COST BENEFIT ANALYSIS OF THE NIGHT-TIME VENTILATIVE COOLING IN OFFICE BUILDING

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ABSTRACT
The indoor temperature can be controlled with different levels of accuracy depending on the building and its HVAC system. The purpose of this study was to evaluate the potential productivity benefits of improved temperature control, and to apply the information for a cost-benefit analyses of night-time ventilative cooling, which is a very energy efficient method of reducing indoor daytime temperatures. We analyzed the literature relating work performance with temperature, and found a general decrement in work performance when temperatures exceeded those associated with thermal neutrality. These studies included physiological modelling, performance of various tasks in laboratory experiments and measured productivity at work in real buildings. The studies indicate an average 2% decrement in work performance per degree ^{o}C temperature rise, when the temperature is above 25 ^{o}C. When we use this relationship to evaluate night-time ventilative cooling, the resulting benefit to cost ratio varies from 32 to 120.

INDEX TERMS
Economics, cooling, productivity, temperature, ventilation

INTRODUCTION
In many commercial buildings, thermal conditions are not well-controlled due to insufficient of cooling or heating capacity, high internal or external loads, large thermal zones, improper control system design or operation, and other factors. For example, in a large US study, 50% of the subjects preferred a change in their thermal state, 38% of subjects in winter were dissatisfied with thermal conditions, and almost 50% of the thermal conditions during summer were outside of the thermal comfort zone (Schiller et al. 1988). Thermal conditions inside buildings vary considerably with time, e.g., as outdoor conditions change, and spatially within buildings. While the effects of temperature on comfort are broadly recognized, the effects on worker productivity have received much less attention. For this paper, we assembled existing information on how temperature affects productivity so that these productivity effects could be incorporated in cost benefit calculations related to building design and operation.

LINKAGE BETWEEN PRODUCTIVITY AND HIGH TEMPERATURES
We assembled existing information on how temperature affects productivity so that these productivity effects can be incorporated in cost benefit calculations related to building design and operation. Air 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.

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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 our review, 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.

Relatively few studies report the effect of temperature on objectively measured performance, and some of the available data are for factory or largely manual work. Niemelä et al. (2001) reported a decrement in productivity of call centre workers corresponding to 1.8% per ^{o}C when the temperature was above 25 ^{o}C. In a second experiment performed in the same call center, Niemelä et al. (2002) reported a productivity decrease of 2.2% per ^{o}C when the temperature increased above 25 ^{o}C. Federspiel et al. (2002) measured the productivity of call center workers in the US. They found no significant relationship of temperature to productivity in the comfort zone but reported a 15% decrease in work speed as the temperature increased from 24.8 to 26 ^{o}C. Link and Pepler (1970) measured productivity in an apparel factory. They found a reduction of 8% in productivity in sewing work as the temperature increased from 23.9 to 32.2 ^{o}C.

Wyon (1996) summarized his earlier experimental work and developed a relationship to estimate the productivity decrement in office work based on experimental data from tests which measured thinking performance, and typing skills and speed. He gave equal weigh to each skill and ended up with a relationship between an over-all decrement of performance in office work as a function of the difference between the actual temperature and the temperature for thermally neutrality. Berglund et al. (1990) used the data from a test relating the performance of wireless telegraph operator in a wide range of thermal conditions from comfortable to very hot. The data were obtained with very lightly clothed subjects and temperatures that are uncommon in today's buildings (29 – 41 ^{o}C). However, Berglund used physiological thermal model to relate performance to "effective temperature" (ET*) and then used this relationship to predict how the productivity of normally clothed office workers would vary for a typical range of indoor temperatures. His analysis is based on an assumption that the thermal stress is the best indicator of the performance and productivity. Roelofsen (2001) used this model further and converted Berglund's ET*-values to two commonly used thermal comfort parameters, predicted mean vote (PMV) and predicted percent dissatisfied (PPD) which enables the model to be used for various combinations of thermal factors. Johansson (1975) exposed 18 boys and 18 girls with light clothing in a climate chamber to effective temperatures of 24, 27 and 30 ^{o}C, corresponding with normally-clothed subjects with the same degree of thermal strain at 23, 30 and 36 ^{o}C. Several tests were used to evaluate the effect of thermal environment on performance. Most tasks, except cue utilization and similar perceptual and non-motor tasks, were impaired for higher two temperatures. Performance in tests of learning, addition and multiplication tests were 10 –14% worse at the effective temperatures of 27, 29 ^{o}C as compared to at 24 ^{o}C. Perceptual tasks measuring cue-utilization and attention had an inverted U-shape relationship with temperature with the best performance in 27 ^{o}C. Pepler and Warner (1968) performed experiments with 36 female and 36 male students in a climate chamber. They found an inversed U-shape relationship between time to complete a task and temperature, with the longest time to complete assignments work at 26.7 ^{o}C. However, the error rate was lowest at 26.7 ^{o}C.

These findings are illustrated in Figure 1. It shows the decrement in work performance as a function of temperature from all of these experiments. The results from laboratory studies were given as the average results from the tests. We combined speed and error results from Pepler and Warner (1968) by calculating an over all effect based on estimated correct answers. We averaged results from seven mental tests by Johansson (1975) (3 memory tests, 2 learning tests, one addition test and one multiplication test) and used that estimate in the performance of office work. All data were normalized using the best value of the productivity in each experiment as a reference.

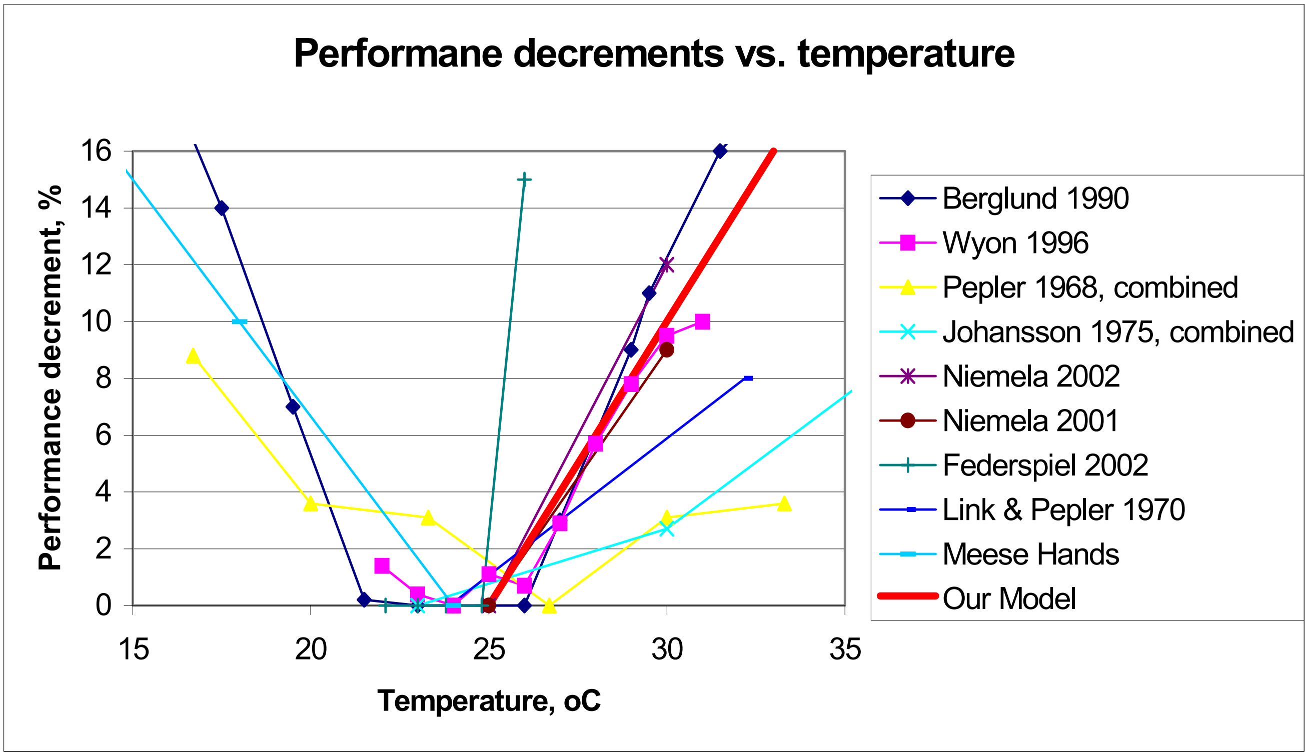

Figure 1. Summary of the studies on the decrement of performance and productivity.

After plotting these findings in the Figure 1, for cost- benefit analyses we assumed that productivity was unaffected by temperature in the 21 to 25 ^{o}C range. While the case for productivity decrements at elevated temperatures seems relatively strong, the relative weight that should be applied to different studies is unknown, thus, we concluded that deriving a linear or non-linear statistical best fit to the available data was not warranted. Thus, we drew a line, shown in Figure 1 (labelled "Our Model" in the legend), with a linear productivity decrease of 2% per degree centigrade as the temperature increased above 25 ^{o}C, yielding the following relationship between decrement in productivity P in % and temperature:

$$P\ (\%) = 2 \times (\text{Temp}, {}^{o}\text{C}) - 50 \qquad (1)$$

Several studies support the hypothesis that there is a temperature range with no significant effect on productivity. For example, in the study within a call center by Federspiel et al. (2002), temperature variations between 21.5 and 24.75 ^{o}C did not appear to significantly affect work speed; however, work speed was significantly diminished at 26 ^{o}C. In a different study of the relationship of air temperatures with occupants´ hot or cold complaints, Federspiel (2001) found that the complaint rate was very low in the temperature range of 22.2 - 23.9 ^{o}C. Avoiding complaints might also prevent productivity decrements. This gives the approximate correspondence with the 21 to 25 ^{o}C range for which productivity decrements in our model are assumed negligible. The no-effect range is also supported by the studies of Witterseh (2001). He did not find significant differences of performance in simulated office work (multiplication, text typing and addition tests) in laboratory experiments for subjects thermally neutral at 22 ^{o}C and 25 ^{o}C or for the subjects slightly warm. The 21 to 25 ^{o}C temperature range is also close to the range of temperatures considered comfortable in some thermal comfort standards.

EXAMPLE 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^{o}C; however, it can be considerably smaller (e.g., on cloudy days) or higher with clear skies and a continental climate. The cool night-time 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. Kolokotroni et al. (2001) provided measured room air and slab temperature for an office room with and without night-time ventilation. We used these data 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 1 provides temperatures based on the data of Kolokotroni et al. (2001). We estimated the operative temperature as average of air and slab temperatures for the room with and without night-time ventilation, and summed the degree hours above 25 ^{o}C for both cases. Without the night-time ventilation there were 21 ^{o}C-hours above 25 ^{o}C. With the night-time ventilative cooling, there were only 1.5 ^{o}C-hours above 25 ^{o}C . The difference of 19.5 ^{o}C-hours per day is the benefit of night-time ventilation.

Using the linear relation between loss of productivity and temperature, with a 2% productivity loss per degree when the temperature is above 25 ^{o}C, the productivity increase with night-time ventilative cooling is equivalent to 0.39 hours of work per day (19.5 ^{o}C-hours per day x 0.02 per ^{o}C = 0.39 h/day). If we assume that the average value of an hour of work is $30 hourly, the productivity benefit is $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.

Table 1. 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	
$T_{operativer}$-25					0.25	0.4	0.45	0.4	1.5

The night-time ventilative cooling can be accomplished either by opening the windows or running the HVAC system. For security and other reasons we did not consider the window opening option, instead we assumed 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. We estimated the fan power based on the common Scandinavian 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 we assumed a 4 air change per hour flow rate, typical of the capacity of many HVAC systems, and assumed a room volume of 83 m^3 per occupant. The resulting costs of fan energy with electricity prices from US$0.05 to US $0.20per kWh are shown in Table 2. The table also shows the corresponding benefit-to-cost ratios which range from 32 to 120.

Table 2. 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 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

CONCLUSION AND IMPLICATIONS

We have developed an initial quantitative relationship between work performance and temperatures within and above the comfort zone. This relationship has a high level of uncertainty; however, use of this relationship may be preferable to the current practice which ignores productivity. The quantitative relationship between temperature 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. We also have demonstrated with a simple example using night-time ventilative cooling that energy efficient methods are available to improve the indoor environment. For this example, the ratio of productivity gains to energy used by fans varied from 32 to 120 depending on cost of the electricity.

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