# Estimate of an economic benefit from investment in improved indoor air quality in an office building

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## ABSTRACT
Life-cycle costs of investments for improving air quality in an office building were compared with the resulting revenues from increased office productivity; benefits from reduced health costs and sickness absence were not included. The building was simulated in a cold, a moderate and a hot climate. It was ventilated by a constant air volume system with heat recovery. The air quality was improved by increasing the outdoor air supply rate and by reducing the pollution loads. These upgrades involved increased energy and maintenance costs, first costs of a HVAC system and building construction costs. But the additional investments were highly cost-effective: productivity benefits resulting from a better indoor air quality were up to 60 times higher than the increased costs; the simple and discounted pay-back time was below 2.1 years; and the annual rate of return was four to seven times higher than the minimum rate set at 3.2%. The present data, although obtained by simulations, constitute a strong incentive for providing indoor air of a quality that is better than the minimum levels required by present standards.

## INDEX TERMS
Productivity; Energy; HVAC system; Office building; Life-cycle assessment

## INTRODUCTION
Recent experiments showed that improving air quality by increasing the outdoor air supply rate or by reducing pollution sources improved the productivity of office workers and developed the quantitative relationship between the indoor air quality and productivity (Wargocki *et al.*, 2000). This relationship was used in the subsequent cost–benefit analysis of measures to improve air quality in a typical office building which showed that the increase in annual energy and maintenance costs due to improved air quality can be several times lower than the resulting benefits from improved office productivity (Djukanovic *et al.*, 2002), matching the similar estimations of Woods and Jamerson (1989). The objective of the present work was to compare life-cycle costs (LCC) of upgrading indoor air quality in an office building with the resulting revenues from increased office productivity and thus to supplement the previous cost-benefit analysis by including the building construction costs, not considered earlier, and by extending the calculation period from an annual to a building life-time.

## METHODS
The operation of a constant air volume (CAV) heating, ventilation and air-conditioning (HVAC) system with rotary heat exchanger was simulated in a typical office building with different levels of air quality. The building was simulated in a cold, a moderate and a hot climate. The structural and architectural layout of the building was adopted from the plans of an existing building. The building construction, lighting and air-conditioning systems complied with ASHRAE Standard 90.1-1999 (ASHRAE, 1999). The main building features are summarized in Table 1.

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

| | |
|---|---|
| Location | Winnipeg, Chicago and Miami |
| Size | 11 581 $m^2$ |
| Shape | U-shape, floor area 965 $m^2$ |
| Number of floors | 12 |
| Number of occupants | 864 |
| Occupancy | 0.07 person/$m^2$ floor |
| 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°C cooling; 21.3°C heating, 13°C night set back |
| Internal loads | 14 W/$m^2$ lighting; 8.1 W/$m^2$ equipment; 864 persons |
| Heating plant efficiency | 75% |
| Cooling plant efficiency | Air cooled, medium efficiency, COP = 3 |

Different levels of air quality in the building were modelled by defining the percentage of occupants entering a given space who are dissatisfied with the perceived air quality. These levels were obtained by changing the pollution load or outdoor air supply rates. The pollution loads from the building materials, furnishing, equipment and HVAC system were assumed to be representative of a low-polluting (0.1 olf/$m^2$ floor) and a non-low-polluting (0.2 olf/$m^2$ floor) building (CEN, 1998). With the occupancy set at 0.07 person/$m^2$ floor, the total pollution load was, respectively, 0.17 and 0.27 olf/$m^2$. For the given total pollution load and a given air quality, outdoor air supply rates were calculated using the comfort model of Fanger (1988) (Table 2).

**Table 2** Outdoor air supply rates at different levels of air quality

| Perceived air quality | Outdoor air supply rate (l/s·person) | |
|---|---|---|
| (% dissatisfied) | Non-low-polluting building | Low-polluting building |
| 50 | 6.3 | 4 |
| 40 | 9.5 | 6 |
| 30 | 15.3 | 9.6 |
| 20 | 27.4 | 17.2 |
| 15 | 39.6 | 24.9 |
| 10 | 63.2 | 39.8 |

**Table 3** Estimates for increase in energy costs

| | |
|---|---|
| Fixed monthly charge per customer | $300/month |
| 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$ |

The following costs were estimated: (1) annual costs for energy, based on ASHRAE 90.1 (1999) for Chicago (Table 3) and a series of parametric building energy simulations performed using the DOE-2.1E building energy analysis program developed for the U.S. Department of Energy (DOE) (Curtis *et al.*, 1984); (2) first costs of HVAC, based on outdoor air supply rate and the resulting heating/cooling capacities and air-handling unit capacity (Saylor, 2002a); (3) annual maintenance costs, assumed to be 5% of the HVAC first cost; and (4) the building construction cost without HVAC (Saylor, 2002b). The building construction costs for a low-polluting building were assumed to be 5% higher than for a non-low-polluting building.

The increase in office productivity with improved air quality was predicted using the experimental relationship showing a 1.1% increase in productivity for each 10% decrease in the percentage dissatisfied with the air quality upon entering a space (Wargocki *et al.*, 2000). This relationship is valid when occupants are kept thermally neutral by the HVAC system during the entire season and when the air quality causes between 25 and 70% dissatisfied; it was linearly extrapolated for the air quality levels causing less than 25% dissatisfied. Benefits from increased productivity were converted into annual revenues, assuming an annual salary of $33 523 per person ($19.4/h per person) (U.S. Department of Labour, 2000); a 1.1% increase in productivity resulted thus in an annual economic benefit of $368.75 per person.

The calculated costs and revenues were used to perform LCC analysis. The National Institute of Standards and Technology (NIST) DOE/NIST LCC-2002 software modified to include the benefits from improved productivity, was used. The rules of the Federal Energy Management Program (FEMP) of DOE were followed. The life-time of the building was set at 25 years. The real discount rate reflecting real earning power of money and not the general price inflation was set at 3.2% (as of the year 2002); it is equivalent to the interest rate. Future energy prices were calculated using real energy price escalation rates for Midwest U.S. and for the commercial sector; they are annually projected by DOE. Natural gas was the second fuel. All future costs and benefits were discounted and they are consequently expressed in present value dollars (US$ as of the year 2002).

The final results of LCC were shown as increases in costs and benefits as a result of improving air quality in the building from the reference condition—a non-low-polluting building where 50% of occupants are dissatisfied with the air quality. This level of dissatisfaction was selected as a reference because it was shown to be typical for the 56 office buildings studied in the European Audit project in nine countries (Bluyssen *et al.*, 1996). The results were tabulated to show: (1) net savings—a difference in all life-cycle costs and benefits; (2) a simple and discounted pay-back time—the number of years between the beginning of operation of the building and the time at which cumulative benefits are sufficient to offset the increments in initial costs of the improvements to air quality; (3) a savings-to-investment ratio—the ratio of benefits of improved productivity to increased investment costs required for improving air quality; and (4) an adjusted internal rate of return - an economic performance of the air quality upgrade by providing an annual rate of return of investment which is compared with the minimum acceptable rate of return, equal to the real discount rate set in this analysis at 3.2%.

**Table 4** Estimated discounted costs in the non-low-polluting building where 50% are dissatisfied with air quality (the reference condition)

| Building location | Energy costs ($/m$^2$) | Maintenance costs ($/m$^2$) | HVAC first costs ($/m$^2$) | Building construction costs ($/m$^2$) |
|---|---|---|---|---|
| Cold climate | 153.8 | 109.9 | 129.0 | 1168 |
| Moderate climate | 147.3 | 113.9 | 133.7 | 1168 |
| Hot climate | 157.3 | 116.6 | 157.3 | 1168 |

## RESULTS

Table 4 shows the estimated costs in the building in the reference condition. Tables 5–7 show the increases in costs and benefits resulting from improvements in indoor air quality in the building in the reference condition for a building located respectively in a cold, a moderate and a hot climate. The negative values in the tables for costs indicate savings.

**Table 5** Results of LCC analysis for the building located in a cold climate

| Building | Air quality (% diss.) | Discounted increase from the reference condition ($/m$^2$): Costs – Energy | Costs – Maintenance | Costs – HVAC first | Costs – Building | Benefits – Productivity | Net savings ($/m$^2$) | Simple pay-back time (years) | Adjusted internal rate of return (%) |
|---|---|---|---|---|---|---|---|---|---|
| Non-low-polluting | 50 | Reference condition | | | | | | | |
| | 40 | 1.8 | 6.4 | 7.5 | 0.0 | 486.9 | 471.1 | 0.3 | 21.9 |
| | 30 | 8.2 | 18.0 | 21.2 | 0.0 | 973.7 | 926.3 | 0.4 | 20.1 |
| | 20 | 14.6 | 43.8 | 51.5 | 0.0 | 1460.6 | 1350.7 | 0.6 | 17.8 |
| | 15 | 17.3 | 70.1 | 82.3 | 0.0 | 1704.0 | 1534.3 | 0.9 | 16.3 |
| | 10 | 24.6 | 111.0 | 130.4 | 0.0 | 1947.5 | 1681.5 | 1.2 | 14.7 |
| Low-polluting | 40 | 0.0 | -0.6 | -0.7 | 0.0 | 486.9 | 429.8 | 2.0 | 12.4 |
| | 30 | 1.9 | 6.6 | 7.7 | 58.4 | 973.7 | 899.1 | 1.2 | 14.9 |
| | 20 | 9.5 | 22.0 | 25.9 | 58.4 | 1460.6 | 1344.8 | 1.0 | 15.6 |
| | 15 | 14.2 | 38.5 | 45.3 | 58.4 | 1704.0 | 1547.7 | 1.1 | 15.3 |
| | 10 | 17.3 | 70.5 | 82.8 | 58.4 | 1947.5 | 1718.4 | 1.3 | 14.4 |

**Table 6** Results of LCC analysis for the building located in a moderate climate

| Building | Air quality (% diss.) | Discounted increase from the reference condition ($/m$^2$): Costs – Energy | Costs – Maintenance | Costs – HVAC first | Costs – Building | Benefits – Productivity | Net savings ($/m$^2$) | Simple pay-back time (years) | Adjusted internal rate of return (%) |
|---|---|---|---|---|---|---|---|---|---|
| Non-low-polluting | 50 | Reference condition | | | | | | | |
| | 40 | –0.2 | 7.8 | 9.2 | 0.0 | 486.9 | 470.0 | 0.3 | 20.9 |
| | 30 | 2.6 | 23.8 | 28.0 | 0.0 | 973.7 | 919.2 | 0.5 | 18.8 |
| | 20 | 9.5 | 56.4 | 66.2 | 0.0 | 1460.6 | 1328.6 | 0.8 | 16.6 |
| | 15 | 12.7 | 86.1 | 101.1 | 0.0 | 1704.0 | 1504.2 | 1.1 | 15.3 |
| | 10 | 19.5 | 130.7 | 153.5 | 0.0 | 1947.5 | 1643.8 | 1.5 | 13.9 |
| Low-polluting | 40 | 0 | –0.7 | -0.8 | 0.0 | 486.9 | 429.9 | 2.0 | 12.4 |
| | 30 | –0.2 | 8.1 | 9.5 | 58.4 | 973.7 | 897.9 | 1.2 | 14.8 |
| | 20 | 4.2 | 29.0 | 34.1 | 58.4 | 1460.6 | 1334.9 | 1.1 | 15.1 |
| | 15 | 8.8 | 49.6 | 58.3 | 58.4 | 1704.0 | 1528.9 | 1.2 | 14.7 |
| | 10 | 12.7 | 86.5 | 101.6 | 58.4 | 1947.5 | 1688.2 | 1.5 | 13.8 |

## DISCUSSION

LCC showed that improving air quality is highly efficient: the benefits from improved air quality can be up to 60 times higher than investments; the investments can generally be recovered in no more than 2 years; and the rate of return can be up to seven times higher than the minimum acceptable interest rate. Based on the above calculations, improving air quality from the ‘mediocre’ level (50% dissatisfied) to the ‘excellent’ level (10% dissatisfied) will, e.g., in a small-sized office building with 100 employees, result in an annual revenue of approximately $100 000 over a period of 25 years. The results showed also that similar economic benefits can be obtained in different climatic zones, probably because the benefits from improved productivity become a dominating factor in the LCC analysis and considerably exceed the increased investment costs.

**Table 7** Results of LCC analysis for the building located in a hot climate

| Building | Air quality (% diss.) | Discounted increase from the reference condition ($/m²) | | | | | Net savings ($/m²) | Simple pay-back time (years) | Adjusted internal rate of return (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | Costs | | | | Benefits | | | |
| | | Energy | Maintenance | HVAC first | Building | Productivity | | | |
| Non-low-polluting | 50 | Reference condition | | | | | | | |
| | 40 | 2.7 | 8.2 | 9.6 | 0.0 | 486.9 | 466.3 | 0.3 | 20.6 |
| | 30 | 7.2 | 24.1 | 28.3 | 0.0 | 973.7 | 914.1 | 0.5 | 18.7 |
| | 20 | 16.0 | 57.9 | 68.0 | 0.0 | 1460.6 | 1318.7 | 0.8 | 16.4 |
| | 15 | 23.3 | 90.4 | 106.2 | 0.0 | 1704.0 | 1484.2 | 1.1 | 15.0 |
| | 10 | 31.6 | 141.1 | 165.7 | 0.0 | 1947.5 | 1609.0 | 1.6 | 13.5 |
| Low-polluting | 40 | –0.3 | –0.8 | –3.8 | 0.0 | 486.9 | 433.3 | 1.9 | 12.6 |
| | 30 | 2.8 | 8.5 | 7.1 | 58.4 | 973.7 | 897.0 | 1.2 | 14.9 |
| | 20 | 8.8 | 29.6 | 32 | 58.4 | 1460.6 | 1331.8 | 1.1 | 15.2 |
| | 15 | 14.3 | 51.2 | 57.2 | 58.4 | 1704.0 | 1522.9 | 1.2 | 14.7 |
| | 10 | 23.5 | 90.9 | 103.9 | 58.4 | 1947.5 | 1670.8 | 1.5 | 13.7 |

The pay-back times estimated in the present simulations are similar to the pay-back of 1.4 years suggested by Dorgan *et al.* (1998). In the earlier simulations, Djukanovic *et al.* (2002) reported pay-back times of investments ≤4 months because they were calculated using the old construction costs (Saylor, 1987) to link them to simulations by Eto and Meyer (1988), and included only the first costs of the HVAC system comprising an increase in boiler and chiller capacity. In the present simulation, the first costs of the HVAC system, comprising all costs related to an increase in air-handling unit capacity and the building construction costs, were used to calculate the pay-back times.

The building construction costs for a low-polluting building were assumed to be 5% higher than in a non-low-polluting building. The simulations for increases in building costs ≥10% were also carried out. However, they showed that the net savings were in some cases lower than the net savings resulting from increasing the outdoor air supply rate, especially when the % dissatisfied with the air quality was reduced from 50 to 40% and to 30%. Since it was felt that high investments in building costs are not justified if higher net savings can be achieved with lower investments in a HVAC system (energy and first costs), a 5% increase in building costs was used.

The present results were obtained by carrying out the simulations and depend upon the set of assumptions provided. They do not include benefits resulting from reduced health costs and reduced absenteeism; lower absenteeism from an increased outdoor air supply rate can result in annual savings of $400 per employee (Milton *et al.*, 2000). The simulations were performed for a medium-sized office building, but the size of the building is not considered to have a strong impact on the findings. The air quality was the only parameter that was changed and assumed to influence productivity; other factors such as noise and thermal conditions were supposed to be constant. However, these factors can also affect productivity. Thermal discomfort can, for example, reduce office productivity by up to 15% (Wyon, 1996), which is nearly three times the maximum effect of 5.5% assumed in the present simulations, but these effects were not considered in the present work. The estimates of increased productivity were obtained from the results of experiments in normal office spaces where subjects performed office work at different indoor air quality levels (Wargocki *et al.*, 2000). There are no comparable data from studies in actual workplaces, but similar estimates were used by others (Fisk and Rosenfeld, 1997; Dorgan *et al.*, 1998). Despite salary levels being taken from U.S.

sources and energy prices being applicable at only one location - Chicago, it is expected that the present result can be applied generally to most other countries of the developed world.

## CONCLUSION AND IMPLICATIONS

The present results provide rough estimates of the probable revenues resulting from improving the air quality in office buildings in developed parts of the world, and constitute a powerful argument and strong incentive for providing indoor air of a better quality than the minimum levels required by present standards.

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