COST-BENEFIT ANALYSIS OF IMPROVED AIR QUALITY IN AN OFFICE BUILDING

R Djukanovic[1,2], P Wargocki[1*] and PO Fanger[1]

[1]International Centre for Indoor Environment and Energy, DTU, Denmark
[2]EnPlus, Belgrade, Yugoslavia

ABSTRACT
A cost-benefit analysis of measures to improve air quality in an existing air-conditioned office building (11581 m^2, 864 employees) was carried out for hot, temperate and cold climates and for two operating modes: Variable Air Volume (VAV) with economizer; and Constant Air Volume (CAV) with heat recovery. The annual energy cost and first cost of the HVAC system were calculated using DOE 2.1E for different levels of air quality (10-50% dissatisfied). This was achieved by changing the outdoor air supply rate and the pollution loads. Previous studies have documented a 1.1% increase in office productivity for every 10% reduction in the proportion of occupants entering a space who are dissatisfied with the air quality. With this assumption, the annual benefit due to improved air quality was always at least 10 times higher than the increase in annual energy and maintenance costs. The payback time of the HVAC first costs involved in improving the air quality was always less than 4 months.

INDEX TERMS
Productivity; Energy; HVAC; Offices; Cost-benefit analysis

INTRODUCTION
Worker salaries in offices exceed typically building energy and maintenance costs by a factor of approximately 100 and they exceed the annual amortized cost of construction or rental by nearly as much (Woods and Jamerson, 1989). An increase in office productivity of a few percent should thus be sufficient to justify the increased energy, maintenance and construction costs when outdoor air supply rates are increased above minimum requirements. Eto and Meyer (1988) and Eto (1990) estimated the impact of an increased outdoor air supply rate on energy costs and on the first cost of heating, ventilation and air-conditioning (HVAC) systems in an office building with a variable air volume (VAV) system with an economizer, using DOE-2 building energy performance software developed for the U.S. Department of Energy (Curtis *et al.*, 1984). They showed that increasing the outdoor air supply rate from 2.5 L/s per person to 10 L/s per person would increase annual energy operating costs by less than 5% and the first cost of the HVAC system by less than 1%. However, at that time data on the impact of an increased ventilation on productivity in offices was not available, and it was thus impossible to compare the increased energy and investment costs with the possible economic benefits of the improved productivity.

Since then, three independent experimental studies have shown that improving air quality improves the performance of typical office work such as typing, arithmetical calculations and proof-reading (Wargocki *et al.*, 1999; 2000a; 2002). The results of these studies indicate that the performance of office work may increase by 5% when the air quality is improved from a mediocre level often found in practice to a high level (Wargocki *et al.*, 2000b). These new

* Contact author email: pw@mek.dtu.dk

results imply that the gains in productivity may exceed the costs required to implement improvements in air quality. The objective of the present work was to examine this hypothesis quantitatively by simulating the operation of typical HVAC systems in an office building with different levels of air quality, comparing increased energy, maintenance and the HVAC first costs with the predicted economic benefits of improved productivity.

METHODS

A series of parametric building energy simulations in an office building were made using the DOE-2 building energy analysis program. The only parameters changed were those of the mechanical ventilation system, climatic conditions and indoor air quality. All the permanent features of the building such as the structural and architectural layout, electrical load for illumination and office equipment, hours of operation and temperature set points were kept unchanged.

The building prototype was adopted from the plans of a typical existing office building, selected because it had an equal distribution of internal and external loads in all zones and was appropriate for an analysis of the air-handling systems considered (Table 1). The building construction, lighting and air-conditioning systems complied with ASHRAE 90.1 (1999). For the simulations, it was assumed that the HVAC system in the building was either a variable air volume (VAV) system with an economizer or a constant air volume (CAV) system with a rotary heat exchanger, both having thus equipment for energy recovery. It was assumed that it was either a "low-polluting" or a "non-low-polluting" building, so according to CR 1752 (CEN, 1998), the building pollution load (including building materials, furnishing, equipment and HVAC system) was thus assumed to be either 0.1 or 0.2 olf/m^{2}floor. The occupancy was 0.07 persons/m^{2}floor. The building was assumed to be situated in three different locations: Miami, Chicago and Winnipeg, representing typical hot, moderate and cold climates in North America. Representative meteorological-year-files with 8760 h of statistically evaluated values for dry and wet bulb temperature, solar radiation and clouds were used in the simulations for these three locations.

Table 1. Description of the main building and HVAC system features.

Size	11581 m^2
Shape	U-shape, floor area 965 m^2
Number of floors	12
Number of occupants	864
Construction	Walls: Heavy construction with 12 cm insulation, U=0.4 W/m^{2}K, Window (glass + frame) U=1.1 W/m^{2}K
Glazing	25% of the wall area
Week schedule	8 a.m. – 6 p.m.; 30% occupancy on Sundays and holidays
Thermostat settings	24 ^{o}C Cooling; 21.3 ^{o}C Heating, 13^{o}C Night set back
Internal loads	14 W/m^2 lighting; 8.1 W/m^2 equipment; 864 persons
HVAC system	VAV with economizer or CAV with rotary heat exchanger
Heating plant efficiency	75 %
Cooling plant efficiency	Air cooled, medium efficiency, COP=3

As a reference condition for the simulations it was assumed that the air quality in the building caused 50% of occupants entering a given space to be dissatisfied. This level of air quality was shown to be typical for the 56 office buildings studied in the European Audit project in 9 countries (Bluyssen *et al.*, 1996). Starting from the reference condition, the air quality was improved in steps of 10% dissatisfied by increasing the outdoor air supply (Table 2); a level of 15% dissatisfied was included to correspond to the requirements of CR 1752 (CEN, 1998). Ventilation rates were calculated using the comfort model (Fanger, 1988), assuming the total sensory pollution load (people+building) to be 0.17 and 0.27 olf/m^2floor respectively in low-polluting and non-low-polluting buildings.

Table 2. Outdoor air supply rates in the building at different levels of air quality.

Air quality		*Outdoor air supply rate*			
		Low-polluting building (LpB)		*Non-low-polluting building (NlpB)*	
% diss.	*decipol*	*L/(s·m²floor)*	*L/(s·person)*	*L/(s·m²floor)*	*L/(s·person)*
10	0.6	2.78	39.8	4.42	63.2
15	1.0	1.74	24.9	2.77	39.6
20	1.4	1.21	17.2	1.92	27.4
30	2.5	0.67	9.6	1.07	15.3
40	4.1	0.42	6.0	0.67	9.5
50	6.1	0.28	4.0	0.44	6.3

The increase in energy use caused by improving air quality (by increasing the outdoor air supply rate) was calculated in simulations using DOE-2. The resulting annual costs for energy, based on ASHRAE 90.1 (1999) for Chicago, and for maintenance and first costs of HVAC (using increases in boiler and chiller capacity) based on Eto and Meyer (1988), were calculated using the data given in Table 3.

Assuming that occupants are kept thermally neutral by the HVAC system during the entire season at the three studied outdoor climates, the increase in office productivity with improved air quality was predicted using the relationship that was determined experimentally by Wargocki *et al.* (2000b): a 1.1% increase in productivity for each 10% decrease in the percentage dissatisfied with air quality upon entering a space. The economic benefits of the increased productivity were calculated assuming an hourly office worker salary of $19.4 /hour (U.S. Department of Labour, 2000). Thus a 1% increase in productivity would result in an economic benefit of $0.194 /hour per person. All costs and benefits were calculated relative to the costs and salaries in the building when operated with air quality causing 50% of occupants entering a space to be dissatisfied.

Table 3. Estimates for increase in costs of energy, maintenance and equipment.

Demand charges per kilowatts of billing demand	12 $/kW
Energy charges per kilowatt-hour	0.078 $/kWh
Natural gas charges per m^3	0.192 $/$m^3$
Annual maintenance costs	5% of initial HVAC costs
Increase in HVAC first costs per increase in boiler capacity	50.3 $/kW
Increase in HVAC first costs per increase in chiller capacity	170 $/kW

The payback time of the investment costs was calculated as a ratio of the increase in HVAC first costs to annual savings, and the annual economic benefit was calculated as the annual economic benefit of increased productivity due to improved air quality minus the estimated increase in annual energy and maintenance costs.

RESULTS

Table 4 shows the predicted increase in the annual cost of energy and maintenance, the increase in HVAC first costs, and the resulting annual benefit in terms of higher productivity. All figures are relative to costs and salaries in the building causing 50% to be dissatisfied.

Based on figures in Table 4, the estimated payback time for the equipment needed to improve air quality is presented in Figures 1 and 2 as a function of the magnitude of improvement in air quality from the level causing 50% to be dissatisfied.

Table 4. Relative increase of costs and benefits of improved air quality.

Increase in air quality (% diss.)	*Increase in HVAC first costs ($/m²floor)*				*Increase in annual energy and maintenance costs ($/m²floor)*				*Increase in productivity ($/m²floor)*
	VAV system		*CAV system*		*VAV system*		*CAV system*		
	LpB[1]	*NlpB[2]*	*LpB[1]*	*NlpB[2]*	*LpB[1]*	*NlpB[2]*	*LpB[1]*	*NlpB[2]*	
Building situated in hot climate									
50%→10%	26.8	31.8	27.0	33.3	3.7	4.2	2.8	3.6	114.3
50%→15%	18.7	26.7	16.4	26.9	2.7	3.7	1.7	2.8	100.1
50%→20%	14.1	20.2	10.7	18.3	2.0	2.9	1.1	1.9	85.8
50%→30%	1.9	11.7	0.9	9.6	0.3	1.8	0.3	1.0	57.2
50%→40%	0.4	1.8	0.1	0.8	0.1	0.3	0.1	0.3	28.6
Building situated in medium climate									
50%→10%	27.0	33.3	15.5	22.3	5.5	8.3	1.5	2.3	114.3
50%→15%	16.4	26.9	9.0	15.5	3.9	5.5	1.0	1.5	100.1
50%→20%	10.7	18.3	5.4	10.5	3.3	4.1	0.5	1.1	85.8
50%→30%	0.9	9.6	1.8	4.5	0.4	3.1	0.1	0.4	57.2
50%→40%	0.1	0.8	0.3	1.7	0.0	0.4	0.0	0.1	28.6
Building situated in cold climate									
50%→10%	25.3	33.7	27.0	33.3	8.0	13.3	2.4	3.1	114.3
50%→15%	15.1	25.2	16.4	26.9	5.2	8.0	1.6	2.3	100.1
50%→20%	9.7	16.8	10.7	18.3	4.3	5.6	1.1	1.8	85.8
50%→30%	1.7	8.5	0.9	9.6	0.5	3.8	0.2	1.0	57.2
50%→40%	0.4	1.6	0.1	0.8	0.0	0.5	0.0	0.1	28.6

[1]LpB=low-polluting building; [2]NlpB=non-low-polluting building

DISCUSSION

The results of the simulations provide a strong incentive to improve air quality in offices compared to the minimum requirements specified in existing standards. The annual increase in productivity was worth at least 10 times as much as the increase in annual energy and maintenance costs (Table 1), similarly to the predictions made by Woods and Jamerson (1989). Because of the resulting increase in productivity, the increased HVAC first costs for improving air quality from the “mediocre” level causing 50% to be dissatisfied to the “excellent” level causing 10% to be dissatisfied will be recovered in no more than 4 months, this figure taking into account the increase in energy and maintenance costs (Figure 1 and 2). The payback time and energy costs will be lower in low-polluting buildings and generally lower in buildings with a CAV system with a rotary heat exchanger. All the above estimates are based on simulations in which air quality is improved by increasing the outdoor air supply rate. Other methods of improving air quality should always be considered, e.g. the systematic use of low-polluting materials and equipment, which may not even cost more when considered during the design of the building.

The present simulations were carried out for North American locations where there are fairly similar building codes and ventilation requirements. Three climatic zones and two ventilation systems were selected so that the results obtained are not limited to one specific climate and one HVAC system. The study was performed for a medium-sized office building, but the size of the building is not believed to have a strong impact on the findings.

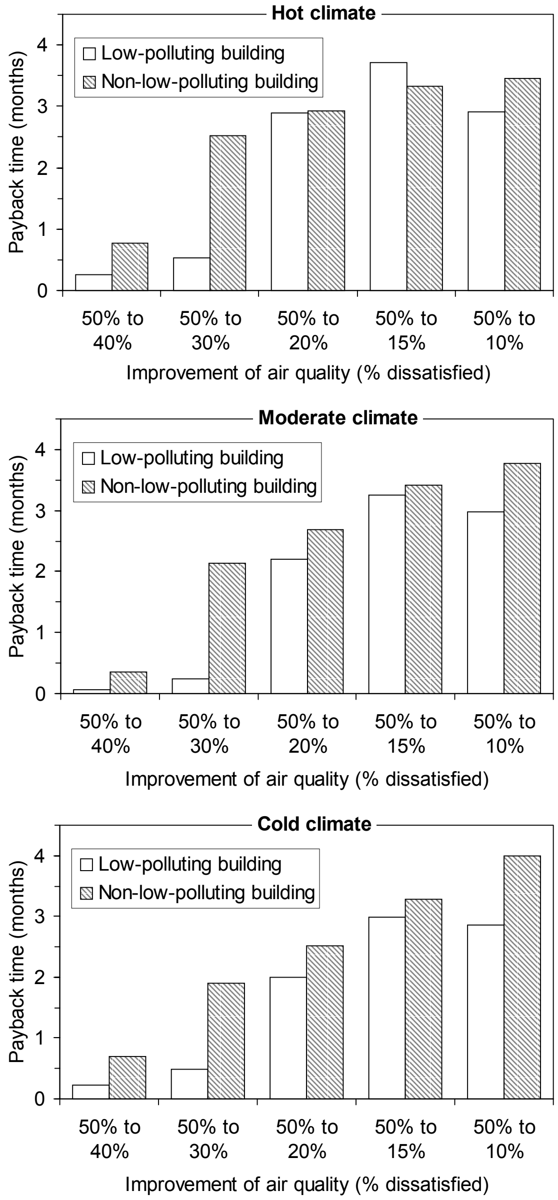

Figure 1. Payback time of the HVAC first costs in the building with VAV system

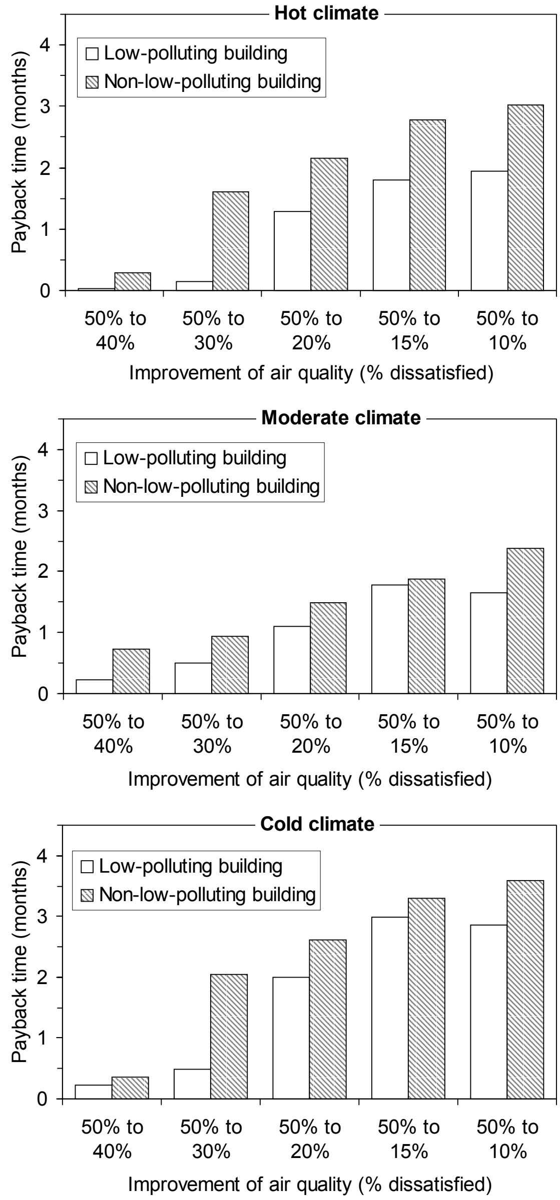

Figure 2. Payback time of the HVAC first costs in the building with CAV system

Present results are analytical only, i.e. based on the simulations, and depend upon the set of assumptions provided. The estimates of increased productivity were obtained from the results of three studies in normal office spaces where subjects performed office work at different indoor air quality levels (Wargocki *et al.*, 2000b), as there are no comparable data from studies in actual workplaces. They were nevertheless similar to the values assumed by other authors who have estimated the impact of improved indoor air quality on office productivity (Fisk and Rosenfeld, 1997; Dorgan *et al.*, 1998). The energy prices are those applicable at only one location, Chicago, even though the energy costs may vary between different locations even within the U.S. Despite salary levels and energy prices being taken from U.S. sources, it is expected that the general result of the cost-benefit analysis is applicable to most other countries of the developed world.

CONCLUSIONS AND IMPLICATIONS

- The present results provide rough estimates of the probable revenues resulting from improving the air quality in offices in developed parts of the world, and constitute a powerful argument for providing indoor air of a better quality than the minimum levels required by present Standards.
- Additional benefits of increased productivity due to improved air quality may be expected if reduced health and sickness absence costs are also taken into account.

ACKNOWLEDGEMENTS

This work was supported by the Danish Technical Research Council (STVF) as part of the research programme of the International Centre for Indoor Environment and Energy established at the Technical University of Denmark for the period 1998-2007.

REFERENCES

ASHRAE/IESNA. 1999. *Standard 90.1-1999*. Energy Standard for Building Except Low-Rise Residential Buildings, Atlanta: American Society of Heating and Air-Conditioning Engineers Inc.

Bluyssen P M, de Oliveira Fernandes E, Groes L, *et al.* 1996. European indoor air quality audit project in 56 office buildings. *Indoor Air*. Vol. 6, pp 221-238.

CEN. 1998. *Technical Report CR 1752*, Ventilation for Buildings: Design Criteria for the Indoor Environment, Brussels: European Committee for Standardization.

Curtis R, Birdsall B, Buhl W, *et al.* 1984. DOE-2 building energy use analysis programme. LBL Report 18046, Berkeley, USA: Lawrence Berkeley Laboratory.

Dorgan C B, Dorgan C E, Kanarek M S, and Willman A J. 1998. Health and productivity benefits of improved indoor air quality. *ASHRAE Transactions*. Vol. 104(1A), pp 658-666.

Eto J H. 1990. The HVAC costs of increased fresh air ventilation rates in office buildings, part 2, *Proceedings of the 5th International Conference on Indoor Air Quality and Climate - Indoor Air '90*, Vol. 4, pp 53-58. Toronto –Indoor Air '90.

Eto J H, and Meyer, C. 1988. The HVAC costs of increased fresh air ventilation rates in office buildings. *ASHRAE Transactions*. Vol. 94(2), pp 331-345.

Fanger P O. 1988. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy and Buildings*. Vol. 12, pp 1-6.

Fisk W J, and Rosenfeld A H. 1997. Estimates of improved productivity and health from better indoor environments. *Indoor Air*. Vol. 7, pp 158-172.

U.S. Department of Labour. 2000. *Bureau of Labour Statistics*. National compensation survey: Occupational wages in US 2000.

Wargocki P, Wyon D P, Baik Y K., *et al.* 1999. Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity in an office with two different pollution loads. *Indoor Air*. Vol. 9, pp 165-179.

Wargocki P, Wyon D P, Sundell J, *et al.* 2000a. The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity. *Indoor Air*. Vol. 10, pp 222-236.

Wargocki P, Wyon D P, and Fanger P O. 2000b. Pollution source control and ventilation improve health, comfort and productivity, *Proceeding of the Third International Conference on Cold Climate Heating, Ventilating and Air Conditioning - Cold Climate HVAC '2000*, pp 445-450. Sapporo - Cold Climate '2000.

Wargocki P, Lagercrantz L, Witterseh T, *et al.* 2002. Subjective Perceptions, Symptom Intensity and Performance: a Comparison of Two Independent Studies, both Changing Similarly the Pollution Load in an Office. *Indoor Air*. Vol. 12, (in press).

Woods J E, and Jamerson W E. 1989. Cost avoidance and productivity in owning and operating buildings. *Occupational Medicine*. Vol. 4, pp 753-770.