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2018

Shan, X., Melina, A. N., & Yang, E.-H. (2018). Impact of indoor environmental quality on students' wellbeing and performance in educational building through life cycle costing perspective. Journal of Cleaner Production, 204298-309. doi:10.1016/j.jclepro.2018.09.002

https://hdl.handle.net/10356/104286

https://doi.org/10.1016/j.jclepro.2018.09.002

Impact of indoor environmental quality on students' wellbeing and performance in educational building through life cycle costing perspective

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Abstract

Effects of indoor environmental quality of office buildings on occupants have been widely studied. However, relatively fewer studies focus on that of educational buildings, through the perspective of building life cycle costing assessment in particular. In this study, effects of indoor thermal condition and air quality on students' wellbeing and performance are investigated with other major building metrics through a life cycle costing case study of two university tutorial rooms. Metrics for students' wellbeing and performance are monetized, and different weighting schemes for the metrics are compared with sensitivity analysis. Results show that consideration of students' wellbeing and performance can lead to significant total net benefits, which highlights that other traditional metrics focusing on building energy and resource efficiency should be balanced with human factors. For more sustainable building design and operation, balanced weighting scheme should be adopted, in contrary to the current practice where weights are mainly given to capital and energy while wellbeing and performance are often ignored. The results underscore the importance of incorporating students' wellbeing and performance into educational building design and operation, as thermal or air quality conditions in school classrooms are often worse than stipulations in standards and building codes.

Keywords: *Life cycle costing; indoor environmental quality; wellbeing; performance; energy; educational building*

1 Introduction

People on average spend up to 90% of their time in buildings, which include offices, factories, schools, or homes (US EPA, 2011). Therefore, the indoor environmental quality (IEQ) of buildings must be satisfactory in order to provide comfort, to enhance work productivity, and to maintain general wellbeing of building occupants. As the report "Health, Wellbeing & Productivity in Offices" (World Green Building Council, 2014) puts it, "green", or environmentally friendly building is often associated with low carbon footprint and efficient energy consumption. However, this does not necessary mean that green building can improve wellbeing and work productivity of occupants. Green technologies and policies generally emphasize reducing impact on environment, while may potentially neglect or overlook the fact that the main purpose of building is to cater welfare of occupants. For instance, the current green building rating system in Singapore (BCA Green Mark for Non-Residential Buildings, 2015) mainly focuses on energy and resources efficiency aspects, while occupants' wellbeing and performance are scarcely considered. While existing building code such as ASHRAE Standard 62.1 (2010) recommends minimum ventilation rates for buildings, these minimum thresholds are often not sufficient for occupants' wellbeing and performance. Therefore, holistic sustainability assessment of buildings should also include impact on wellbeing and work productivity of occupants.

Various sustainability assessment tools have been developed (Pomponi and Lenzen, 2018) and widely used, such as life cycle assessment (LCA) (Shan et al., 2017). LCA is an approach to analyze the environmental impact of products or activities throughout their life cycle stages (ISO14044: 2006). As LCA lacks an economic dimension, another framework is often used to make different metrics in LCA more comparable in the form of economic or financial LCA (also called life cycle costing, LCC) (Soam et al., 2018), which monetizes metrics in LCA over the lifetime and discounts to current values (Hoogmartens et al., 2014). For buildings, the full LCA/LCC stages normally include material extraction, production, transportation, building construction, operation and renovation, demolition, and recycling (Geng et al., 2017). Ortiz et al. (2009) conducted a literature review on building LCA, including whole building LCA and building materials or components LCA. Typical metrics in LCA are energy consumption, pollutant emission, carbon footprint and other factors that lead to potential environmental impact. Building LCC has also been widely used to optimize different building parameters such as insulation thickness or building shape, in order to minimize potential cost during the building lifespan (Han et al., 2014; Tam et al., 2017). For LCA/LCC, owing to different objectives, the life cycle stages and impact assessment indicators that are taken into account vary from case to case, and some of the life cycle stages can be excluded if there are supportive assumptions and reasons.

There are already quite many studies that have investigated wellbeing and work productivity through the life cycle perspective, and these studies mainly focused on indoor environment of office buildings and the corresponding cost-benefit metrics in the LCC framework. Better indoor environment in these studies often refers to condition that can provide better thermal comfort and indoor air quality (IAQ). Woods (1989) suggested that in office buildings, salaries of workers exceed building energy and maintenance costs by approximately a factor of 100, and salaries exceed annualized construction or rental costs by almost as much. Another study showed that increased benefits from reduced sick building syndromes (SBS) and increased productivity due to better indoor environment in office buildings had benefit-cost ratios of 9 to 14 (Fisk, 2001). Wargocki et al. (2005) conducted a simulation by using the relationship between office work performance and IAQ from previous studies, and concluded that annual increase in productivity was worth 6-115 times as much as increase in annual energy and maintenance costs, and the LCC results showed that discounted payback time for additional capital cost were below 2.1 years. Fisk et al. (2005) focused on health and wellbeing by using the relationship between IAQ and sick leave from previous studies, and they estimated that economic benefit from reduced sick leave could also be significant. Johansson (2009) conducted a more general simulation by incorporating costs of health, wellbeing and work productivity into LCC, and concluded that benefit of human factors is clear and can be used to optimize air supply rate in building design. Mostavi et al. (2017) also developed an optimization model to minimize life cycle cost and life cycle emission, and maximize occupant satisfaction level in a typical commercial building.

For other building types, especially the educational buildings, studies of effects of indoor environment on wellbeing and work productivity are relatively fewer. Two literature review studies (Wargocki et al., 2013; Mendell et al., 2005) summarized results from various field interventions or experimental studies, attributing adverse health effects and reduced performance of students to poor indoor thermal or air quality conditions. On the other hand, study of these effects on students through the perspective of building LCC/LCA cannot be found. This lack of study may be due to the fact that unlike office buildings, educational buildings are for non-profit purposes, which is difficult to investigate through LCC perspective. However, such issues still need to be properly addressed. Wargocki et al. (2013) pointed out in the literature review that thermal or air quality conditions in school classrooms are often worse than the stipulations in standards and building codes, partly due to inadequate financial resources for maintenance and upgrade of school buildings. Without proper sustainability assessment tools like LCA/LCC, such issues may not be properly assessed and addressed in a more holistic way.

Therefore, in this study, the effects of indoor environmental quality on students' wellbeing and performance in educational building are investigated with other major building metrics through

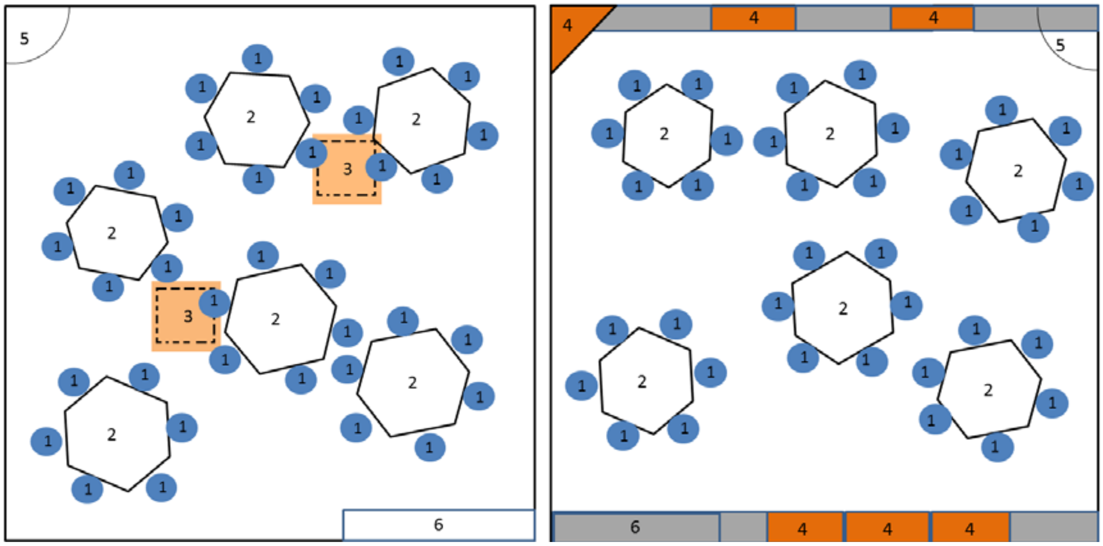
LCC perspective, with a case study of two university tutorial rooms. Firstly, the effects of indoor environmental quality on students' wellbeing and performance are quantified into different metrics and these metrics are then monetized. Different weighting schemes are then explored through LCC perspective. Finally, sensitivity analysis is conducted for the baseline balanced weighting scheme. It is hoped that through this study the effects of indoor environmental quality on students in educational building can be more properly addressed and evaluated with other traditional evaluation metrics that mainly focus on energy and resource efficiency.

2 Methodology

2.1 Previous experiment and current scope

A field study was already conducted that compared differences in IEQ and the corresponding impacts on students' thermal comfort, sick building syndromes, and short-term performance in two side-by-side tutorial rooms in Nanyang Technological University (NTU), Singapore (Shan et al., 2016). The layout of the two tutorial rooms is illustrated in Figure 1. The two rooms are 8 meters in length, 8 meters in width, and 2.75 meters in height (floor to false ceiling). The two rooms are identical except for their ventilation systems. One tutorial room has traditional mixing ventilation (MV) with cooling coil, and this system supplies fresh air from ceiling level with high velocity to achieve an even distribution of temperature and pollutant. The other room has displacement ventilation with cooling coil, and this system supplies fresh air from floor level. In particular, this displacement ventilation is passive displacement ventilation (PDV). The PDV system employs natural convection of heat transfer without mechanical fans to deliver chilled air to occupants. By taking advantage of the natural buoyancy of warm air, chilled air produced by the cooling coil sinks to the floor and is driven by temperature gradient. Stable stratification is achieved across the height in the room.

In the previous field study, a controlled experiment was conducted with two MV scenarios and two PDV scenarios. Student volunteers were recruited to the experimental sessions, and each experimental session lasted for two hours, similar to the duration of a typical lecture/tutorial session. In the first MV scenario, it was found that the CO_2 concentration was high due to low air exchange rate (AER) caused by fan deficiency, which led to poor IAQ. To rectify this issue, an additional fan was installed in the duct located outside the room to increase AER in the second MV scenario, such that the CO_2 concentration was reduced to normal level. No change was made to the PDV room, and the two PDV scenarios were essentially the same, both having normal ventilation rate and CO_2 concentration. Therefore in this study, the first PDV scenario is excluded, and the three remaining scenarios are considered. The environmental data for these three scenarios are shown in Table 1. These three scenarios mainly differ in capital cost of air-conditioning and mechanical ventilation (ACMV) systems, operational energy consumption, IEQ, and IEQ's impact on occupants. Other aspects in construction, operation & maintenance and demolition stages are considered essentially the same.



(a) (b)

Figure 1 Layout of the tutorial rooms: (a) MV room; (b) PDV room. 1 = seats; 2 = tables; 3 = overhead MV diffusers; 4 = floor PDV diffusers; 5 = doors; 6 = computer control panels (Shan et al. 2016)

Table 1 Environmental background for the three scenarios in the previous experiment (Shan et al. 2016)

Scenarios	MV IAQ 1	MV IAQ 2	PDV
Temp I$^{\sim}$ (°C)	23.6 ± 0.2	24.3 ± 0.8	24.0 ± 0.2
Temp II* (°C)	23.7 ± 0.1	24.1 ± 0.4	21.9 ± 0.1
Temp III$^{\$}$ (°C)	22.8 ± 0.4	23.0 ± 1.2	17.9 ± 0.7
Air velocity$^{@}$ (m/s)	4.52 ± 0.07	4.67 ± 0.10	0.31 ± 0.19
RH$^{\&}$ (%)	76.1 ± 3.5	74.3 ± 5.4	57.3 ± 2.5
$CO_2^{\#}$ (ppm)	1709-2690	< 1000	< 1000
AER (/h)	0.78 ± 0.03	1.65 ± 0.07	2.24 ± 0.08
Chilled water consumption (kw)	10.15 ± 0.47	13.26 ± 2.25	16.70 ± 1.02

$^{\sim}$ Temperature at 1.5m above the ground at room center

* Temperature at 0.7m above the ground at room center

$^{\$}$ Temperature at ground level at room center

$^{@}$ Average air velocity at diffusers

$^{\&}$ Relative humidity at 1.5m above the ground at room center

$^{\#}$ Concentration during the second half (60-120 min) of each session at 1.5 m above ground at room center

The previous experimental results showed that students' wellbeing (quantified by sick building syndrome responses in questionnaires) and performance (quantified by computerized tasks) deteriorated when IAQ was poor. The questionnaires adopted 7-point scale to rate thermal comfort and SBS (ASHRAE standard 55, 2013; Raw et al., 1996; Wargocki et al., 1999; Gong et al., 2006; Melikov et al., 2013). For SBS in particular, scale 1 refers to very unacceptable/very bad, and scale 7 refers to very acceptable/very good. These results will be used to quantify the wellbeing category in the current study. Students' working performance under different IEQ was evaluated by computerized tasks. These results will be used to quantify the performance category. Representative types used in the current study that represent different aspects of mental activities are listed below, which are believed to be relevant skills and ability for students in classroom setting.

- Short term memory. Two types of short term memory tests were selected. Pair recall asked human subjects to remember two groups of character pairs each time, followed by recalling the missing character in each pair (Kantowitz et al., 2009). Words recall asked subjects to remember two groups of words each time followed by recalling the words in each group (Solso et al., 2008).
- Perception. Two types of perception tests were selected. Visual trace asked human subjects to visually trace each curve and correctly label it (Yin et al., 2003). Stroop test asked human subjects to judge whether the meaning of words correspond to their actual color as shown (Solso et al., 2008).
- Mental arithmetic. This test asked human subjects to compute 2-digit by 2-digit multiplications to evaluate mental arithmetic (Wetherell, 1996). The results of multiplications were all 3 digits.

The energy consumptions of the three scenarios are also summarized in Table 1. The capital costs of the two ACMV systems are collected from the University's facility management department, with SGD 13,200 for the MV system, and SGD 23,800 for the PDV system. The cost of the extra fan and additional equipment added to the MV IAQ 2 scenario during the experiment is less than SGD 200, and the energy consumption of the fan is less than 100 W. Both are much less than those of the existing ACMV systems.

In this study, the data from the experiment will be used to establish the link between IEQ and the two impact categories, namely students' wellbeing and performance. The metric to quantify wellbeing of building occupants is the number of sick leave days, and the metric to quantify performance is the weighted average marks (WAM). The monetized metrics for these two impact categories are benefit of avoided sick leave and benefit of WAM respectively. The overall LCC framework is illustrated in Figure 2. The MV IAQ 1 scenario was also found in other MV system rooms on the same campus and therefore is used as reference. Only the main metrics that are different among the three scenarios are shown in Figure 2.

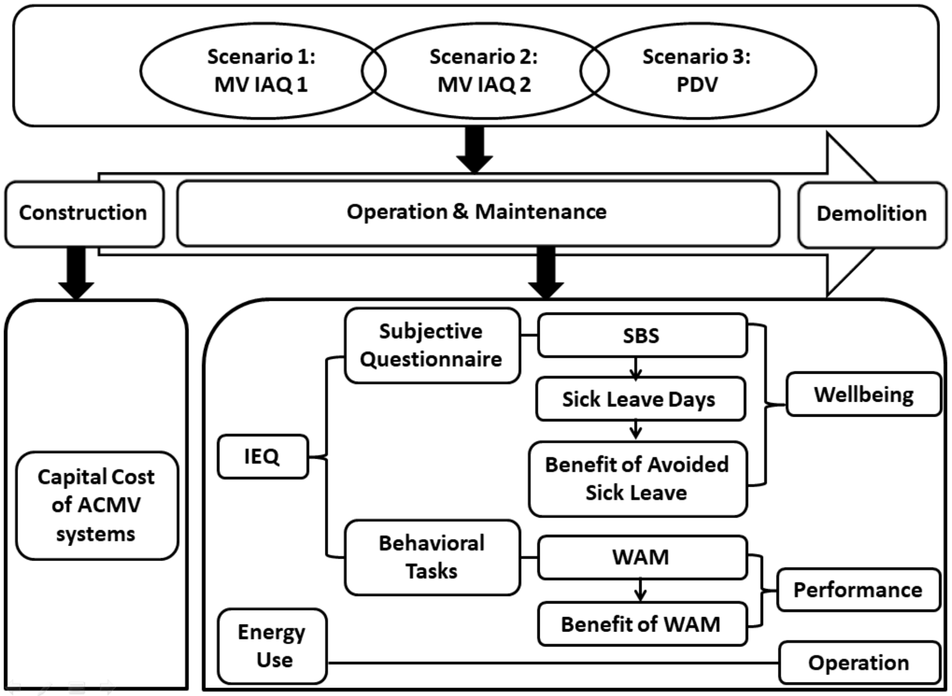


Figure 2 Scope and framework of LCC

2.2 Quantification and monetization of indoor environmental impact on occupants

2.2.1 Sick building syndromes, sick leave days and the costs

The report "Health Optimization Protocol for Energy-Efficient Buildings" (HOPE, 2005) of the program "Energy, Environment, and Sustainable Development" defined Building Symptoms Index (BSI) as the mean number of acute health symptoms closely related to SBS. A total of 10 fundamental symptoms are counted for the BSI10. The ten symptoms are:

- Dry eyes
- Itching/watering eyes
- Blocked/stuffy nose
- Runny nose
- Dry/irritated throat
- Headache
- Tiredness/lethargy
- Flu-like symptoms
- Breathing difficulty
- Chest tightness

Sick leave is another indicator that has been widely used to study indoor environment (Milton et al., 2000), and can be measured by the number of spells and the number of days of sick leave (Raw, 1992). The number of spell counts the number of people that report sick leave only, not specific sick leave days. In general, respiratory illnesses account for a large fraction of sick leaves (Milton et al., 2000). Fisk et al. (2005) further confirmed this and stated that short-term sick leave was proportional to prevalence of respiratory illnesses. Six respiratory symptoms from BSI10 were considered important, which were blocked/stuffy nose, runny nose, dry/irritated throat, flu-like symptoms, breathing difficulty, and chest tightness. Clark et al. (2004) in their research on impact of asthma to school absenteeism also included cough as a major asthma symptom. Additionally, headache was considered as another symptom which might make students report absenteeism and was therefore included in their computation. According to these literatures, eight symptoms from BSI10 are chosen to calculate sick leave, excluding dry eyes and itching/watering eyes.

Raw (1992) conducted a statistical analysis on staff absence records, and his method is used in this study. He found that there was a relationship between the numbers of SBS occurred among workers and the sickness absences; i.e. there was only very minimal change in sickness absence until workers reported four or more symptoms. He concluded by highlighting that sickness absence would only be expected if this score was exceeded. In the previous tutorial room experiment, there were no data on how frequently the symptoms occurred. The methods are thus modified accordingly. As the subjective questionnaire in the experiment adopted 1-7 scale, so if the respondent answered a particular SBS question with ‘4’ and below, it is counted as one symptom occurred. Otherwise, it is counted as no symptom. It is further assumed in the current study that if a student reported four or more symptoms out of the eight symptoms mentioned above, the student would report a sick leave.

To further calculate the number of days of sick leave, Milton et al. (2000) conducted an analysis among 600 office workers and studied their absence for one calendar year. The average CO_2 level in office was at 800-900 ppm. The study concluded that the indoor air quality accounted for 1.2 to 1.9 days of increased short-term sick leave per person per year. This indoor air quality was most similar to that of MV IAQ 2 scenario. Therefore, the number of days of sick leave in MV IAQ 2 scenario is assumed to be the same as the value in that study, i.e. 1.2 to 1.9 days of sick leave per person per year, or averaged to be 1.55 days/person/year. As the number of students in the tutorial rooms is constrained by room capacity, for the other two scenarios the values can be estimated by using the percentage of students reporting sick leave. The numbers of sick leave days are shown in Table 2. It can be seen that for a given number of students, PDV scenario has the least amount of sick leave days, while the MV IAQ 1 has the most amount of sick leave days.

Table 2 Sick leave indicator results

	MV IAQ 1	MV IAQ 2	PDV
Number of subjects reporting sick leave (≥4 symptoms in the experiment)	6	2	1
Percentage of population (out of total subjects in the experiment)	15.48%	5.13%	2.56%
No. of total off days due to sick leave for a given room capacity, e.g. 30 students (days/year)	15.38/5.13*46.5 = 139.4	30*1.55=46.5	2.56/5.13*46.5 = 23.2
Normalizing by these 30 students, (days/person/year)	4.65	1.55	0.77
Total cost of sick leave (SGD/person/year)	565.35	188.45	94.22

Sick leave days are then monetized. Cost of sick leave is the amount of dollars that is lost or has to be spent for sick leave. This value is assumed to be proportional to the number of sick leave days. Many previous studies were in office context, and monetization was made by calculating employee’s salary per day and additional medical fees. As for students, a more relevant literature review is conducted to find out the costs, which are categorized to three different costs as shown in Table 3. The total value sums to approximately SGD 122 per day of sick leave. Together with the sick leave days in Table 2, the costs of sick leave per person per year in each scenario are shown in Table 2.

Table 3 Different types of costs of sick leave

Breakdown of costs of sick leave	Approximate value (SGD/day)
• Capital cost, i.e. the amount of tuition fee that has been paid and is lost due to absence from school. This is based on average annual tuition fee of SGD10, 775 (NTU, 2014) and 150 school days per year.	71.83
• Direct cost, i.e. the average amount of medical expenses students have to pay for consultation in clinics/polyclinics (Singhealth Polyclinics, 2014; National Health Group Polyclinics, 2013).	18.38
• Indirect cost, i.e. the average amount of subsidy provided by government for each consultation at clinics/polyclinics (Singhealth Polyclinics, 2014; National Health Group Polyclinics, 2013).	31.38
Total	121.58 (≈ 122.0)

2.2.2 Weighted average marks and the benefits

Average scores or grades have been used widely and accepted in most schools and colleges to measure performance. The results from computerized tasks in the previous experiment are used as substitutes for students' grades, as these tasks measure different aspects of mental activities and therefore the performance in these tasks is regarded to be correlated to real-life grades.

There are many methods to compute students' average grades. Many colleges and universities use Grade Point Average (GPA) to measure performance. This is done by converting numeric scores to letter grades that correspond to a grade point. In colleges in Australia, weighted average marks (WAM) system is used, where weights are assigned directly to numeric scores instead of grade points. The final WAM will be numeric scores out of 100. In this study, numeric scores similar to WAM will be used for simplicity and to avoid any inaccuracy that might arise for conversions to grade points. Furthermore, it is assumed that different tasks contribute equally to reflect students' performance in the experiment, and therefore they are assigned with equal weights. All scores are then normalized out of 100.

The benefits of WAM are then monetized to compare with other impact categories and to fit into the LCC framework. The WAM can have great impact on students' income after they graduate. It has been shown in many studies that there is a positive relationship between students' performance and starting salary. These studies concluded that students with higher GPA or final marks have a tendency to receive higher starting salary. A summary of these literatures is shown in Table 4.

Table 4 Summary of literatures on student performance and starting salary

% salary increase per unit marks	Location of study	Year of study	Student population	Source
5 % per 1 point of GPA increase	USA	1983-1984	Female students	Rumberger et al., 1993
8.9 % per 1 point of GPA increase	USA	1982-1985	Business major	Jones et al., 1990
9 % per 1 point of GPA increase	USA	1983-1984	Science & maths major	Rumberger et al., 1993
10 % per 1 point of GPA increase	USA	1983-1984	Business & education major	Rumberger et al., 1993
0.68 % per 1 mark increase	West Australia	2002-2004	University of Western Australia students	Chia et al., 2008

In this study, the final marks are not associated with gender or college major. Furthermore, the marks in this study are also normalized out of 100, which is similar to the WAM in Australia. Thus, the increase in salary per one mark of 0.68% from Chia et al. (2008) in Table 4 is assumed to be relevant, as the study by Chia et al. (2008) also comprised general student population regardless of gender and college major.

Data of starting salary of NTU graduates are available from the Singapore Ministry of Education (MOE) Graduate Employment Survey (2013). The average starting salary of all students across all majors is weighted by the number of students. This weighted average monthly starting salary is estimated to be approximately SGD 3,107. This equals to an annual starting salary of approximately SGD 37,280, which is set as baseline. The percentage difference in annual starting salary from this baseline can be obtained by computing the deviation from the baseline score and multiplying this deviation by 0.68% change in starting salary per 1 mark difference. The baseline score is taken as the average score of the three scenarios. The normalized scores and the corresponding starting salaries are shown in Table 5.

Table 5 Normalized scores and annual starting salary

	MV IAQ 1	MV IAQ 2	PDV
Average scores*, out of 100	50.25	62.32	58.19
Starting salary# (SGD/year)	35,589	38,649	37,602

* Baseline score, out of 100: 56.92

\# Baseline starting salary (SGD/year): 37,280

2.3 Weighting schemes

One way to guide decision making is by assigning weights to different metrics, as was done by Mansour et al. (2013) in their social life cycle study on material selection for a building. Only the final monetized metrics, i.e. ACMV capital expenses, energy expenses, benefit of avoided sick leave days and benefit of increased average marks, are used in this section. Other intermediate metrics are not used here to avoid double counting. For the weighting schemes, higher weight refers to more important. For instance, schemes b and c in Table 6 are more close to real-life situation, as capital and energy are often regarded as more important than wellbeing and performance. There is no fixed rule of assigning weights because the importance of each metric is highly subjective to different stakeholders. The weighting schemes of metrics are shown in Table 6. The sum of weights is chosen as 4 for simpler calculation.

Table 6. Weighting schemes of metrics. Higher weight refers to more important, and the sum of weights is 4.

Metrics	Weighting schemes of metrics				
	a	b	c	d	e
ACMV capital expenses	1	3	1/3	1/3	1/3
Energy expenses	1	1/3	3	1/3	1/3
Benefit of avoided sick leave days	1	1/3	1/3	3	1/3
Benefit of increased average marks	1	1/3	1/3	1/3	3

2.4 Life cycle costing

The weighting schemes in Table 6 are then investigated through the building lifecycle perspective. Monetized metrics are used for LCC calculations. In real-life situation, the two tutorial rooms are used daily by different students. Therefore, the effects of tutorial rooms' IEQ as shown in the previous experiment are experienced by different groups of students (morning and afternoon groups) daily. Each group of students therefore will only be affected partially; i.e. they will only be affected during the time when they are in these two tutorial rooms. Counting all the effects on different groups of students is impractical. In order to pool these partial effects, an equivalent model is needed. It is observed that the two tutorial rooms are constantly under use during school days, and the capacity for both rooms is 36 students. Therefore, a group of 30 hypothetical students (baseline scenario) is used as equivalence for each room scenario, and this group of students will spend all their study time in that scenario. Furthermore, the final weighted average mark for students is the average mark in their entire 4 years. Therefore for each 4-year cycle, the equivalent model is further simplified such that this group of 30 hypothetical students will spend their 4-year school time in that scenario and then graduate.

It should be noted that the simplification is only to pool the impacts experienced by different groups of students to one group for each room scenario, as the impacts used for the subsequent analysis are still from results of the two-hour sessions in the previous experiment that is representative of real-life situation. Furthermore, the number of students in each of the two-hour session in the previous experiment only reached half of the room capacity, so the impacts estimated from the experiment are lower bounds, because in real-life situation more people in the room will lead to even poorer IAQ. In this study, a moderate service life of 32-year is used for baseline scenario for conservative purpose.

In LCC, it is necessary to calculate the present value of all future values by discounting. One commonly used discounting rate is the interest rate set by central banks. In Singapore, the savings interest rate is 0.14% per year (Monetary Authority of Singapore, 2016).

2.4.1 Life cycle costing of sick leave

Eqn. 1 is used for calculating the total cost of sick leave in building lifespan.

$$\text{Total Cost of Sick Leave} = N \times \sum_{t=1}^{T} C \left(\frac{1}{1+I}\right)^{t} \quad (1)$$

where N is the number of hypothetical students (N = 30 for the baseline scenario); T is the service life years of tutorial rooms (T = 32 for the baseline scenario); C is the average annual cost of sick leave per student (present value); and I is the interest rate.

It should be noted that in Eqn. 1, potential inflation of the sick leave costs due to potential inflation of tuition fees and medical costs are not considered. Therefore, the value calculated by Eqn. 1 is the lower bound, which means the present value of the sick leave costs could be even higher.

2.4.2 Life cycle costing of weighted average marks

For the baseline scenario, only the first year's salary after graduation is considered. The potential continuing income differences in student's lifetime due to different starting salaries are ignored for conservative purpose. The wage growth rate is also ignored for conservative purpose. The salary income in the future is discounted as shown in Eqn. 2.

$$\text{Total Benefit of Weighted Average Marks} = N \times \sum_{M=1}^{T/4} \sum_{t=1}^{S_t} S \left(\frac{1}{1+I}\right)^{4\times M+S_t} \quad (2)$$

where N is the number of hypothetical students ($N = 30$ for the baseline scenario); M is one 4-year cycle to count average marks; T is the service life years of tutorial rooms ($T = 32$ for the baseline scenario); S_t is the number of years of salary to be considered ($S_t = 1$ for the baseline scenario); S is the average starting salary per student (present value); and I is the interest rate.

2.4.3 Life cycle costing of ACMV capital expenses and energy expenses

The capital costs of the ACMV systems are one-time present values, and therefore do not need to be discounted. Energy bills are expected in the entire service lifespan of the tutorial rooms, and therefore need to be discounted to the present values. The Energy Market Authority of Singapore published the electricity tariffs increase as 5.7% (EMA, 2017) as compared with previous year's counterpart, and the most recent electricity tariff is SGD 0.2/kWh. This growth rate is already much higher than the inflation rate, which is below 1.5% in recent years in Singapore (Monetary Authority of Singapore, 2016). Therefore to be conservative 5.7% will be used for the annual growth rate of electricity tariff. The number of total school days per year is around 150, and the average operation hours of tutorial room facilities in each school day is estimated to be 8 hours. The total costs of electricity bills in the future will be discounted to the present value as shown in Eqn. 3.

$$\text{Total Electricity Bills} = \sum_{t=1}^{T} C \left(\frac{1+X_{energy}}{1+I}\right)^{t} \quad (3)$$

where T is the service life years for tutorial rooms ($T = 32$ for the baseline scenario); C is the annual costs of electricity bills (present value); X_{energy} is the average annual growth rate of electricity tariff; and I is the interest rate.

2.5 Summary of assumptions and sensitivity analysis of metrics

Summary of major assumptions and the corresponding final values as illustrated in the previous sections are shown in Table 7.

Table 7 Summary of major assumptions and the corresponding values

Assumptions	MV IAQ 1	MV IAQ 2	PDV
Sick leave days (days/person/year) can be estimated from major BSI symptoms (HOPE, 2005; Raw, 1992) and IAQ (Milton et al., 2000) based on experimental questionnaire	4.65	1.55	0.77
Cost of sick leave (SGD/person/year) has three major categories and is proportional to the sick leave days	565.35	188.45	94.22

Experimental task results can be used as substitutes for students' academic mark	50.25	62.32	58.19
Starting salary (SGD/year) increases 0.68% per one mark increase (Chia et al., 2008)	35,589	38,649	37,602
For the LCC calculation, the effects experienced by different groups of students can be pooled to one group	A group of students is used as equivalence, spending all their study time in each scenario.		

Sensitivity analysis is conducted by assigning higher and lower factors to various important metrics used for life cycle costing calculation. This is conducted for the balanced scheme a. Although the metrics are already conservatively estimated, sensitivity analysis can further investigate how the results will change accordingly if the metrics deviate from the baseline estimation. The metrics for baseline and sensitivity analysis are shown in Table 8. For most metrics, the range for sensitivity analysis is ±50%. For the room service life and the number of students, ±50% is impractical and therefore the range is within the possible maximum. For the interest rate, since the baseline value is very small, a value higher than 50% is used for higher bound. For the avoided sick leave days and average marks, sensitivity factors are applied to the differences relative to the lowest baseline values (for the sick leave days metric PDV has the lowest baseline value, and for the average marks metric MV IAQ 1 has the lowest baseline value), and therefore lower factor means the differences among three scenarios are smaller.

Table 8 Metrics for baseline and sensitivity analysis

Metrics	Lower bound	Baseline	Upper bound
Interest rate (%)	0.10	0.14	1.00
Room service life (years)	24	32	40
Energy tariff growth rate (%)	3.0	5.7	9.0
Years of salary (years)	0.5	1.0	1.5
Number of students	25	30	35
Change of sick leave days difference relative to the lowest baseline value (%)	-50	0	50
Change of average marks difference relative to the lowest baseline value (%)	-50	0	50

3 Result and Discussion

For preliminary comparison purpose, major metrics are plotted in radar chart in Figure 3, where the MV IAQ 1 scenario is normalized as 100%. In general, better wellbeing and work performance require more investment in capital and energy.

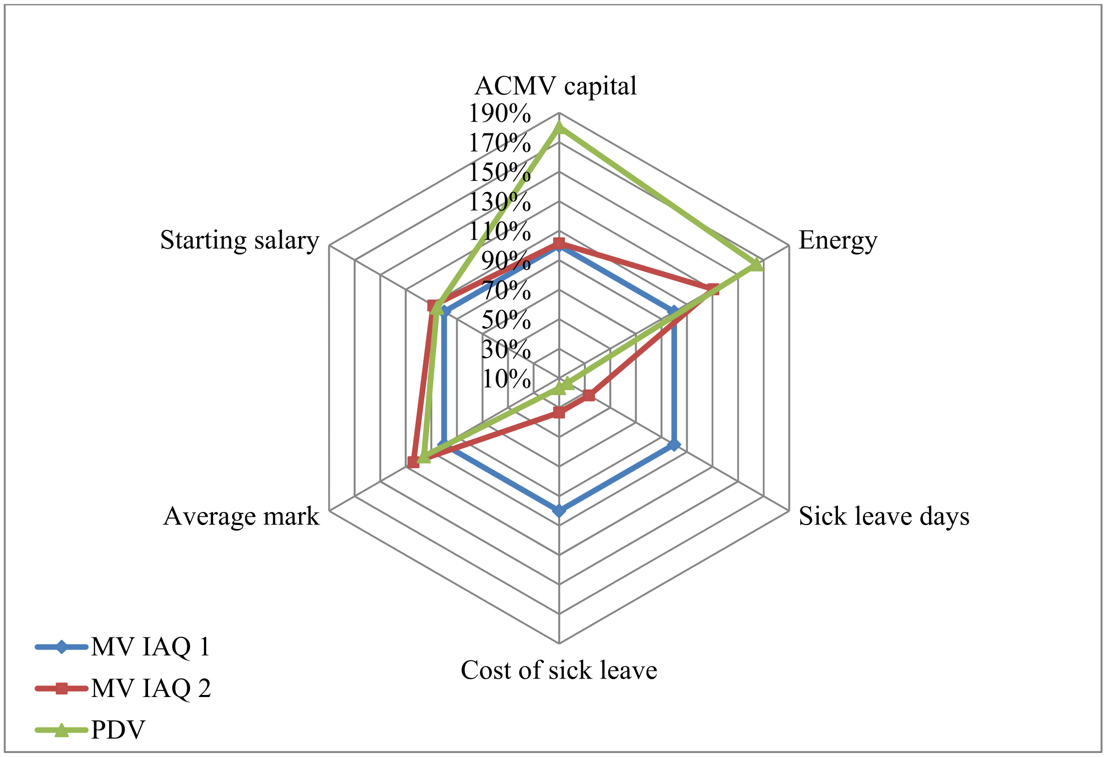


Figure 3 Summary of metrics. MV IAQ 1 is normalized as 100%.

3.1 Life cycle costing

The life cycle costing is calculated based on monetized metrics. The MV IAQ 1 scenario is used as reference, and therefore all computed values for the MV IAQ 2 scenario and PDV scenario are relative values to the MV IAQ 1 scenario.

3.1.1 Baseline (balanced scheme a)

The baseline results of balanced scheme are shown in Figure 4, where the extra expenses are negative and the benefits are positive, and the total net benefit is the summation of all benefits and extra expenses. The benefits to extra expenses ratio is the absolute value of the ratio of all benefits to all extra expenses.

As can be seen, the extra operational energy expenses are much more than the extra capital expenses. The PDV scenario has more benefit of avoided sick leave, while the MV IAQ 2 scenario has more benefit of increased average mark. The MV IAQ 2 scenario also has more total net benefit, and the main contributor is the benefit of increased average mark. For the benefits to extra expenses ratios, the MV IAQ 2 scenario has a larger ratio than the PDV scenario (15.7 as compared to 6.1), which is mainly due to lower extra expenses in the MV IAQ 2 scenario. In general, after incorporation of students' wellbeing and performance, both the two improved scenarios can lead to significant net total benefits, and the improvement carried out in the MV room has even larger benefits to expenses ratio due to less extra expenses.

For the baseline balanced scheme, ratios are more comparable to the review study for office buildings by Fisk (2001), which considered improved health and productivity due to improved air filtration or increased air supply rate, and calculated benefit to extra cost ratios as 9 and 14, respectively. On the other hand, the benefit to extra cost ratio estimated by Woods (1989) for office buildings was much higher. In his calculation, this ratio was close to 100, which may be unfit in today's setting. The current results further underscore the importance of considering students' wellbeing and performance in educational building design and operation, as the thermal or air quality conditions in school classrooms are often worse than the relevant stipulations in standards and building codes (Wargocki et al., 2013; Mendell et al., 2005).

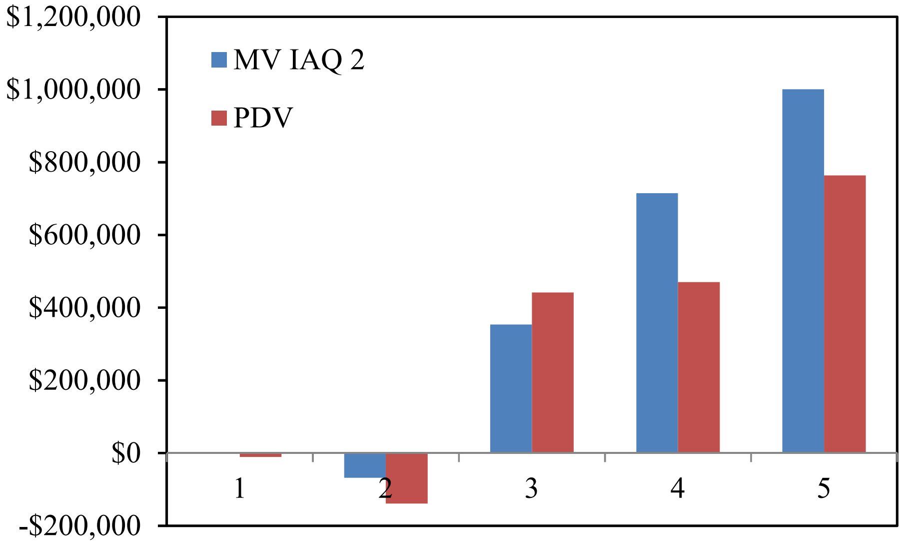


Figure 4. Baseline (balanced scheme a): 1: Extra ACMV capital expenses; 2: Extra operational energy expenses; 3: Benefits of avoided sick leave; 4: Benefits of increased average mark; 5: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2: 15.7; (b) PDV: 6.1. All values are relative to the MV IAQ 1 scenario.

3.1.2 Weighting schemes b to e

The results of four different weighting schemes are shown in Figures 5 to 8. For scheme b, higher weight on capital expenses leads to higher evaluation of capital expenses and lower evaluation of benefits. The general shape of the graph is similar to that of balanced scheme a, because the magnitude of one-time capital expenses is relatively small compared with other metrics. The benefits to extra expenses ratios are also similar to those of balanced scheme a.

For scheme c, higher weight on energy leads to higher evaluation of energy and lower evaluation of benefits. Because the service life energy expense is larger than capital expense, this reduces the benefits to extra expenses ratio of MV IAQ 2 scenario to only 2.1. Furthermore, the benefits to extra expenses ratio of PDV scenario drops below 1, meaning that it has negative total net benefit. These results suggest that if service life energy expense is the primary concern in practice and higher weight is given, then the net benefits of wellbeing and performance are almost negligible or even negative.

For schemes d and e, higher weights on wellbeing or performance lead to higher evaluation of the corresponding categories and lower evaluation of expenses. When more weight is given to wellbeing, PDV scenario has more total net benefit. When more weight is given to performance, MV IAQ 2 has more total net benefit. Because in balanced scheme a, benefits of wellbeing and performance are already larger than extra expenses, higher weights for wellbeing and performance therefore further increase the benefit to extra expenses ratios.

Schemes b and c are more close to real life practice where resources and energy are mostly concerned. On the other hand, schemes d and e might put too much emphasis on occupants. Therefore in reality weights should be more or less similar to those in balanced scheme a, i.e. building metrics and human metrics should be considered as equally important. Simulation of different weighting schemes during the planning stage can also be included in other frameworks and models, e.g. models by Johansson (2009) or Mostavi et al. (2017).

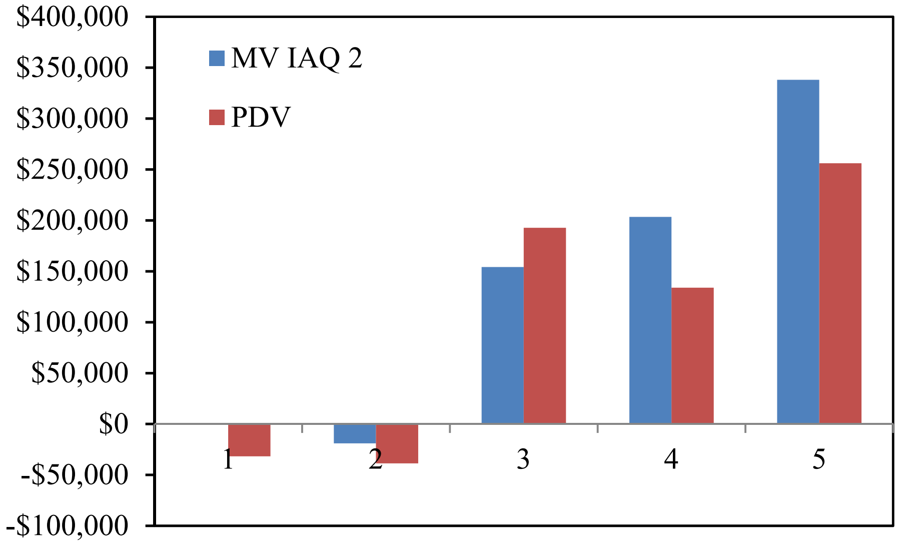


Figure 5. Weighting scheme b (capital): 1: Extra ACMV capital expenses; 2: Extra operational energy expenses; 3: Benefits of avoided sick leave; 4: Benefits of increased average mark; 5: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2: 18.3; (b) PDV: 4.6. All values are relative to the MV IAQ 1 scenario.

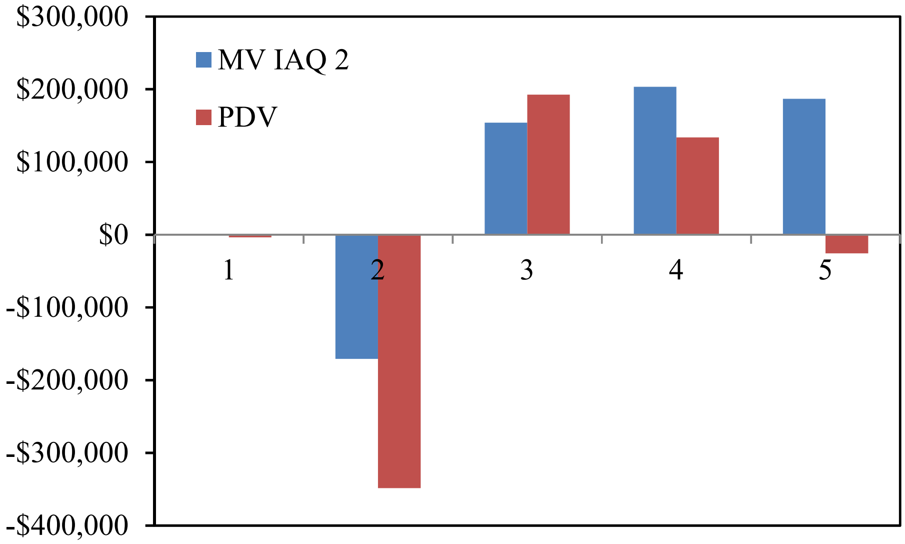


Figure 6. Weighting scheme c (energy): 1: Extra ACMV capital expenses; 2: Extra operational energy expenses; 3: Benefits of avoided sick leave; 4: Benefits of increased average mark; 5: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2: 2.1; (b) PDV: 0.9. All values are relative to the MV IAQ 1 scenario.

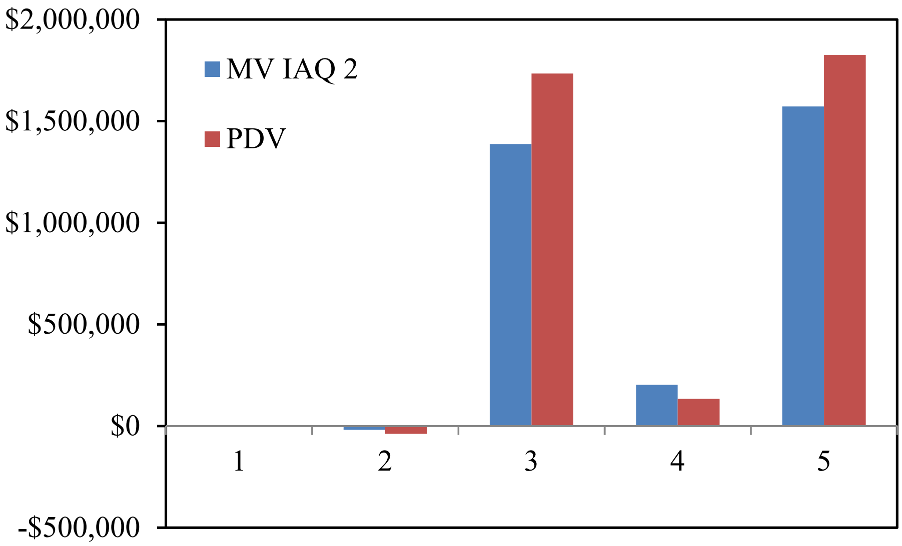


Figure 7. Weighting scheme d (wellbeing): 1: Extra ACMV capital expenses; 2: Extra operational energy expenses; 3: Benefits of avoided sick leave; 4: Benefits of increased average mark; 5: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2: 83.5; (b) PDV: 44.2. All values are relative to the MV IAQ 1 scenario.

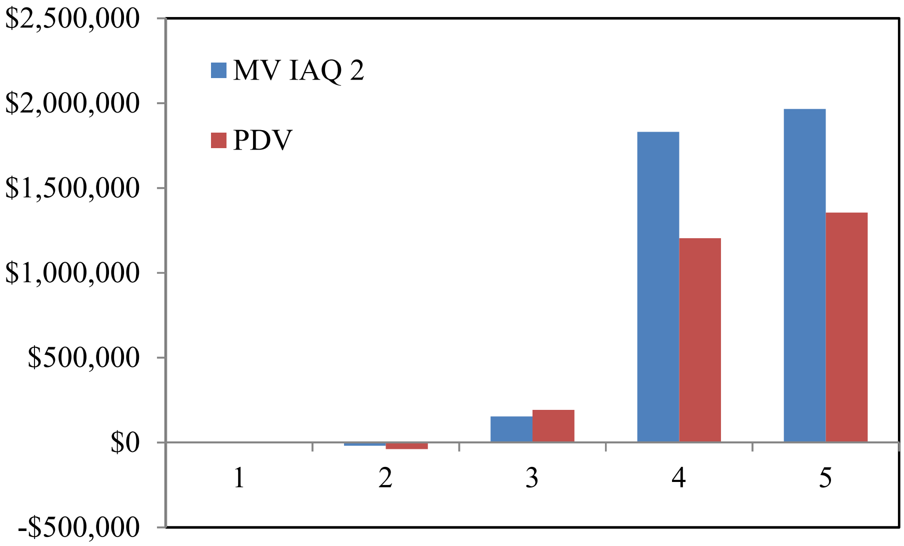


Figure 8. Weighting scheme e (performance): 1: Extra ACMV capital expenses; 2: Extra operational energy expenses; 3: Benefits of avoided sick leave; 4: Benefits of increased average mark; 5: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2: 104.2; (b) PDV: 33.1. All values are relative to the MV IAQ 1 scenario.

3.2 Sensitivity Analysis

Sensitivity analysis is further conducted for the balanced scheme a. For each sensitivity analysis, only the affected benefits or extra expenses are plotted. The sensitivity analysis results are shown in Figures 9 to 15, where the error bars denote the deviations from baselines. As can be seen, the metrics are generally robust, as there are no abrupt changes when individual metric varies within the range considered. The total net benefits are also significant and variations of total net benefits among different metrics are also comparable.

The metric that causes the largest deviation of benefits to extra expenses ratio is the energy tariff growth rate: 8.0 to 26.2 for MV IAQ 2 scenario, and 3.2 to 9.7 for PDV scenario. Deviations of the benefits to extra expenses ratio caused by varying other metrics are relatively smaller. Since the baseline values of metrics are already conservatively estimated, in general the two improved scenarios can still have good benefits to extra expenses ratio even under uncertainty. The main reason that the benefits to extra expenses ratio is most sensitive to energy tariff growth rate is because the extra expenses are predominately determined by energy expense. The individual benefits or extra expenses deviations in this case actually are not the most significant.

For the interest rate, the benefits to extra expenses ratios have very little deviations from the baseline. This suggest that monetary values in the future have very little impact on the ratio, as both benefits and extra energy expenses are discounted by the same proportion. Nonetheless, the total net benefit is less under the high interest rate case, because the benefits are much more than the extra expenses, and therefore the absolute value reduction of benefits is larger when all values are discounted by the same proportion.

For the room service life, the range of benefits to extra expenses ratio is 11.8 to 20.6 for MV IAQ 2 scenario, and 4.7 to 7.6 for PDV scenario. The total net benefits are less when the room service life is shortened. This is again because the benefits are much more than the extra expenses, and therefore although both the expenses and benefits are reduced when the room service life is shortened, the absolute value reduction of benefits is larger.

For the avoided sick leave days, increased average marks, year of salary and number of students, the overall range of benefits to extra expenses ratios is similar to that of the room service life metric. These four metrics are related to students' wellbeing and performance only. The range of deviations for the number of students is similar to that of avoided sick leave days. The deviations of the ratios and the individual benefits or extra expenses for avoided sick leave days metric are relatively smaller than those of increased average marks and year of salary. This is mainly due to the higher monetary value of performance than that of avoided sick leave days. Wargocki et al. (2005) estimated that the annual increase in productivity was worth 6-115 times larger than the increase in annual energy and maintenance costs. This range of benefits to extra expenses ratio is much larger than the range as shown in Figure 13 in the current study. For the baseline case, only the first year after graduation is considered, and the sensitivity analysis only varies in the range of ±0.5yr. As students' starting salaries normally have longer impact after graduation, incorporation of an extra 2 to 3 years' salary after graduation could lead to even more total net benefits.

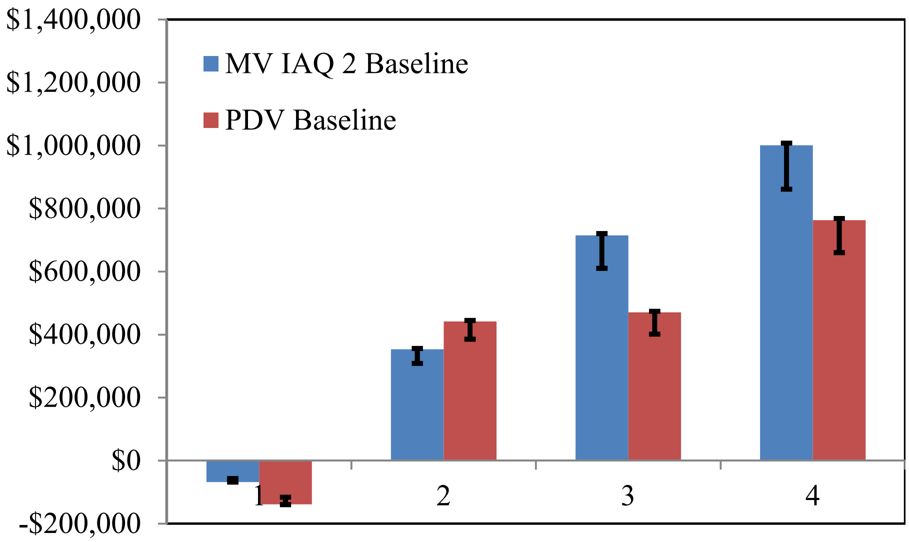


Figure 9. Sensitivity analysis for interest rate: 1: Extra operational energy expenses; 2: Benefits of avoided sick leave; 3: Benefits of increased average mark; 4: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 15.7; (b) PDV-Low Bound: 6.1; (c) MV IAQ 2-High Bound: 16.1; (d) PDV-High Bound: 6.2. All values are relative to the MV IAQ 1 scenario.

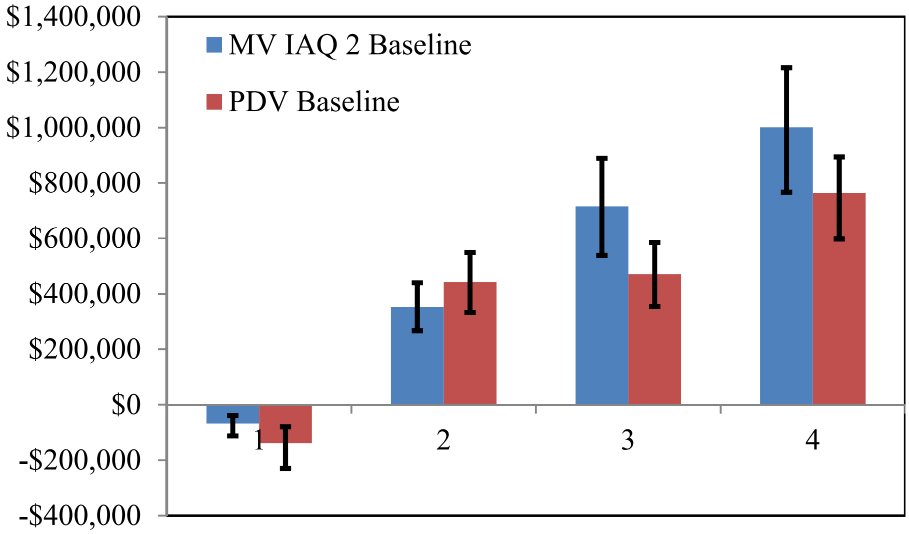


Figure 10. Sensitivity analysis for room service life: 1: Extra operational energy expenses; 2: Benefits of avoided sick leave; 3: Benefits of increased average mark; 4: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 20.6; (b) PDV-Low Bound: 7.6; (c) MV IAQ 2-High Bound: 11.8; (d) PDV-High Bound: 4.7. All values are relative to the MV IAQ 1 scenario.

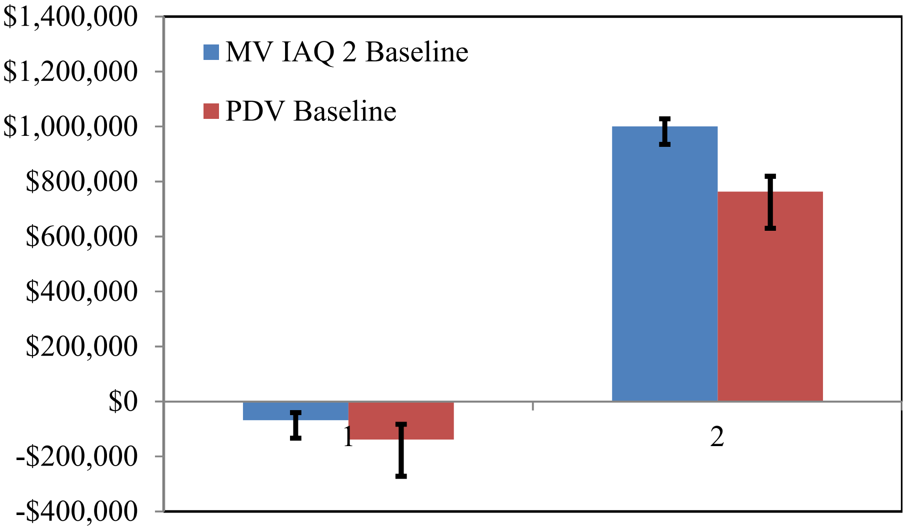


Figure 11. Sensitivity analysis for energy tariff growth rate: 1: Extra operational energy expenses; 2: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 26.2; (b) PDV-Low Bound: 9.7; (c) MV IAQ 2-High Bound: 8.0; (d) PDV-High Bound: 3.2. All values are relative to the MV IAQ 1 scenario.

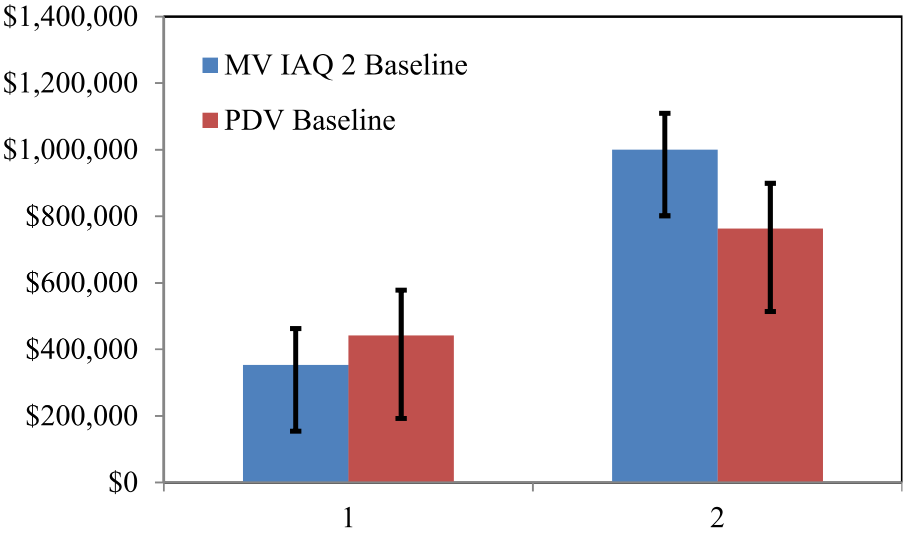


Figure 12. Sensitivity analysis for sick leave days: 1: Benefits of Avoided Sick Leave; 2: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 12.8; (b) PDV-Low Bound: 4.4; (c) MV IAQ 2-High Bound: 17.3; (d) PDV-High Bound: 7.0. All values are relative to the MV IAQ 1 scenario.

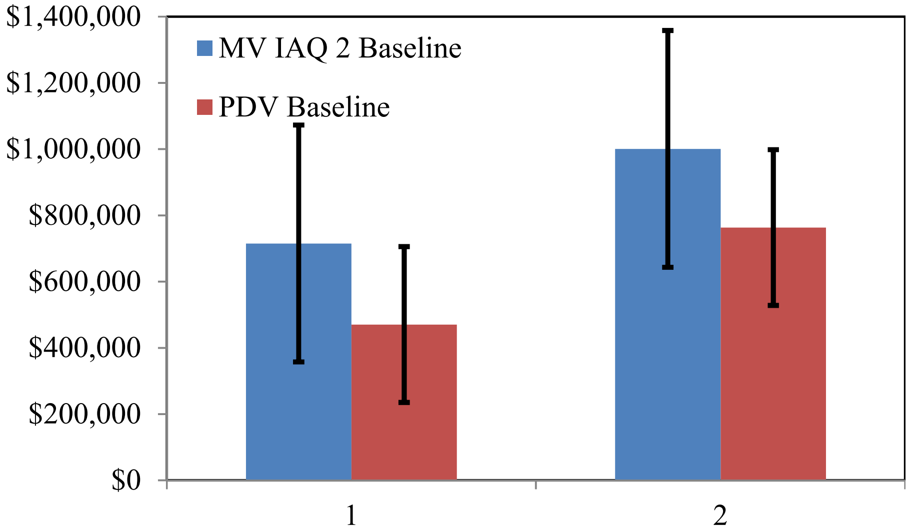


Figure 13. Sensitivity analysis for average marks: 1: Benefits of Increased Average Mark; 2: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 10.4; (b) PDV- Low Bound: 4.5; (c) MV IAQ 2-High Bound: 20.9; (d) PDV- High Bound: 7.7. All values are relative to the MV IAQ 1 scenario.

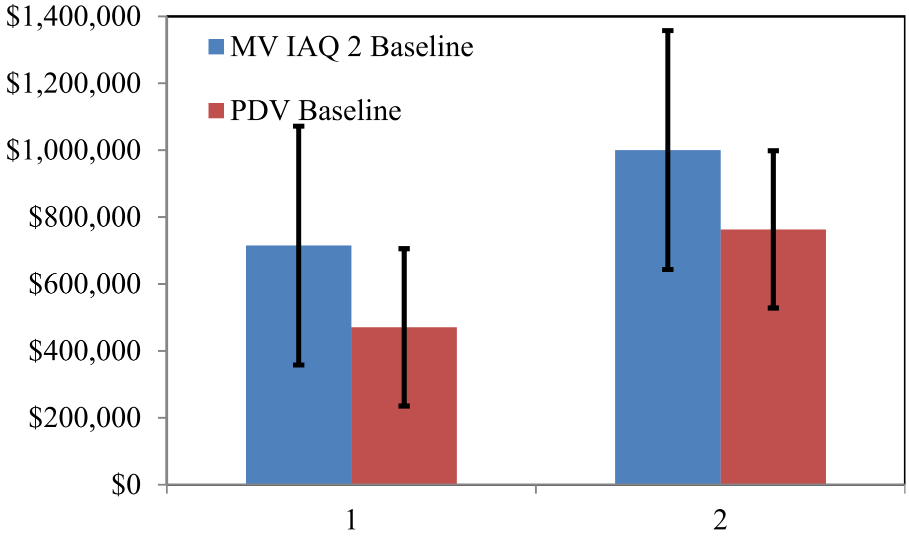


Figure 14. Sensitivity analysis for salary years: 1: Benefits of Increased Average Mark; 2: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2-Low Bound: 10.4; (b) PDV- Low Bound: 4.5; (c) MV IAQ 2-High Bound: 20.9; (d) PDV-High Bound: 7.6. All values are relative to the MV IAQ 1 scenario.

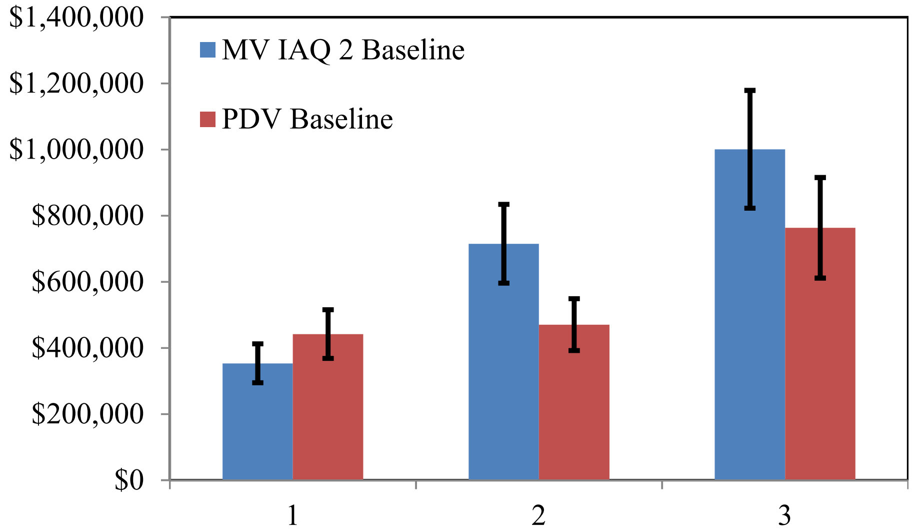


Figure 15. Sensitivity analysis for number of students: 1: Benefits of Avoided Sick Leave; 2: Benefits of Increased Average Mark; 3: Total net benefits. The Benefits to Extra Expenses Ratios: (a) MV IAQ 2- Low Bound: 13.1; (b) PDV- Low Bound: 5.1; (c) MV IAQ 2- High Bound: 18.3; (d) PDV-High Bound: 7.1. All values are relative to the MV IAQ 1 scenario.

4 Conclusions

In this study, effects of indoor environmental quality on students' wellbeing and performance in educational building are investigated with other major building metrics through the LCC perspective, with a case study of two university tutorial rooms. The metric for wellbeing of students is the number of sick leave days, and the metric for performance is the weighted average marks. The monetized metrics for these two primary metrics are benefit of avoided sick leave and benefit of weighted average marks, respectively. Different weighting schemes for the metrics are explored through the LCC perspective. Sensitivity analysis is further conducted for the balanced weighting scheme. Main conclusions from this study include:

- For the baseline balanced weighting scheme a, extra operational energy expenses are much more than extra capital expenses. The PDV scenario has more benefit of avoided sick leave, while the MV IAQ 2 scenario has more benefit of increased average mark. The MV IAQ 2 scenario also has more total net benefit. For the benefits to extra expenses ratios, the MV IAQ 2 scenario has a larger ratio than the PDV scenario (15.7 as compared to 6.1), which is mainly due to lower extra expenses in the MV IAQ 2 scenario.
- For weighting schemes b to e, the benefits to extra expenses ratios of scheme b (capital) are similar to those of balanced scheme a. For scheme c (energy), the net benefits of wellbeing and performance are almost negligible or even negative. For scheme d (wellbeing) and e (performance), higher weights for wellbeing and performance further increase the benefit to extra expenses ratios as compared with baseline balanced scheme a.
- For the sensitivity analysis of balanced weighting scheme a, the metrics are generally robust, as there are no abrupt changes when individual metric varies within the range considered. The total net benefits are also significant, and the variations of total net benefits among different metrics are also comparable. The metric that causes the largest deviation of the benefits to extra expenses ratio is the energy tariff growth rate: 8.0 to

26.2 for MV IAQ 2 scenario, and 3.2 to 9.7 for PDV scenario. For the interest rate, the benefits to extra expenses ratios have little deviations from baseline. For the room service life, the range of benefits to extra expenses ratio is 11.8 to 20.6 for MV IAQ 2 scenario, and 4.7 to 7.6 for PDV scenario. For the avoided sick leave days, increased average marks, year of salary and number of students, the overall range of benefits to extra expenses ratios is similar to that of the room service life metric.

For more sustainable building design and operation, balanced weighting scheme should be adopted, in contrary to the current practice where weights are heavily given to capital and energy while wellbeing and performance are often ignored. The consideration of students' wellbeing and performance can lead to significant total net benefits for the two improved scenarios, and the improvement carried out in the MV room has larger benefits to expenses ratio due to less extra expenses. The baseline values for different metrics are already conservatively estimated. In general, the two improved scenarios can still have good benefits to extra expenses ratio even under uncertainty.

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