions d-n in Figure 1) of how these conditions affect health, absence, performance, and other financial outcomes. It is obvious that better data are highly desirable for all functions (a-s) relating IEQ conditions to human outcomes. However, it is not essential to quantify all functions because some data directly link building design (HVAC type) or operation (ventilation rate) to a health or performance outcome (Figure 2). This type of linkage is not shown in Figure 1. In the following paragraphs the information available on these links is summarized.

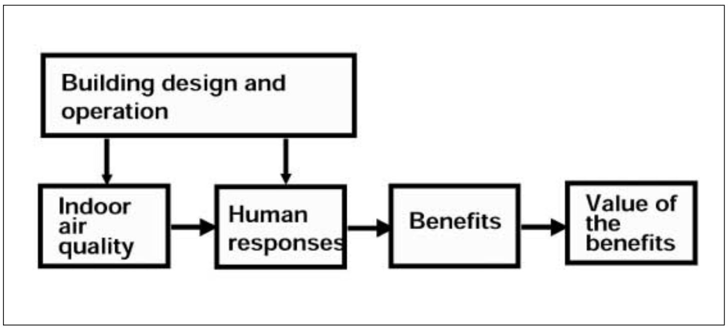


Figure 2: Simplified linkage between building, human responses and benefit.

IEQ-respiratory diseases

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

IEQ-allergy and asthma

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

IEQ-SBS symptoms

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

Thermal environment

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

Perceived air quality

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

Benefits

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

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

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

Reduced responses of facility management to IEQ complaints (#14) are an economic benefit. [Federspiel 2001] analyzed data from 575 buildings and reported that 18.4% of complaints were IEQ complaints. 77% of IEQ complaints were about conditions perceived as too hot or too cold. He showed that the rate of complaints depends on the average temperature and its standard deviation and he estimated maintenance cost savings of $0.0035/ft2 per year.

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

Linkage between human responses and potential benefits

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

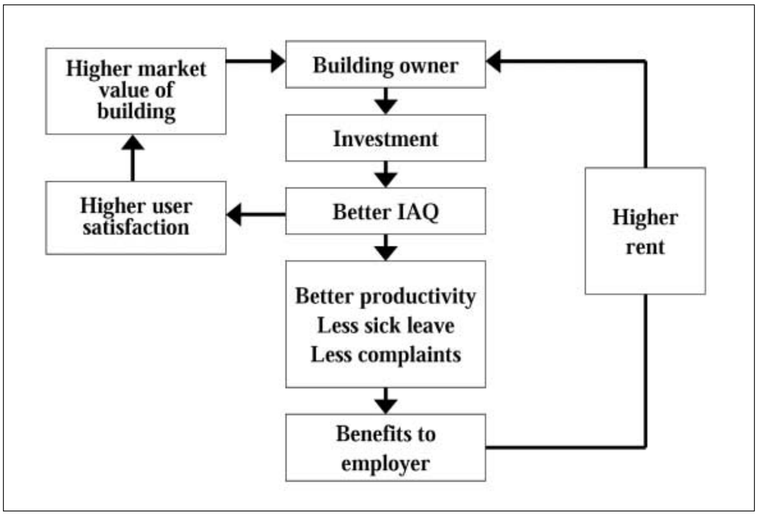
Investment and operational cost

The model includes the cost of investments and building operation and maintenance. The estimation of those costs is a well-developed practice, and not discussed here.

Perspective

The cost effectiveness of measures that improve IEQ conditions varies with the perspective taken (e.g., building owner, employer, broader society). Different benefits would be considered for a rented building from the perspectives of lessor and lessee. Benefits from IEQ improvements may be transferred to a building owner (lessor) via increased rent (Fig 3); however, minimal information is available about how IEQ affects rent. The market value of a building and the ability to renew leases or attract new lessees may also be increased by a reputation of high IEQ. [Hanssen 1997] refers to a study which concluded that a tenant does not renew the lease agreement (e.g., due to frequent IEQ complaints) the costs of lost rental income, remodeling, etc. to the owner will be equivalent to one and half years rent. The owner (lessor) may also benefit from reduced maintenance costs resulting from fewer IEQ complaints. An employer (lessee) receives the benefits of improved productivity. Lessees will generally not directly experience the costs of building design or operational changes. Lessees might benefit from lease terms that require IEQ

Figure 3: Benefits of improved IEQ are transferred to building owner via rent and long term value of the building.



maintenance measures. In general, neither the owner (lessor) nor the employer (lessee) benefit from reduced medical care costs which are usually covered nationally or by insurance.

Linkage between productivity and high temperatures

Temperature could influence productivity indirectly through its impact on prevalences of SBS symptoms or satisfaction with air quality; however, for cost-benefit calculations it is most feasible to use the available data directly linking temperature, or thermal state, to productivity.

Some research e.g. [Griffiths and McIntyre 1975; Gonzales 1975] indicates that the most comfortable temperature yields optimal work performance, while others research provides evidence of better performance outside the comfort zone due to arousal effect of the environment [Wyon et al. 1979]. Based on the review [Seppänen et al. 2003], available data do not provide compelling or consistent evidence that temperature variations within the comfort zone significantly affect worker performance. However, performance decrements are more clearly established for temperatures outside of the comfort zone. Decrements are most clearly documented for high temperatures.

These findings of the review are summarized in Figure 4. It shows the decrement in work performance as a function of temperature from all of the experiments. All data were normalized using the best value of the productivity in each experiment as a reference.

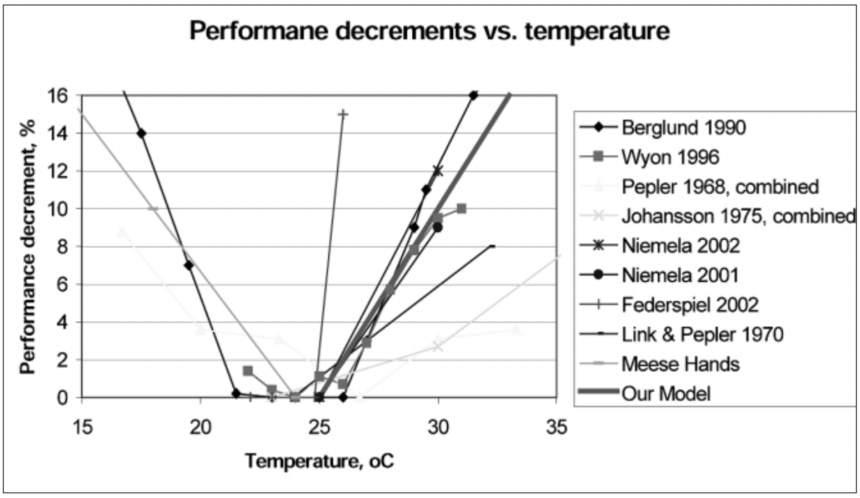


Figure 4: Summary of the studies on the decrement of performance and productivity [Seppänen et al 2003]

After plotting these findings it is obvious that productivity is unaffected by temperature in the 21 to 25 °C range. While the case for productivity decrements at elevated temperatures seems relatively strong. A line, shown in Figure 4 and labeled "Our Model" in the legend, with a linear productivity decrease of 2% per degree centigrade as the temperature increased above 25 oC, yields the following relationship between decrement in productivity P in % and temperature:

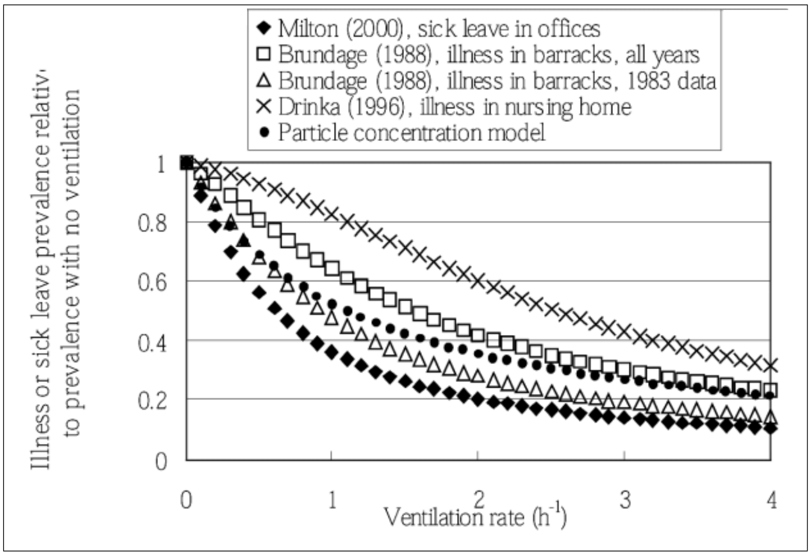
P (%) = 2 x (Temp, °C) – 50

Linkage between ventilation rates, health and productivity

Ventilation and health effects

The review of ventilation rates and human responses [Seppänen et al. 1999] summarises the results of four studies available at that time on the health effects of ventilation rates. These were performed in a jail, barracks, a home for the elderly and offices. All of them reported significant association between low ventilation rates and increase in health problems: pneumonia, upper respiratory illnesses, influenza and short term sick leave respectively. Even though the ventilation rates were estimated and not measu-

Figure 5: Predicted trends in illness of sick leave versus ventilation rate [Fisk et al. 2003]



red, the consistent findings are a strong indication of the association of ventilation rates with health effects. The estimated effect of ventilation on the prevalence of infectious disease based on several studies and theoretical Wells-Riley equation [Nardell et al. 1991] on airborne transmission of infectious respiratory diseases is presented in figure 5. The strongest evidence is provided by the most recent study of these [Milton et al. 2000]. The association with sick leave was analysed for 3720 employees in 40 buildings using 115 independently ventilated ventilation areas. Among office workers, the relative risk for short term sick-leave was 1.53 (1.22 – 1.92 c.i.) with the estimated ventilation of 12 L/s per person compared with a ventilation rate of 24 L/s per person.

Ventilation rates and SBS-symptoms

Two reviews by [Seppänen et al. 1999] and [Wargocki et al. 2002] on the association of ventilation rates and human responses show that ventilation rates below 10 L/s per person are associated with a significantly inferior prevalence or value of one or more health or perceived air quality outcomes. Most studies indicated a significant association with ventilation rate. Available studies further show that increases in ventilation rates above 10 L/s per person, up to approximately 20 – 25 L/s per person, are associated with a significant decrease in the prevalence of SBS symptoms, or with improvements in perceived air quality. The less consistent findings for relationships in the range above 10 L/s per person are compatible with the prediction that benefits per unit increase in ventilation would be likely to diminish at higher ventilation rates and, thus, be more difficult to detect epidemiologically.

Ventilation and productivity

The effect of ventilation on productivity was demonstrated by [Wargocki et al. 2000] in a simulated office environment. They exposed five groups of six female subjects to three ventilation rates (3, 10, and 30 L/s per person), one group and one ventilation rate at a time. The performance of four simulated office tasks improved monotonically with increasing ventilation rates, and the effect reached significance in the case of text typing. For each twofold increase in ventilation rate, performance improved on average by 1.7%. The study indicates the benefits of ventilation at rates well above the minimum levels prescribed in existing standards and guidelines.

Example 1

Cost-benefit analysis of air conditioning and operation time

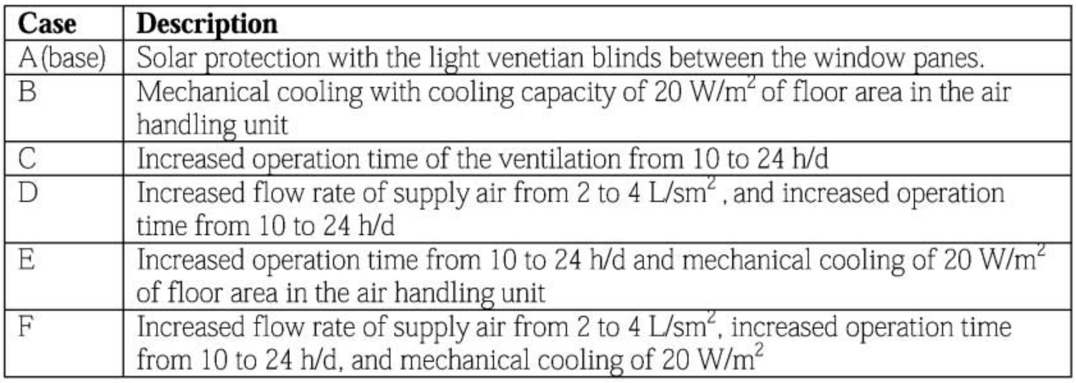
High indoor air temperature is often a problem in office buildings. Not all buildings are air conditioned or protected with other means against high temperatures either due to the solar radiation or high outdoor temperatures. The following example focuses on cost effectiveness of alternative remedial measures for existing buildings to reduce high summer time indoor temperatures. The cost items, which are included in the analysis, are: capital cost of the remedial measure, cost of the used energy (heat and electricity), and the cost of deteriorated productivity due to high temperatures.

A typical Finnish office building was selected for the analysis [Seppänen and Vuolle 2003]. It is a concrete structure with narrow bays and private offices located in the exterior zone of building (no open plan offices). A small office was selected in the detailed analysis. The main features of the room are described in the table 1.

Table 1. Main features of the office room used in the analysis.

Floor area	9.7 m^2	Construction	Heavy
Room volume	18.2 m^3	Windows	3 panes, clear glass
Outdoor wall area (excl. windows)	5.3 m^2	Glass area of the windows	2.5 m^2
Lighting load	15 W/m^2	Lights on	8 am to 4 pm
Heat load from office equipment	100 W	Load on	8 am to 4 pm

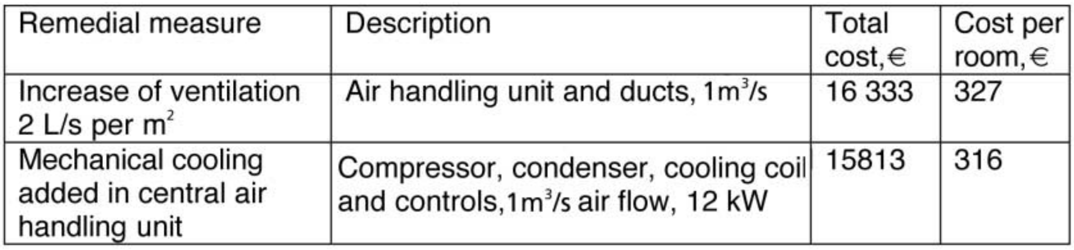
The basic case used as a reference had solar protection of windows, and heavy construction to decrease the daily high temperatures with the thermal capacity. Thus the other means to reduce high temperatures are limited to those related to ventilation. The options to reduce high room temperature are: increase the outdoor air low rate (usually the outdoor air temperature is lower than indoor air temperature in Finnish climate), increase the operation time of ventilation (typically the ventilation is running only during the office hours plus a couple of hours), and mechanical cooling. The base case A, and the remedial measures of the cases (B-F) are summarized in the table 2.



Case	Description
A (base)	Solar protection with the light venetian blinds between the window panes.
B	Mechanical cooling with cooling capacity of 20 W/m^2 of floor area in the air handling unit
C	Increased operation time of the ventilation from 10 to 24 h/d
D	Increased flow rate of supply air from 2 to 4 L/sm^2 , and increased operation time from 10 to 24 h/d
E	Increased operation time from 10 to 24 h/d and mechanical cooling of 20 W/m^2 of floor area in the air handling unit
F	Increased flow rate of supply air from 2 to 4 L/sm^2, increased operation time from 10 to 24 h/d, and mechanical cooling of 20 W/m^2

Table 2: The description of base case A and remedial measures used in calculations

The investment costs of the remedial measures are given in the 3. The investment cost are based on a large Finnish database on refurbishment costs. The first costs have been calculated assuming 50 similar rooms to be repaired under the same contract. The total cost has been divided by 50 to get the cost per room. The first cost has been converted to annual cost using the annuity factor of 0.1098 which corresponds the life cycle of 15 years and interest rate of 7 %.



Remedial measure	Description	Total cost, €	Cost per room, €
Increase of ventilation 2 L/s per m^2	Air handling unit and ducts, 1m^3/s	16 333	327
Mechanical cooling added in central air handling unit	Compressor, condenser, cooling coil and controls, 1m^3/s air flow, 12 kW	15813	316

Table 3: First cost of some remedial measure to control high room temperatures

The effect of the remedial measures on room temperature, productivity and energy consumption was calculated with a modular computer program IDA Indoor Climate and Energy [Vuolle and Salin 2000]. The energy consumption was calculated using Helsinki reference year weather data.

The energy costs used in the calculations reflect the average energy cost in Finland, for heating 0.03 Euro/kWh was used and 0.1 Euro/kWh for electricity. The calculated electrical energy in the table 5 includes all electricity used per room: lighting, office equipment, fans, and mechanical cooling (COP=3). Heating energy includes only the energy used for heating of the outdoor air. Heat recovery from ventilation air with temperature efficiency of 50% is used in calculations.

The estimated loss of productivity is based on equation presented earlier in the paper. The value of annual production of each employee was assumed to Euro 50.000. The operative temperature of assumed working location in the room was calculated for each hour and the loss of productivity summarized over the whole year.

In the total cost calculations the case A in the Table 4 was been taken as a reference case and the other cases compared with it. Three cost items ware included: investment cost, operation cost (mainly energy), and the changes in productivity. Investment cost is the total investment of the remedial measure per room. In the final analysis the changes in productivity is calculated using as the reference the base case A. In all other cases the losses in productivity are smaller then in the base case, and the difference is a positive gain. The cost of this gain is investment, and penalty in the increased use of energy. The increase in energy consumption has been calculated using the case A as a reference.

Results

The results of the calculations are shown in table 4. The total consumption of electricity and heat are presented for all 50 rooms. The costs of heat and electricity are in all cases of same order of magnitude. The cost of heat increases considerably with the increase of outdoor air flow rate and operation time which can be expected. It is interesting to notice that the increase in electricity consumption is higher if the outdoor air flow rate is doubled (case D vs C) than if the mechanical cooling is used with lower flow rate (case E vs. C).

The maximum room temperature in the base case is 32.7 °C, and corresponding degree hours above 25 °C are 330 °Ch. The maximum temperature can be lowered to 29.8 °C and degree days to 164 °Ch by increasing the operation time and air flow rate of ventilation, but to 27.1 °C and 17 °Ch with mechanical cooling. The investment cost and energy costs are considerably higher in the case of increased ventilation than with mechanical cooling.

In respect of over all economy the both alternatives with mechanical cooling are best e.g. give the highest annual savings.

Table 4. The basic data of and results of the calculations with different remedial measures. The case A is used as a reference when incremental costs and savings are calculated.

Factor	**Case**					
	A	B	C	D	E	F
Supply air flow, L/sm^2	2	2	2	4	2	4
Solar protection	Yes	Yes	Yes	Yes	Yes	Yes
Operation time of air supply h/d	10	10	24	24	24	24
Mechanical cooling W/m^2	0	20	0	0	20	20
Electricity kWh/a	24 403	26379	31 273	43 217	35 453	50 523
Heat kWh/a	38 636	38448	65 007	109 719	65 209	110 326
Electricity /a	5 740	5929	6 170	7 115	6 528	7 731
Heat /a	3 864	3844	6 501	10 972	6 521	11 032
First cost of remedial measure, /room	-	316	-	327	316	643
Degree hours above 25 °Ch	890	390	367	164	51	17
Max room temperature during working hours, °C	32.7	29.5	30.8	29.8	27.3	27.1
Annual cost of lost productivity per room (per person)	330	142	139	64	19	7
Value of improved productivity per room (a)	**0**	**188**	**191**	**266**	**311**	**323**
Annual **cost of investment per room** (15 years, 7 %) **/a (b)**	**0**	**35**	**0**	**36**	**35**	**71**
Annual energy cost per room /a	192	195	253	361	260	375
Increase in energy cost, per room (c)	**0**	**3**	**58**	**169**	**68**	**183**
Total annual savings per room /a (a-b-c)	**0**	**150**	**133**	**61**	**208**	**69**

The share of the first cost is small compared to other costs in all cases. The annual cost of the energy and savings in increased productivity are in order of same magnitude. The effect of mechanical cooling and increased supply air flow are approximate equal in first cost but mechanical cooling is more effective in controlling the room temperatures. The results presented in table 6 are illustrated in the figure 4.

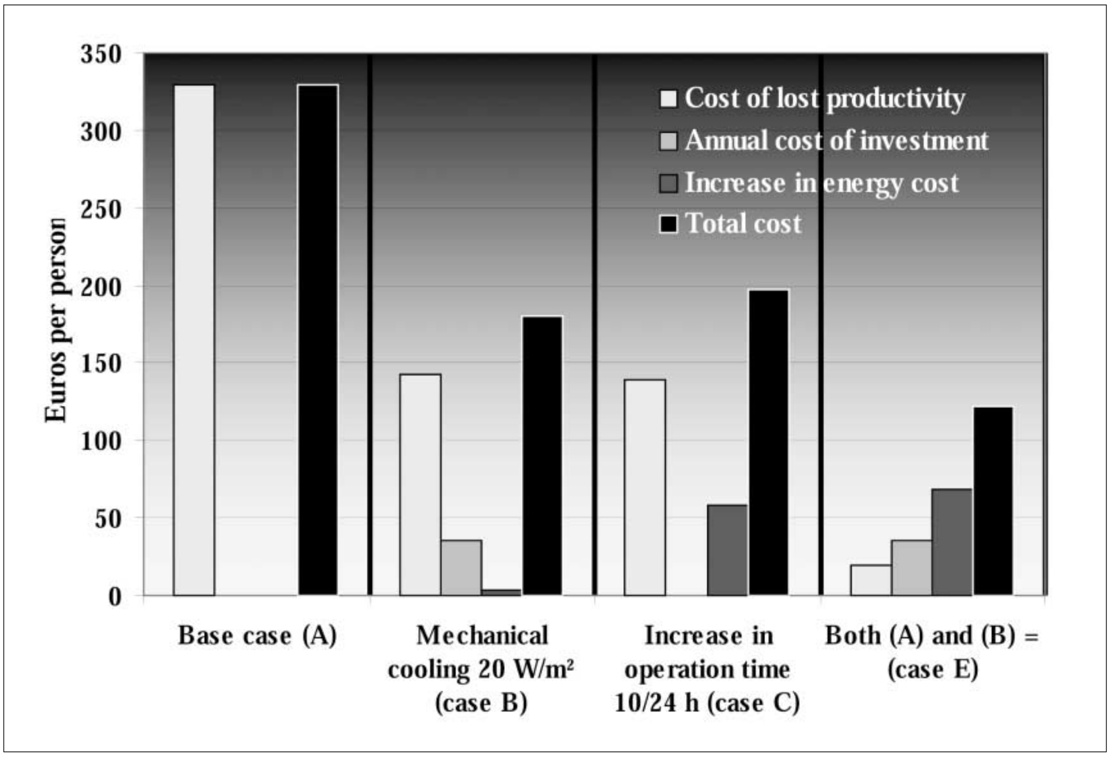


Figure 6: The effect of mechanical cooling (20 W/m^2) and increased operation time of ventilation (from 10 to 24 h) on the cost items related to room temperature control in a typical Finnish office building (Euros per person).

The results show clearly how important it is to control the room temperature in summertime in office buildings for good over all economy. Of course, the investment cost depends on the specific case, and may vary depending on the difficulties in actual installation considerably. This is specifically true if the increase of ventilation requires also new duct work. The mechanical cooling is usually easier to install in the existing system. In this case also the existing air handling unit may set some restrictions as well. However, even the doubling of the first cost will not change the annual savings negative. The interest rate of 7 % may be high at the moment but has only a minor effect on the annual, cost of the investment. The expected life cycle of the air handling system and air conditioning is 15 years. This can be considered typical and is taken from a reliable source.

The unit costs of energy used in calculations represent average Finnish energy prices which may a little low in respect of electricity for the Middle Europe and a little high in comparison to the area where for example natural gas is available. The first cost of the remedial measures as well as the value of work may vary considerably by case to case, however, the marginal in the results is so large that a similar result can be expected in other climates and conditions as well.

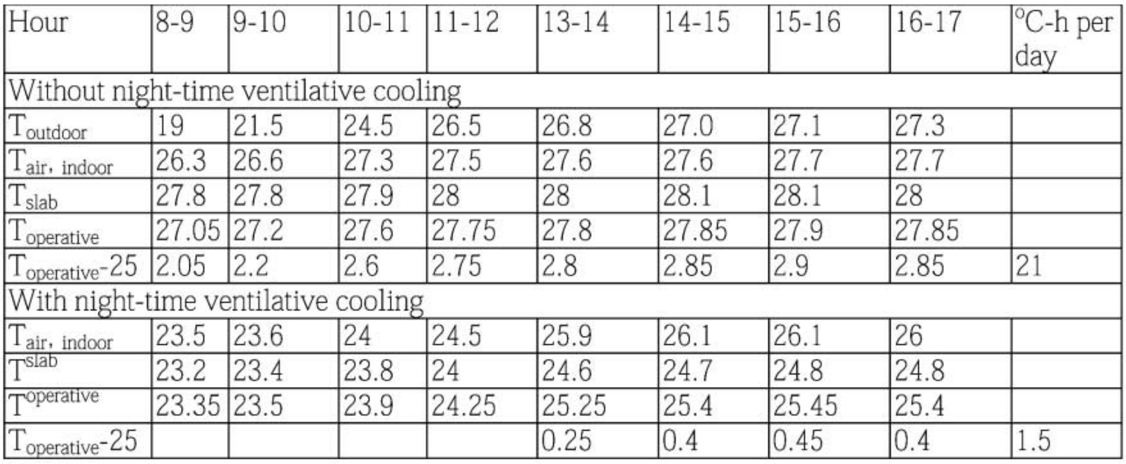
Example 2
Cost-benefit analysis of night-time ventilative cooling

Natural and mechanical night-time ventilative cooling is a cooling strategy that has been used throughout the centuries especially in climate regions with hot summers. Recently, there is a renewed interest in night-time ventilative cooling in both hot and moderate climates due to its potential benefits in indoor temperature control with low energy use and, hence, with low environmental impact. Its principle is based on the daily temperature swings during hot periods. A typical daily temperature swing is around 12 °C; however, it can be considerably smaller (e.g., on cloudy days) or higher with clear skies and a continental climate. The cool nighttime air can be used to cool the building during night. This cools the structure and furnishings, which become a heat sink during the day, thus, reduce the day-time temperatures.

The following example shows the cost effectiveness of night time ventilative cooling when applied in the measured data by [Kolokotroni et al. 2001] who have provided measured room air and slab temperature for an office room with and without night-time ventilation. These data was used in conjunction with the simple productivity decrement model and an estimate of the cost of fan energy to perform a cost-benefit analysis of providing night-time ventilative cooling in an non air conditioned office building.

Table 5 provides temperatures based on the data of [Kolokotroni et al. 2001]. The operative temperature was estimated as average of air and slab temperatures for the room with and without night-time ventilation, and degree hours above 25 °C was calculated for both cases. Without the night-time ventilation there were 21 °C-hours above 25 °C. With the night-time ventilative cooling, there were only 1.5 °C-hours above 25 °C . The difference of 19.5 °C-hours per day is the benefit of night-time ventilation.

Table 5: Hourly temperatures without (above) and with night-time ventilation and hourly temperature differences above limit temperature of 25 °C

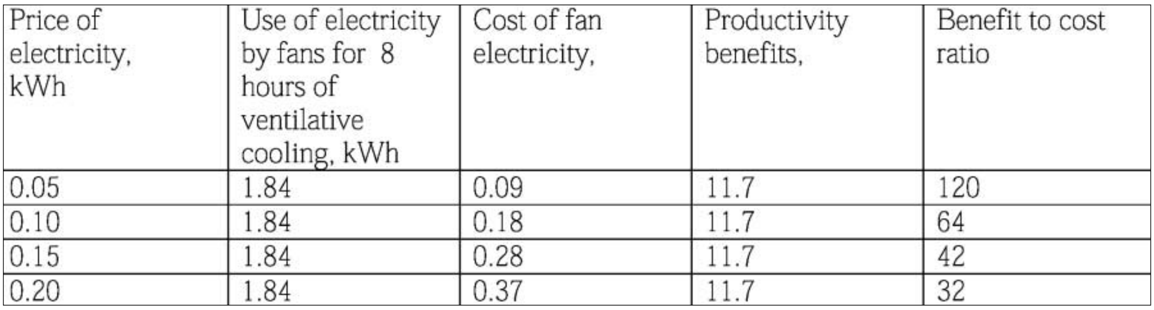


Hour	8-9	9-10	10-11	11-12	13-14	14-15	15-16	16-17	°C-h per day
Without night-time ventilative cooling									
$T_{outdoor}$	19	21.5	24.5	26.5	26.8	27.0	27.1	27.3	
$T_{air, indoor}$	26.3	26.6	27.3	27.5	27.6	27.6	27.7	27.7	
T_{slab}	27.8	27.8	27.9	28	28	28.1	28.1	28	
$T_{operative}$	27.05	27.2	27.6	27.75	27.8	27.85	27.9	27.85	
$T_{operative}$-25	2.05	2.2	2.6	2.75	2.8	2.85	2.9	2.85	21
With night-time ventilative cooling									
$T_{air, indoor}$	23.5	23.6	24	24.5	25.9	26.1	26.1	26	
T^{slab}	23.2	23.4	23.8	24	24.6	24.7	24.8	24.8	
$T^{operative}$	23.35	23.5	23.9	24.25	25.25	25.4	25.45	25.4	
$T_{operative}$-25					0.25	0.4	0.45	0.4	1.5

Using the linear relation between loss of productivity and temperature, with a 2% productivity loss per degree when the temperature is above 25 °C, the productivity increase with night-time ventilative cooling is equivalent to 0.39 hours of work per day (19,5 °C-hours per day x 0.02 per °C = 0.39 h/day). If we assume that the average value of an hour of work is Euro 30 hourly, the productivity benefit is Euro 11,7 per day per person. Of course, this benefit can be only realized during periods of hot outdoor daytime temperatures, and the magnitude of the benefit will depend on both the daytime temperatures and the daily temperature swing.

It was assumed that the air handling system was used for night ventilation with a running time of 8 hours a night. The use of fans requires some energy. The fan power in calculati-

Table 6: Cost of electricity and value of improved productivity due to night ventilation. All values per occupant per day.



Price of electricity, kWh	Use of electricity by fans for 8 hours of ventilative cooling, kWh	Cost of fan electricity,	Productivity benefits,	Benefit to cost ratio
0.05	1.84	0.09	11.7	120
0.10	1.84	0.18	11.7	64
0.15	1.84	0.28	11.7	42
0.20	1.84	0.37	11.7	32

ons was based on the Finnish building code value (D2 2002) for total energy consumption of return, exhaust and supply fans of 2.5 kW per m^3/s of air flow. For the basic night ventilation rate a 4 air change per hour flow rate was assumed, typical of the capacity of many HVAC systems, and a room volume of 83 m^3 per occupant. The resulting costs of fan energy with electricity prices from Euro 0,05 to Euro 0,20 per kWh are shown in Table 6. The table also shows the corresponding benefit-to-cost ratios which range from 32 to 120.

Discussion

For cost-benefit analyses, the relationships between IEQ conditions (or IEQ improvement measures) and financial outcomes related to health and productivity must be quantifiable. Thus mathematical functions are needed for arrows between the boxes in Figure 1. To date, we have some quantitative functions as demonstrated above but more are needed.

The quantitative relationship between indoor environmental factors and productivity may vary depending on other building features, and on the characteristics of building occupants and their type of work. Remedial measures will generally also be more cost effective in buildings that have poorer initial IEQ or more existing adverse health effects.

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

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

References

Berger M, Murray J, Xu J, Pauly M 2001. Alternative valuations of work loss and productivity. J Occup Environ Med. 43:18-24.

Bornehag C-G, Blomquist G, Gyntelberg F, Jarvholm B, Malmberg P, Nordvall L, Nielsen A, Perhagen G, Sundell J. 2001. Dampness in Buildings and health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to "dampness" in building and health effects (NORDDAMP). Indoor Air 11:2:72-86.

D2. 2002. Finnish Building code, part D2. Indoor Climate and Ventilation. 2003.

Djukanovic R, Wargaocki R, Fanger PO. 2002. Cost-benefit analysis of improved air quality in an office building. Proc. of Indoor Air 2002, vol 1 , pp 808-813, Indoor Air 2002, Inc, Santa Cruz, CA.

Federspiel C. 2001. Estimating the Frequency and Cost of Responding to Building Complaints In: Spengler, J. Sammet J. and McCarthy, J. eds. Indoor Air Quality Handbook, McGraw Hill

Fisk, W. J. 2000. Health and productivity gains from better indoor environment and their relationship with building energy efficiency. Annual Review of Energy and the Environment 25: 537-566.

Fisk WJ, Seppänen O, Faulkner D, Huang J (2003) Cost benefit analysis of ventilation control strategies in an office building, Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3:361-366.

IOM 2000. Committee on the Assessment of Asthma and Indoor Air. Clearing the air- Asthma and Indoor Air Exposures. National Academy Press. Washington, DC.

Goetzel R, Guidon A, Turshen J, Ozminkowski R. 2001 Health and Productivity Management - Establishing Key Performance Measures, Benchmarks, and Best Practices. J. Occup Environ Med 43:10-17

Gonzales R. 1975. Effect of ambient temperature and humidity on human performance. Special technical report #4. John B Pierce Foundation Laboratory. New Haven, Connecticut, USA

Griffiths T, McIntyre D, 1975. The effect of mental effect on subjective assessments on warmth. Ergonomics, vol 18, No 1, 29-32

Hanssen S-O. 1997. Economical consequences of poor indoor air quality and its relation to the total building operation costs. Proc. EuroFM/IFMA Conference & Exhibition, Torino, Italy, pp. 1-21, International Facility Management Association.

Kolokotroni M, Perera M, Azzi D, Virk G. 2001. An investigation of passive ventilation cooling and control strategies for an educational building. Applied Thermal Engineering 21:183-199

Lahtinen M, Huuhtanen P, Kahkonen E, Reijula K. 2002. Psychosocial dimensions of solving an indoor air problem. International Journal of Indoor Environment and Health 12:33-46

Mendell M.1993. Non-specific symptoms in office workers: A review and summary of the epidemiological literature. Indoor Air 3:227-236.

Mendell M, Fisk WJ, Kreiss K, Levin H, Alexander D et al. (2002) Improving the health of workers indoor environments: Priority research needs for a national of occupational research agenda, American Journal of Public Health. 92:9;14301-440

Milton K, Glenross P, Walters M (2000) Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaint, Indoor Air 10 :212-221.

Nardell, EA, Keegan J, Cheney SA et al. 1991 Theoretical limits of protection achievable by building ventilation. American Review of Resiratory Disease. Vol. 144, pp. 302-306

Niemelä R, Hannula M, Rautio S, Reijula K, Railio J (2002) The effect of indoor air temperature on labour productivity in call centers – a case study. Energy and Buildings 34: 759-764.

Seppänen O. 1999. Estimated cost of indoor climate in Finnish buildings. Proceedings of Indoor Air 1999, 3, pp 13-18.

Seppänen O, Vuolle M. 2000. Cost effectiveness of some remedial measures to control summer time temperatures in an office building. Proc of Healthy Buildings 2000, vol.1 pp.665-660, SIY Indoor Air Information Oy, Helsinki, Finland

Seppänen O, Fisk WJ. 2002. Association of ventilation system type with SBS symptoms in office workers. International Journal of Indoor Environment and Health, 12:98-112.

Seppänen O, Fisk WJ, Mendell M. 1999. Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. Indoor Air 9:226-252.

Seppänen O, Vuolle M. 2003. Cotrol of temperature for productivity. REHVA Journal. September 2003.

Seppänen O, Fisk WJ. (2003). A Conceptual Model to Estimate the Cost Effectiveness of the Indoor Environment Improvements. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3, 368-373

Seppänen O, Fisk WJ , Faulkner D, (2003) Cost benefit analysis night-time ventilative cooling. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3:394-399.

Smolander J et al. Potential benefits of reduced summer time room temperatures in an office building. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3, 389-394

Tuomainen M. et al. Potential economic benefits of balancing air flows in an office building. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 2, 516—521.

von Kempski D. Air and well being – A way to more profitability. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3, 348-354.

Vuolle M and Salin P. IDA indoor climate and energy – a new generation simulation tool. Proceedings of Healthy Buildings 2000, vol 2:523-528. Espoo, Finland.

Wargocki, P., Wyon, D., Fanger, P (2000). Productivity is affected by the air quality in offices, Proceedings of Healthy Buildings 2000, vol. 1, 635 – 640, SIY Indoor Air Information Oy, Helsinki, Finland

Wargocki P. Estimate of economic benefits from investment in improved indoor air quality in office building. Proceedings of Healthy Buildings 2003 Conference. Singapore. December 2003. Vol 3, 383-387.

Wargocki PW, Sundell J, Bischof W, et al. 2002. Ventilation and health in non-industrial indoor environments. Report from a European multidisciplinary scientific consensus meeting. Indoor Air Vol 12 (2), pp 113-128.

Wyon D. (1996) Individual microclimate control: required range, probable benefits and current feasibility. Proceedings of Indoor Air 1996, vol 1:1067-1072

Wyon DP, Andersen IN, and Lundqvist GR. 1979. The effects of moderate heat stress on mental performance. Scandinavian Journal of Work Environment and Health 5: 352-361