Cost-effectiveness Analysis of Improved Indoor Temperature and Ventilation Conditions in School Buildings

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Abstract
This paper reports simulation results of the potential fiscal benefits from investment in improved indoor environmental quality in school buildings. Improving indoor environmental quality can result in substantial benefits due to improved academic performance, but it can also result in increased energy and heating, ventilation, and air-conditioning (HVAC) maintenance costs. The aim of this paper is to demonstrate the cost-effectiveness of additional indoor environmental control by HVAC and the associated benefit of improved academic performance in a limited-scale school building model. This study estimated the impact of an increased ventilation rate and an alteration of target room air temperature on energy costs and on academic performance. The annual benefit due to improved thermal conditions (room air temperature) was up to five times higher than the benefit of increased ventilation rate per person. Lifecycle cost analysis showed that the benefit (improved academic performance) resulting from better indoor temperature conditions was up to 20–40% against the increased costs (increased HVAC total cost) of a few thousand JPY per year [JPY/year/person].

Keywords: academic performance; classroom; indoor environmental quality

1. Introduction
Many research papers have been published on the potential effects on productivity of indoor environmental quality in classrooms and offices (Fisk, 1997; Wargocki, 2005, 2006, 2007). In particular, Wargocki (2005) pointed out that productivity benefits resulting from better indoor air quality were up to 60 times higher than the increased energy cost, and the simple and discounted payback time was below 2.1 years for typical office buildings.

On the other hand, a lot of studies show that the environmental conditions in schools are often inadequate, even in developed countries, and that they are frequently much worse than in office buildings (Daisey, 2003, Dijken, 2005). Although the conditions in classrooms are often inadequate very little research has been performed on whether the performance of schoolwork by children is affected by poor air quality and elevated temperatures in classrooms (Mendell, 2005).

This series of studies evaluated the effects of changes in the air quality and thermal environment on student performance in the classroom and proposed a prediction model of academic performance as a function of various indoor environmental factors in the classroom. The effect of indoor environmental quality on student academic performance based on field intervention surveys and realistic laboratory experiments has already been reported (Murakami, 2006; Ito, 2006, 2008). In these reports, it was concluded that the change in environmental conditions from low to high ventilation rate significantly improved academic performance, and academic performance correlated strongly with room air-temperature conditions. Furthermore, the results of nationwide field measurements based on subjective questionnaire surveys and objective test scores were also reported in a unified way (Kameda, 2007).

This paper reports the results of numerical predictions that estimate the energy consumption in typical school buildings and academic performance in accordance with changes in ventilation rate per person and indoor air-temperature conditions.
2. Summary of Field Intervention Surveys and Realistic Simulation Experiments

The results of field intervention surveys and realistic simulation experiments in a climate chamber using a nationwide college for students that received lectures to prepare them to take certification examinations for 1st class authorized architects in Japan have been reported previously. The college provided a uniform teaching environment nationwide using DVD-based video lectures (usually three hours of lectures once a week). The previous studies also conducted standardized examinations to measure the level of understanding after each lecture.

Generally, the teaching level of lecturers or teachers had a significant effect on the learning performance of the student. In other words, academic performance is strongly dependent on the teaching ability of the teachers. Because lectures are held in different classrooms and by different lecturers, it is very difficult to compare the effects of indoor environmental quality on learning performance. The college chosen for this study provides standardized lectures nationwide, using the same DVD-based course, and checks on learning achievements from each lecture were conducted using standardized tests. This college provides a reproducible learning environment and allows cross-environmental evaluation of field measurements. In addition, the use of DVD-based lectures allows the classroom environment used in the field measurements to be precisely replicated in the laboratory.

Based on the above characteristics, this study evaluated the effect of indoor environmental quality on academic performance using the approaches of field intervention surveys and laboratory experiments in a climate chamber. Standardized tests were adopted as used in the actual classroom to evaluate learning performance objectively. This allowed the use of a standardized method for all college buildings and classrooms in order to evaluate learning performance through field measurements and to compare learning performance among classrooms with different indoor environments. The use of a standardized method of evaluating academic performance based on standardized tests in the field measurements and laboratory experiments allowed evaluation of the effect of the indoor environment on academic performance from various perspectives. (Refer to Murakami, 2006 and Ito, 2006 for details of the results of field surveys and laboratory experiments).

2.1 Relationship between academic performance and ventilation rate per person

Fig.1 shows the results of field surveys and laboratory experiments on the effects of ventilation rate per person on academic performance. In this analysis, standardized test scores were adopted for measuring academic performance. Concerning the relationship between test scores and ventilation rate per person, relative learning performance, which was normalized to the test score for the ventilation rate of 1.0 \([\text{m}^3/\text{hour}/\text{person}]\) condition, was defined as shown in Fig.1. For consistency between the results of field surveys and laboratory experiments on the effects of ventilation rate per person on academic performance. In this analysis, standardized test scores were adopted for measuring academic performance. Concerning the relationship between test scores and ventilation rate per person, relative learning performance, which was normalized to the test score for the ventilation rate of 1.0 \([\text{m}^3/\text{hour}/\text{person}]\) condition, was defined as shown in Fig.1.

For consistency between the results of field surveys and laboratory experiments, the differences of these were estimated as about 2–3%. For both cases, a logarithmic relationship was observed between the standardized test score (relative academic performance) and ventilation rate per person \([\text{m}^3/h/\text{person}]\). The approximation formula estimated by the method of
least squares was as follows:

\[ y = 0.039 \ln(x) + 1.000 \]  (1) (Field survey)
\[ y = 0.034 \ln(x) + 1.000 \]  (2) (Lab. Exp)

In these formulas, \( x \) denotes the ventilation rate per person \([\text{m}^3/\text{h}/\text{person}]\).

Fig. 2 shows the relationship between ventilation rate \([\text{m}^3/\text{h}/\text{person}]\) and the percentage of students dissatisfied with the air environment. A logarithmic relationship was also observed between these factors and the approximation formula as follows:

\[ y = -3.130 \ln(x) + 17.331 \]  (3) (Field survey)
\[ y = -19.088 \ln(x) + 77.453 \]  (4) (Lab. Exp)

### 2.2 Relationship between academic performance and room air temperature

Fig. 3 shows the results of field surveys and laboratory experiments for the effects of room air temperature on academic performance (relative standardized test score). Academic performance was strongly affected by room air temperature. A quadratic relationship was observed between academic performance and room air temperature.

\[ y = -0.0273(x^2) + 1.3302(x) - 15.178 \]  (5) (Field)
\[ y = -0.0817(x^2) + 4.0594(x) - 49.438 \]  (6) (Lab. Exp)

In these formulas, \( x \) denotes the room air temperature \( [\text{°C}] \).

Fig. 4 shows the relationship between air temperature and the percentage of students dissatisfied with the thermal environment based on the results of field surveys and laboratory experiments. A quadratic relationship was also observed, and the approximation formula was as follows:

\[ y = 12.145(x^2) - 611.49(x) + 7730 \]  (7) (Field)
\[ y = 9.3292(x^2) - 467.12(x) + 5877 \]  (8) (Lab. Exp)
Following numerical analysis and discussion, the formulas based on the field intervention survey (equations (1) and (5)) were adopted. According to these formulas, which indicate academic performance as a function of ventilation rate or indoor air temperature, indoor environmental quality has a large impact on academic performance compared with the results of a previous reported study (Wargocki, 2007).

In the authors' previous studies, the thermal conditions changed with the change in the ventilation rate and hence the formulas based on the field intervention survey have the possibility of containing the combined effects of ventilation rate and air temperature (Ito, 2008). In other words, following cost-effectiveness analysis of improved indoor temperature and ventilation conditions in School Buildings, there is a possibility of overestimating the indoor environmental impact on the learning performance.

3. Outline of the Numerical Analysis

In this study, annual energy consumption and HVAC total costs, including maintenance, running, and initial costs, were analyzed by a series of parametric building energy simulations using TRNSYS, and optimization of the HVAC system that considered part-load operation and lifecycle analysis were conducted using E-passplan software.

The only parameters changed in this analysis were the ventilation rate per person and room air temperature.

Table 1. shows the numerical and boundary condition of heat loads in a target school building. The student density of a classroom was assumed to be 25 [persons/classroom] (= 0.5 [person/m²]) in accordance with the data from field surveys. Heat generation from humans, lighting, office automation (OA) equipment, and thermal transmission from walls were considered as internal heat loads. The time period for lectures in the classroom was assumed to be 9:00 AM – 5:00 PM throughout one week, including not only weekdays but also weekends. The climate conditions are shown in Table 2. Three types of climate conditions, Sapporo (cold climate), Tokyo (moderate climate) and Fukuoka (hot climate) in Japan, were targeted. The air conditioning system in this target school building was assumed to process a constant air volume using a single duct system, and direct-coldness-and-warmth water heat source equipment by the using absorption was adopted. The patterns of load demand were estimated using the results of dynamic heat load simulations for every hour for one year, and energy demand and energy consumption were analyzed in consideration of the part-load operation of heat source equipment corresponding to the frequency of load demand.

3.1 Target building and classroom conditions

The outline of the target school building model (school building) is shown in Fig.5. This target school building consisted of three stories and four classrooms on each floor. The total floor area was 1,310.72 m², 983.04 m² of which consisted of classrooms, and it was classified as a small-scale building in Japan. Details concerning the construction of the target school building are described in Appendix [A].

3.2 Cases analyzed

The cases for the numerical predictions were set for a total of 10 conditions as functions of the ventilation rate per person and the room air temperature settings. The ventilation rate was changed and gradually increased from 10 to 60 [m³/h/person] at 10 [m³/h/person] intervals. The room air temperature was changed in 1°C intervals from a basic condition of (25°C...
4. Results

4.1 Effect of changes in ventilation rate

Fig.6. (1) shows the change in academic performance as a function of ventilation rate per person based on the relationship expressed in equation (1). This relative increase in academic performance [%] was normalized and standardized using the results of the 10 [m³/h/person] scenario. A logarithmic relationship exists between academic performance and ventilation rate, as shown in equation (1), and academic performance increased 2.5 % when the ventilation rate increased from 10 [m³/h/person] to 20 [m³/h/person]. The academic performance increased further by about 4 % in the case where the ventilation rate per person increased from 10 to 30 [m³/h/person], and academic performance increased by about 6.4 % when the ventilation rate increased from 10 to 60 [m³/h/person].

The analytical results of the change in annual energy consumption [GJ/year/m²] as a function of ventilation rate per person are shown in Fig.7. (1). The energy consumption in Sapporo was larger compared with that in Tokyo and Fukuoka. This was because of the low temperature in the winter season in Sapporo. The energy consumption in Sapporo was 6.7 [GJ/y/m²] for the ventilation conditions of 10 [m³/h/person], 7.2 [GJ/y/m²] for 30 [m³/h/person] and 7.5 [GJ/y/m²] for 60 [m³/h/person]. The analytical results of the change in HVAC total cost [*10³ JPY/ year/m²] as a function of ventilation rate per person are shown in Fig.8. (1). The HVAC total cost in Sapporo was larger compared with that in Tokyo and Fukuoka. The tendency of the change in HVAC total costs was similar to the results of energy consumption. This was because of the low temperature in the winter season in Sapporo. The HVAC total cost was 19,000 [JPY/ year/m²] with ventilation conditions of 10 [m³/h/person], 29,100 [JPY/ year/m²] for 30 [m³/h/person], and 46,600 [JPY/ year/m²] for 60 [m³/h/person].

4.2 Effect of changes in temperature conditions

Fig.6. (2) shows the change in academic performance as a function of room air temperature. In this study, academic performance [%] was standardized using the result of conditions of 28°C in summer/20°C in winter. A quadratic relationship was observed between academic performance and room air temperature, as shown in equation (5), and academic performance increased 26 % when the room air temperature was lowered 1°C from 28°C to 27°C in the summer season. Academic performance increased further by about 43% in the case where the room air temperature decreased 2°C from 28°C to 26°C and by 53 % when room air temperature was lowered by 3°C from 28°C to 25°C. In the winter season, academic performance increased 41 % when the room air temperature condition was increased 1°C from 20°C to 21°C, by 73 % for an increase of 2°C from 20°C to 22°C, and by about 93 % for an increase of 3°C from 20°C to 23°C.

The analytical results of the change in annual energy consumption [GJ/year/m²] as a function of room air temperature settings are shown in Fig.9. (1). The energy consumption in Sapporo was relatively large compared with Tokyo and Fukuoka. This was because of the low temperature conditions in the winter season in Sapporo. The energy consumption was 6.7 [GJ/y/m²] for the room air temperature conditions of 28°C in summer/20°C in winter, 7.2 [GJ/y/m²] for 27°C in summer/21°C in winter), 7.5 [GJ/y/m²] for 26
5. Discussion

In this study, a prediction model of academic performance as functions of ventilation rate per person and room air temperature was developed using the data of field intervention surveys and realistic simulation experiments in a climate chamber. The temperature dependence of academic performance was higher than that of the ventilation rate in this prediction model. In other words, the potential fiscal benefit from investment in improved indoor temperature conditions in classrooms was relatively high and effective from the viewpoint of improvement of academic performance. In this numerical prediction, the energy consumption and HVAC total costs, in which the ventilation rate was changed gradually, was relatively large compared with that where the indoor air temperature condition was changed.

In Tokyo, the HVAC total cost increased about 1,200 [JPY/year/m² floor] when the temperature condition changed by 1°C from 28°C in summer/20°C in winter to 27°C in summer/21°C in winter. The student density of the target classroom was about 0.5 [person/m² floor]. Roughly speaking, in a case where the cost was converted from [JPY/year/m² floor] to [JPY/year/person], the increment of cost burden of students in the classroom was estimated as about 2,000-3,000 [JPY/year/person]. If this amount of expense was considered to be an investment in education, it was estimated that the efficiency of ROI (return of investment) was very high because of the strong dependency of academic performance on indoor air temperature.

6. Conclusions

The numerical simulation of energy consumption and HVAC total cost for a school building model was carried out as a function of ventilation rate per person and room air temperature, and the effects on academic performance were also estimated. The findings obtained from this study can be summarized as follows:

1. In these limited analytical conditions, academic performance improved by about 4% in a case where the ventilation rate per person increased from 10 to 30 [m³/h/person], and academic performance increased by about 6.4% when the ventilation rate increased from 10 to 60 [m³/h/person]. In comparison, the energy consumption of the entire school building increased by about 200% or more.

2. In the present performance–IEQ model, academic performance increased by about 26% when room air temperature decreased 1°C from 28 to 27°C in summer conditions, and academic performance improved by about 43% when room air temperature decreased by 2°C from 28°C. In comparison, the energy consumption of the entire school building increased by about 40% in the same conditions.

3. Academic performance was strongly dependent on room air temperature. Room air temperature control with high accuracy and sensitivity is important in order to maintain both academic performance and energy consumption in building.

Appendix 1. Details of the Construction of the Target School Building

| Roof               | Autoclaved lightweight concrete + rock wool insulation + sprayed with urethane |
|--------------------|--------------------------------------------------------------------------------|
| Ceiling            | Rock wool insulation + sprayed with polyurethane + steel sheet                |
| Walls (Southwest and northwest) | External: gypsum plaster board + ALC or glass with aluminum sash  |
| Floor              | Intermediate story: PC concrete + rock wool insulation + steel sheet + carpet |
|                    | Ground floor: PC concrete + waterproof sheet + rock wool insulation + sprayed with urethane + steel sheet + carpet |

°C in summer/22°C in winter, and 8.0 [GJ/y/m² floor] for 25°C in summer/23°C in winter.

Fig. 9. (2) shows the increasing rate of energy consumption based on the results for room air temperature conditions of 28°C in summer/20°C in winter. The increase in energy consumption in Tokyo was relatively large compared with Sapporo and Fukuoka. Energy consumption increased about 12% when the temperature conditions changed from 28°C in summer/20°C in winter to 27°C in summer/21°C in winter. Furthermore, energy consumption increased about 37% when the temperature condition changed from 28°C in summer/20°C in winter to 25°C in summer/23°C in winter in Tokyo.

The analytical results of HVAC total cost [*10³ JPY/year/m² floor] as a function of temperature setting in the school building are shown in Fig. 10. (1). The HVAC total cost in Sapporo was large compared with that of Tokyo and Fukuoka. The HVAC total cost was 26,900 [JPY/y/m² floor] for temperature conditions of 28°C in summer/20°C in winter, 28,200 [JPY/y/m² floor] for 27°C in summer/21°C in winter, and 30,400 [JPY/y/m² floor] for 25°C in summer/23°C in winter.

Fig. 10. (2) shows the HVAC total cost based on the results for room air temperature conditions of 28°C in summer/20°C in winter. HVAC total cost increased by about 7% when the temperature setting changed by 1°C from 28°C in summer/20°C in winter to 27°C in summer/21°C in winter, by about 18% for a change from 28°C in summer/20°C in winter to 27°C in summer/21°C in winter and for 28°C in summer/20°C in winter to 25°C in summer/23°C in winter in Fukuoka.
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