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Relationships between indoor environmental quality and environmental factors in university classrooms

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Abstract

Indoor environmental quality (IEQ) is co-determined by several environmental factors (thermal, indoor air, lighting, and acoustics). In this paper, a four-layer IEQ assessment model for university classrooms was proposed based on fuzzy comprehensive evaluation (FCE) methods. The assessment model was evaluated based on a survey with a sample of 224 respondents in selected eight university classrooms in Hong Kong. Besides, objective measurements were performed in each classroom. Several parameters were included, such as operative temperature, CO_2 concentration, illuminance level, and A-weighted background noise level in the measurements. Then a set of prediction formulas were proposed to illustrate the relationships between IEQ and the environmental factors. The analysis results showed that the quality of the thermal environment was the most essential factor in the indoor environment. The results also discussed the significance rankings of sub-factors based on the weightings calculated from the analytic hierarchy process (AHP). The methods can give proper suggestions to authorities to manage the appropriate treatment and improve the indoor environmental quality. It is also useful for indoor environment design based on the proposed prediction formulas.

Keywords: indoor environmental quality; prediction formulas; assessment model; Fuzzy comprehensive evaluation; Analytic hierarchy process.

1. Introduction

Classrooms are essential places where most formal education takes place. A high level of indoor environmental quality (IEQ) is a crucial factor in achieving healthy environments in classrooms. Previous studies have shown that the IEQ had a significant effect on human comfort, productivity, effectiveness, health, and satisfaction [1-5]. It is necessary to investigate the impact of environmental factors on the assessment of indoor environmental quality. The latest review article proposed by Wu et al. [6] indicated that numbers of separate effects of single environmental factors were published in recent years. Each environmental factor independently contributed to indoor environments with different weighting factors [6]. For instance, the thermal environment [7-9], indoor air quality [10-11], lighting environment [12-14], and acoustic environment [15-17] on human perception were investigated by several researchers.

Nevertheless, occupants are subjected not to a single but multiple environmental factor simultaneously [18]. Various combination of multiple indoor environmental factors affects their overall environmental satisfaction. Many studies have indicated that it is complicated to break down satisfaction into categories and determine how these categories contribute to overall satisfaction [19-21].

Xue et al. [22] proposed a three-step structural approach of overall environment satisfaction in high-rise residential buildings in Hong Kong. The authors pointed out that the combined aspect of air quality and thermal comfort has the greatest influence on overall environment satisfaction in high-rise residential buildings, followed by luminous comfort and acoustic comfort. Kang et al. indicated a four-part IEQ assessment framework to investigate the impact of IEQ on work productivity in university open-plan research offices [23]. Merabtine et al. showed a method combined to build energy audit, thermal, and IAQ assessment of a school building in France [24]. The results indicate that increasing the indoor temperature by 1 °C can improve the indoor thermal sensation but lead to the increased energy consumption of about 12%. Yang and Moon [21] investigated the influence of multisensory interaction on acoustic comfort, thermal comfort, visual comfort, and indoor environmental comfort with three physical indoor environmental factors in South Korea. The authors concluded that the impact of acoustics on indoor environmental comfort was the greatest among the three environmental factors tested in the study. Ricciardi and Buratti [25] conducted a subjective and objective evaluation of thermal, acoustic, and lighting comfort in 7 university classrooms in Italy. The authors indicated that lighting indexes are higher than thermal and acoustical ones. Kim and de Dear [26] estimated individual impacts of 15 IEQ aspects on occupants' overall satisfaction and distinguished linear and a non-linear relationship between those aspects and overall satisfaction in various climate zones (Australia, Canada, Finland, and the USA). Frontczak et al. [27-28] found that noise level and sound privacy had a significant influence on office occupants' satisfaction.

From the results mentioned above, one can see that the relative importance of the four key aspects differs from one country to another. Different regions, cultures, and population densities make it impossible to develop a valid general formula to evaluate

IEQ. Hong Kong is one of the most densely international cities where attracts numbers of international students from all over the world. Besides, Hong Kong is a special city in which English is not the native language for students but the official educational language. These conditions may have an impact on students' evaluation of acoustic environment and speech intelligibility in classrooms.

The objective of the present study is to propose an approach assessing the impact of IEQ aspects. This study also aims to understand how sub-factors such as temperature affect each IEQ aspect separately and to investigate the effects of the physical environment and residents' adaptive behaviors on their subjective feelings about those sub-factors. The analysis is based on response data collected from the spring semester in 2018 to the autumn semester in 2019 at Hong Kong Polytechnic University. The results also indicated the relationship between environmental factors and indoor environmental quality. This result is a fundamental work to quantify the overall indoor environmental quality. It will also be possible to find and benchmark the key parameters with these questionnaire data. Therefore, guiding the building-efficiency design without eroding occupants' satisfaction with the overall environment could be achieved.

2. Literature review

2.1 Thermal quality

Thermal environment quality plays essential role in students' satisfaction and productivity in classrooms [29-31]. According to the recent review paper [32], the authors summarize that two different approaches for the definition of thermal comfort coexist at present, the rational or heat-balance approach and the adaptive approach. The most well-known prediction models based on the heat-balance approach are predicted mean vote (PMV) index and predicted percentage of dissatisfied (PPD) index [33]. PMV index is determined by six parameters, including four physical parameters (air temperature, relative humidity, air velocity and mean radiant temperature) and two human variables (clothing insulation and metabolic rate) [34]. Several adaptive analysis studies were proposed in recent years. Yao et al. presented an adaptive predicted mean vote model that took into account factors affected thermal comfort such as culture, climate, social, psychological, and behavioral adaptations [35]. Buratti and Ricciardi [36] found a linear correlation between the PMV versus the difference between the Equivalent Uniform Temperature and the Comfort Uniform Temperature. At the same time, a second-degree polynomial relation was obtained between the PPD versus the absolute value of the same difference between temperatures in Italian university classrooms.

2.2 Indoor Air quality

Indoor air quality (IAQ) is another environmental factor that has a high impact on indoor environmental quality as well as indoor productivity. A low degree of IAQ in classrooms can cause a reduction in students' productivity and even sick building syndrome (SBS) symptoms [37-38]. A multidisciplinary review [39] of 27 scientific papers on the effects of ventilation rates on health reveals that SBS symptoms can be effectively reduced when the ventilation rate is up to approximately 25 L/s per person. The previous study illustrated that CO_2 level was related to a greater respiratory symptomology in Portugal schools [40]. Xue et al. [22] put the air odor/freshness as the subjective option for occupants to evaluate the IAQ. They pointed out that air freshness had a strongly positive correlation with IAQ. In recent years, a high levels of CO_2 is still considered as the main factor affecting indoor air quality [77]. In a recent study, [78] a long-term monitoring 24-h mean indoor CO_2 concentrations for different regions of China were conducted by several researchers. The results pointed out that the mean indoor CO_2 concentrations remained almost the same throughout the seasons in southern China except in regions Yangtze River Delta and Wu Han & Chang Sha. Lei et al. proposed a comprehensive evaluation method for evaluating indoor air quality based on rough sets and a wavelet neutral network [79].

2.3 Lighting quality

Lighting quality is a crucial factor for good indoor environmental quality in classrooms [41]. The assessments of the lighting quality are still the subject of discussion in the scientific studies. A previous study pointed out that lighting quality was often limited to the evaluation of the quantity of light (illuminance and luminance) [42]. Several researchers proposed assessment methods based on luminance values or illuminance values [43-44]. Leccese et al. [45] proposed an assessment model to assess the lighting quality in the educational room using the analytic hierarchy process (AHP). Natural lighting (daylight) and artificial lighting are the main light sources of indoor lighting. Xue et al. [46] studied the effects of daylight and human behavior patterns on luminous comfort in residential buildings in Hong Kong. The authors illustrated that the degree of luminous comfort was most affected by satisfaction with daylight.

However, daylight is much more satisfying for human preference. The artificial lighting system provides a visual condition for the place where the natural lighting is lack of adequate levels or not available. Hong Kong is one of the world's most densely populated cities, with many skyscrapers and high-rise buildings. Actually, artificial lighting is widely used in Hong Kong university classrooms. Therefore, it is especially essential to assess the lighting quality in the current case study.

2.4 Acoustic quality

Some researchers have already pointed out the indoor acoustical environment is not only related to productivity, health anxiety, and comfort but also is related to acoustical quality in a space [47-50, 76]. Evidence showed that poor room acoustics, such as excessive noise and reverberation, reduced speech intelligibility in a classroom and interrupt verbal communication between teachers and students [51].

The various existing types of noise becomes the major cause of annoyance in classrooms [52-54]. The authors [15] proposed an assessment model previously to evaluate the acoustical environment quality in university classrooms in Hong Kong. The model summarized almost all the noise sources that existed around the university affected the acoustical environment. Moreover, these adverse effects are caused by many acoustical factors. Yang and Mak [55] carried out the speech intelligibility test to middle school students (aged 12-16) and undergraduate students (aged 19-21). They found out the relationships between speech intelligibility scores and speech transmission index (STI) in Hong Kong. In lower STI conditions, Younger students performed worse and seemed to be affected easily by the acoustical environment.

Besides, various studies indicated that reverberation time (RT), signal to noise ratio (SNR), sound insulation, and background noise level affected the acoustic comfort [56-57].

3. Methodology

3.1 Classrooms for investigation

In this study, eight classrooms in the Hong Kong Polytechnic University (PolyU) were investigated. All the classrooms were well decorated with acoustical treatment (sound absorptive panels, sound absorptive ceilings, floor isolation mat, etc.). The criteria of the selected classrooms contained the following considerations. Firstly, the selected classrooms were located in different buildings with different dimensions and characteristics. These conditions aim to cover the whole university. Secondly, the classrooms were selected to cover both modes of the light source (Combination of natural and artificial or artificial) in university. Thirdly, several classrooms near the street were chosen to obtain the data under high background noise levels. Fourthly, the classrooms with different volumes, windows surfaces area, exposures, etc. were taken into account to have a significant sample. The descriptions of the classrooms are shown in Table 1. The characteristics are shown in the following table, including essential issues which may affect the indoor environmental quality.

Table. 1 Classroom characteristics in case study

Classroom	1	2	3	4	5	6	7	8
Width[m]	7.12	7.84	12.11	8.91	11.26	8.17	16.53	10.99
length[m]	7.18	3.85	7.68	6.85	7.84	5.54	12.65	8.22
Height[m]	2.63	2.68	3.62	3.09	3.25	2.41	5.03	2.53
Volume[m3]	134.45	80.89	336.68	188.59	286.90	109.08	1051.80	228.56
No of seats	40	20	118	54	86	32	208	72
No of doors	2	1	2	2	2	1	2	2
No of windows	3	3	5	3	4	2	0	0
SA of windows[m2]	9.79	7.78	18.12	9.79	13.06	6.53	0	0
SA of doors [m2]	4.2	2.1	4.2	4.2	4.2	2.1	4.2	4.2
Light source	Artificial and natural						Artificial	
No of fluorescent tubes	20	8	48	28	32	12	64	40
Type of artificial lighting	Fluorescent tubes							
Materials of ceilings	Metal perforated plates							
Materials of floors	Loop pile tufted carpet							
Materials of surface walls	Sidewalls: Painted concrete walls							

	Front and rear walls: Wooden perforated plates
Materials of windows	Double glazing windows
Building Services system	HVAC

Where "No" denotes the numbers of each classroom facilities. "SA" denotes the surface area of each classroom facilities.

3.2 Subjective Questionnaires and assessment method

3.2.1 Questionnaire survey

A pilot study with 300 respondents in 8 mentioned classrooms in PolyU participated in the questionnaire survey. A total of 273 questionnaires returned, out of 224 were valid (valid rate 82%). The valid results referred to the ones passed the consistency checking process. These participants include undergraduates, postgraduates, PhD students, and academic staff (assistant professors, associate professors, and professors). General information of respondents is given in Table 2. The surveys were conducted from September 2018 to June 2019. The participants were asked to compare every two factors of one main criterion and to give scale according to the importance. They were asked to answer the questionnaire according to their feeling in prescript classrooms in PolyU. These classrooms were selected in different buildings in PolyU. In terms of each criterion, participants can choose the evaluation score from the assessment system. They were told to answer each question independently.

Table.2 General Information of respondents participated in the questionnaire survey

Classification	Gender		Students			Staffs
	Male	Female	Undergraduates	Postgraduates	PhD	
Number	135	89	116	92	12	4
Proportion (%)	60.27	39.73	51.79	41.07	5.35	1.79
Total	224		224			

3.2.2 Combined Fuzzy comprehensive evaluation (FCE) and analytic hierarchy process (AHP) method

In the real world, precise data on measurement indicators are tough to extract from human judgments. This is because human preferences encompass a degree of uncertainly, and decision-makers may very well be reluctant or unable to assign crisp numerical values to comparison judgments. Fuzzy comprehensive evaluation method (FCE) is a multi-layer comprehensive evaluation index system based on Fuzzy mathematics, which has been applied in various fields [58-61]. The analytic hierarchy process (AHP) leads from simple pairwise comparison judgments to priorities arranged within a hierarchy [62]. The AHP's crisp 9-point scale and synthesis of the relative weights are appropriate for calculating fuzzy sets, membership functions, and fuzzy members. The authors have proposed an assessment model to evaluate the acoustical environment quality using the FCE-AHP method [15]. In this study, a more complex multi-layer assessment model, including indoor environmental quality, is proposed.

The FCE method involves five steps as following:

The fuzzy multi-layer assessment model generally classifies those major factors affecting the overall assessment model into several subsets' alternatives. Assuming the set of evaluation criteria $O = [O_1, O_2, ... O_n,]$. Since$O_i (i \in [1,2 ... n])$ is composed of sub-criteria, $O_i = [O_{i1}, O_{i2}, ... O_{in}]$

The evaluation index set V is composed of all evaluation indexes. V is divided into subsets, i.e., $V = [V_1, V_2, ... V_k]$ which satisfy the following:

$$\bigcup_{i=1}^{k} V_i = V, \ V_i \cap V_j = \emptyset, \quad i, j \in [1,2 ... n].$$

Next, assuming that the evaluation index set $V = [V_1, V_2, ... V_k]$has n_i evaluation indexes, the eigenvalue of n_i evaluation matrix R_i can be represented as follows,

$$R_i = \left\{ \begin{matrix} r_{11}^{(i)} & r_{12}^{(i)} & \cdots r_{1m}^{(i)} & \\ r_{21}^{(i)} & r_{22}^{(i)} \cdots & r_{2m}^{(i)} & \\ \vdots & \vdots & \vdots & \vdots \\ r_{ni1}^{(i)} & r_{ni2}^{(i)} \cdots & r_{nim}^{(i)} & \end{matrix} \right\}$$

Assuming that $A_i = [{a_1}^{(i)}, {a_2}^{(i)}, \dots, {a_{n_i}}^{(i)}]$ is the weighting coefficient evaluation matrix.

The result set of a comprehensive evaluation is as follows,

$$B = A \circ R = (b_1, b_2, \dots, b_m),$$

where $\circ$ represent a kind of fuzzy operation symbol, the computational formula is

$$b_j = \sum_{i=1}^{n} (a_i r_{ij})$$

In the current study, A four-layer overall indoor environmental quality assessment model (O) is established in Fig.1. Each of these criteria is made up of some independent indexes.

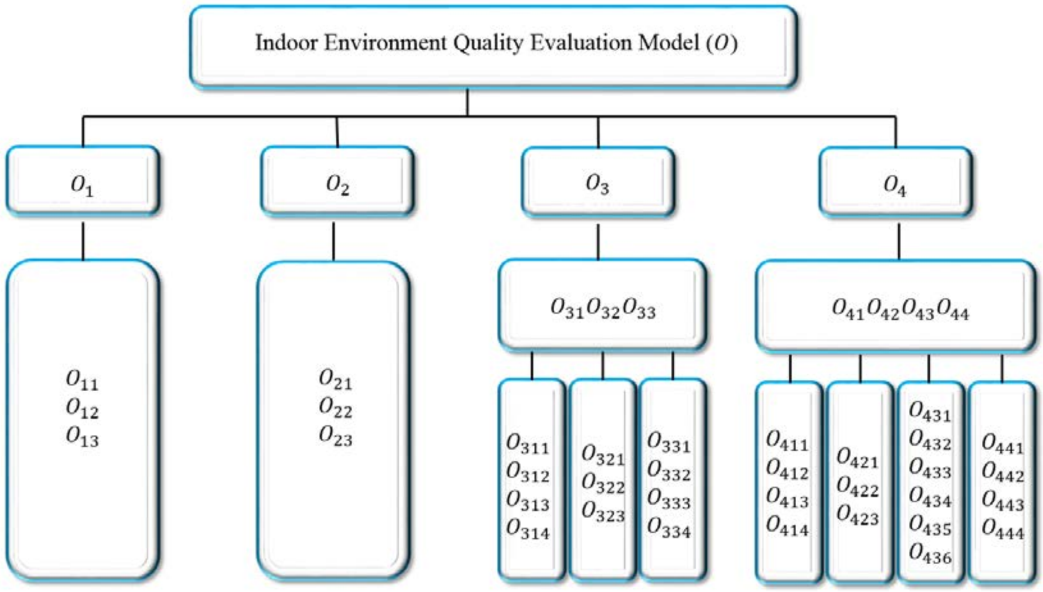

Fig 1 assessment model framework of indoor environmental quality

As shown in Fig.1, the indoor environmental quality FCE-AHP assessment model consist of 4 main criteria. These 4 main criteria are including thermal quality (O_1), indoor air quality (O_2), lighting quality (O_3), and acoustic quality (O_4).

Thermal quality (O_1) includes three sub-factors O_{11} to O_{13}. O_{11} represents the feelings of temperature for the subjects in the classrooms. O_{12} represents the feeling s of relative humidity for the subjects in the classrooms. O_{13} represents the effect of the clothing insulation for the subjects in the classrooms.

Indoor air quality (O_2) includes three sub-factors O_{21} to O_{23}. O_{21} represents the feelings of natural ventilation conditions for subjects in the classrooms. O_{22} represents the feelings of air-conditioning ventilation conditions for subjects in the classrooms. O_{23} is the feelings of the air freshness for subjects in the classrooms.

Lighting quality (O_3) includes three sub-factors O_{31} to O_{33}. O_{31} represents the quality of the artificial lighting system in classrooms. This criterion includes four sub-factors named O_{311} to O_{334}. O_{311} is the illuminance level of the classrooms. O_{312} is the illuminance uniformity of the classrooms. O_{313} is the feelings of uncomfortable glare for subjects in classrooms. O_{314} is the feelings of visual comfort for subjects to evaluate the artificial lighting system in classrooms. O_{32} represents the quality of natural lighting in classrooms. This criterion includes four sub-factors named O_{321} to O_{324}. O_{321} is the amount of daylight. O_{322} is the hours of the daylight. O_{323} is the sunlight reflection of the walls, blackboard, floors and desk in classrooms. O_{324} is direct solar radiation in classrooms. O_{33} represents the quality of the performance of the fluorescent tubes in classrooms. This criterion includes four sub-factors named O_{331} to O_{334}. O_{331} is the color rendition in classrooms. O_{332} is the color temperature in classrooms. O_{333} is the color rendering index. O_{334} is the lighting power density of the fluorescent tubes.

Acoustic quality (O_4) is determined by four evaluation indexes: the classroom facility(O_{41}), inside classroom noise(O_{42}), outside classroom noise(O_{43}), Interactive teaching(O_{44}). O_{41} represents the noise effects of the classroom facility. This criterion includes six sub-factors named O_{411} to O_{414}. Acoustical properties *(*O_{411}*)*: such as the acoustical design of walls and ceilings. Equipment (O_{412}): facilities includes data projector, projection screen, teacher's computer and network connection for students' computer and laptops. Classroom specification (O_{413}): this criterion is mainly referred to as the classroom size. Insufficient classroom space may influence students in daily education. Classroom architecture (O_{414}): such as shape and style of the classroom, the location of the classroom. All of these are important factors that affect students learning process and education quality. O_{42} is further determined by three alternatives. Heating Ventilation and Air conditioning (HVAC) system (O_{421}) are the primary sources of noise inside the classroom. The system includes air handlers and fans, acoustical treatment of ducts, returns, and diffusers. Besides, students' activity and interacting (O_{422}) can increase the noise level inside the classrooms. Besides, another factor that contributed to the noise inside the classroom is the lighting system (O_{423}). Corresponding to O_{42}, noise sources outside the classroom (O_{43}) is another important criterion of the classroom acoustics. O_{43} is further considered by the following six criteria: traffic noise (O_{431}), noise generated from the neighboring classroom (O_{432}), noise from corridor, hallway, and lobby (O_{433}), the noise coming from surrounding playgrounds (O_{434}), mechanical equipment noise (O_{435}), noise generated from the nearby building (O_{436}).

Universities aim to increase the effectiveness of teaching students so that the teaching methods and styles (O_{44}) play an essential role in classroom education. These teaching methods and styles mainly include practice work (O_{441}), group work (O_{442}), blackboard teaching (O_{443}) and multimedia techniques (O_{444}). Different ways of communication between students and speakers affect the different learning experiences.

3.3 Objective experimental measurement

In order to measure the indoor environment variables, different kinds of instruments were used in the objective experimental measurements. The authors have already investigated the acoustic conditions in university classrooms and middle school classrooms [55]. However, other aspects, apart from acoustic conditions, need to be taken into account for evaluating overall indoor environmental quality in classrooms. In this work, the investigation is extended to analyze also the thermal, indoor air, and lighting quality environment. General information of instruments used in the measurements was shown in Table 3.

Table 3 Information of instruments in IEQ measurements

IEQ aspect	Parameter	Instrument	Unit	Range	Accuracy
Thermal	Temperature	HOBO data logger	°C	-20-100	0.45°C
	Air velocity	Dantec Low Air velocity Meter	m/s	0.05-5.00	2% or 0.02m/s of reading
	RH	HOBO data logger	%	0-100	5%
IAQ	CO_2 concentration	Telaire 7001 CO_2 sensor	ppm	0-10,000	50ppm or 5% of reading
Lighting	Illuminance level		lux	0-50,000	5%
	Illuminance Uniformity	Luntron LX-101A	N/A	0.000-1.000	N/A
Acoustic	L_{Aeq}	B&K 2270	dB	0-123	1.5dB
	T_{30}	B&K 7841 Dirac	s	0.02-100	N/A
	STI	B&K 7841 Dirac	N/A	0-1	N/A

In Table 3, "RH" denotes to relative humidity. "L_{Aeq}" denotes to A-weighted Noise Continuous Equivalent Level. "T_{30}" denotes to Reverberation Time related to the decay from - 5 dB to - 35 dB. "STI" means Speech Transmission Index.

4. Evaluation results of IEQ in university classrooms

Refer to the multi-criteria assessment model (see Fig.1), a combination of the AHP method and the FCE method is employed to calculate the model. The AHP enables decision-makers to structure complex problems in a simple hierarchical form and to evaluate a large number of quantitative and qualitative factors systematically despite the presence of multiple conflicting criteria. The participants were asked to compare every two factors of one main criterion and to give scale according to the importance. Besides, respondents were asked about the quality of indoor environmental quality in PolyU. In terms of each criterion, students can choose an evaluation score from the assessment system. They were told to answer each question independently. They were arranged to complete the questionnaires in prescript classrooms. The statistical results of the results were shown in the following tables.

Table 4. The subjective results of thermal and indoor air quality in classrooms

Main Criteria	Sub-criteria	Excellent V_1	Good V_2	Medium V_3	Poor V_4	Very Poor V_5
Thermal environment quality(O_1)	Temperature (O_{11})	38	95	72	14	5
	Relative Humidity (O_{12})	23	106	58	31	6
	Clothing insulation (O_{13})	69	76	63	12	4

Indoor Air quality (O_2)	Natural ventilation condition (O_{21})	8	25	42	102	47
	Air-conditioning ventilation condition (O_{22})	88	53	51	22	10
	air freshness (O_{23})	27	76	72	36	13

Table 5. The subjective results of lighting quality in classrooms

Main Criteria	Sub-criteria	Excellent V_1	Good V_2	Medium V_3	Poor V_4	Very Poor V_5
Quality of the artificial lighting system (O_{31})	Illuminance level (O_{311})	41	108	60	12	3
	Illuminance uniformity(O_{312})	12	92	66	43	11
	Uncomfortable glare (O_{313})	34	102	47	25	16
	Visual comfort (O_{314})	42	80	58	32	12
Quality of natural lighting (O_{32})	Amount of daylight (O_{321})	12	32	77	66	37
	Sunlight reflection effects (O_{322})	53	86	52	18	15
	Direct solar radiation (O_{323})	55	43	82	35	9
Performance of the fluorescent tubes (O_{33})	Color rendition (O_{331})	65	73	67	12	7
	Color temperature (O_{332})	106	66	30	21	1
	Color rendering index (O_{333})	102	72	36	10	4
	Lighting power density (O_{334})	103	46	42	25	8

Table 6. The subjective results of acoustic quality in classrooms

Main Criteria	Sub-criteria	Excellent V_1	Good V_2	Medium V_3	Poor V_4	Very Poor V_5
The classroom facility (O_{41})	Acoustical properties (O_{411})	141	65	12	4	2
	Equipment (O_{412})	48	66	58	34	18
	Classroom specification (O_{413})	32	88	78	22	4
	Classroom architecture (O_{414})	42	150	18	12	2
Inside classroom noise (O_{42})	HVAC system (O_{421})	80	82	27	22	13
	Students' activity and interacting (O_{422})	182	31	12	1	0
	lighting system (O_{423})	142	55	20	6	1
Outside classroom noise (O_{43})	Traffic noise (O_{431})	93	42	67	18	4
	Noise generated from neighboring classroom (O_{432})	168	46	10	0	0
	Noise from corridor, hallway, and lobby (O_{433})	100	82	36	4	2
	Noise coming from surrounding playgrounds (O_{434})	177	12	20	10	5
	Mechanical equipment noise (O_{435})	113	43	41	14	13
	Noise generated from the nearby building (O_{436})	98	79	26	12	9
Interactive teaching (O_{44})	Practice work (O_{441})	106	49	42	23	4
	Group work (O_{442})	89	65	44	23	3
	Blackboard teaching (O_{443})	52	76	48	42	6
	Multimedia techniques (O_{444})	99	53	45	18	9

The results of 224 valid FCE questionnaires in every part of indoor environmental quality were summarized in Table 4-6. Besides, the AHP pairwise comparison results and weightings were shown in Table 7-15. Assuming that the evaluation index set:

$V = [V_1, V_2, V_3, V_4, V_5] =$

$["Excellent", "Good", "Medium", "Poor", "Very\ \ Poor"]$,

where "Excellent" refers to score more than 90, "Good" refers to score between 80 and 90, "Medium" refers to score from 70 to 80, "Poor" refers to score from 60 to 70, and "Very Poor" refers to score up to 60.

Table 7 Pairwise comparisons among thermal quality assessment

	$\boldsymbol{O_{11}}$	$\boldsymbol{O_{12}}$	$\boldsymbol{O_{13}}$	**Weighting**
$\boldsymbol{O_{11}}$	1.00	1.62	1.23	41.24%
$\boldsymbol{O_{12}}$	0.62	1.00	0.85	26.47%
$\boldsymbol{O_{13}}$	0.81	1.18	1.00	32.28%

Table 8 Pairwise comparisons among indoor air quality assessment

	$\boldsymbol{O_{21}}$	$\boldsymbol{O_{22}}$	$\boldsymbol{O_{23}}$	**Weighting**
$\boldsymbol{O_{21}}$	1.00	0.43	0.70	20.94%
$\boldsymbol{O_{22}}$	2.32	1.00	1.77	50.04%
$\boldsymbol{O_{23}}$	1.43	0.56	1.00	29.02%

Table 9 Pairwise comparisons among artificial lighting systems quality alternatives

	$\boldsymbol{O_{311}}$	$\boldsymbol{O_{312}}$	$\boldsymbol{O_{313}}$	$\boldsymbol{O_{314}}$	**Weighting**
$\boldsymbol{O_{311}}$	1.00	1.56	2.47	0.80	30.70%
$\boldsymbol{O_{312}}$	0.64	1.00	1.62	0.54	20.04%
$\boldsymbol{O_{313}}$	0.40	0.62	1.00	0.38	12.84%
$\boldsymbol{O_{314}}$	1.25	1.84	2.65	1.00	36.42%

Table 10 Pairwise comparisons among natural lighting quality alternatives.

	$\boldsymbol{O_{321}}$	$\boldsymbol{O_{322}}$	$\boldsymbol{O_{323}}$	**Weighting**
$\boldsymbol{O_{321}}$	1.00	0.48	0.65	20.87%
$\boldsymbol{O_{322}}$	2.08	1.00	2.39	52.53%
$\boldsymbol{O_{323}}$	1.54	0.42	1.00	26.61%

Table 11 Pairwise comparisons among fluorescent tubes performance alternatives.

	$\boldsymbol{O_{331}}$	$\boldsymbol{O_{332}}$	$\boldsymbol{O_{333}}$	$\boldsymbol{O_{334}}$	**Weighting**
$\boldsymbol{O_{331}}$	1.00	0.34	4.75	2.38	26.84%
$\boldsymbol{O_{332}}$	2.98	1.00	4.26	3.83	51.89%
$\boldsymbol{O_{333}}$	0.21	0.23	1.00	0.35	7.11%
$\boldsymbol{O_{334}}$	0.42	0.26	2.83	1.00	14.16%

Table 12 Pairwise comparisons among three major criteria in lighting quality assessment

	$\boldsymbol{O_{31}}$	$\boldsymbol{O_{32}}$	$\boldsymbol{O_{33}}$	**Weighting**
$\boldsymbol{O_{31}}$	1.00	0.54	1.67	29.77%
$\boldsymbol{O_{32}}$	1.85	1.00	2.44	50.92%
$\boldsymbol{O_{33}}$	0.60	0.41	1.00	19.31%

Table 13 Pairwise comparisons among classroom facilities alternatives

	$\boldsymbol{O_{411}}$	$\boldsymbol{O_{412}}$	$\boldsymbol{O_{413}}$	$\boldsymbol{O_{414}}$	**Weighting**
$\boldsymbol{O_{411}}$	1.00	3.26	4.39	2.56	50.59%
$\boldsymbol{O_{412}}$	0.31	1.00	0.45	0.28	9.32%
$\boldsymbol{O_{413}}$	0.23	2.22	1.00	0.52	14.48%
$\boldsymbol{O_{414}}$	0.39	3.57	1.92	1.00	25.62%

Table 14 Pairwise comparisons among inside classroom noise alternatives.

	$\boldsymbol{O_{421}}$	$\boldsymbol{O_{422}}$	$\boldsymbol{O_{423}}$	**Weighting**
$\boldsymbol{O_{421}}$	1.00	2.55	2.83	57.28%
$\boldsymbol{O_{422}}$	0.39	1.00	1.25	23.33%
$\boldsymbol{O_{423}}$	0.35	0.80	1.00	19.39%

Table 15 Pairwise comparisons among outside classroom noise alternatives.

	$\boldsymbol{O_{431}}$	$\boldsymbol{O_{432}}$	$\boldsymbol{O_{433}}$	$\boldsymbol{O_{434}}$	$\boldsymbol{O_{435}}$	$\boldsymbol{O_{436}}$	**Weighting**
$\boldsymbol{O_{431}}$	1.00	0.27	0.36	0.49	1.25	1.96	9.74%

$\boldsymbol{O_{432}}$	3.68	1.00	0.60	2.88	3.71	3.94	30.15%
$\boldsymbol{O_{433}}$	2.76	1.66	1.00	2.08	2.86	2.91	29.54%
$\boldsymbol{O_{434}}$	2.06	0.35	0.48	1.00	2.32	2.55	15.69%
$\boldsymbol{O_{435}}$	0.80	0.27	0.35	0.43	1.00	0.83	7.57%
$\boldsymbol{O_{436}}$	0.51	0.25	0.34	0.39	1.20	1.00	7.31%

Table 16 Pairwise comparisons among interactive teaching alternatives.

	$\boldsymbol{O_{441}}$	$\boldsymbol{O_{442}}$	$\boldsymbol{O_{443}}$	$\boldsymbol{O_{444}}$	**Weighting**
$\boldsymbol{O_{441}}$	1.00	1.28	1.16	0.76	24.82%
$\boldsymbol{O_{442}}$	0.78	1.00	0.83	0.44	17.58%
$\boldsymbol{O_{443}}$	0.86	1.20	1.00	0.54	20.75%
$\boldsymbol{O_{444}}$	1.32	2.25	1.85	1.00	36.85%

Table 17 Pairwise comparisons among four sub-criteria of acoustic quality.

	$\boldsymbol{O_{41}}$	$\boldsymbol{O_{42}}$	$\boldsymbol{O_{43}}$	$\boldsymbol{O_{44}}$	**Weighting**
$\boldsymbol{O_{41}}$	1.00	1.33	1.79	1.52	33.55%
$\boldsymbol{O_{42}}$	0.75	1.00	1.39	1.60	27.55%
$\boldsymbol{O_{43}}$	0.56	0.72	1.00	1.22	20.31%
$\boldsymbol{O_{44}}$	0.66	0.63	0.82	1.00	18.60%

Table 18 Pairwise comparisons among four main criteria alternatives of IEQ

	$\boldsymbol{O_1}$	$\boldsymbol{O_2}$	$\boldsymbol{O_3}$	$\boldsymbol{O_4}$	Weighting
$\boldsymbol{O_1}$	1.00	1.88	1.36	1.15	31.77%
$\boldsymbol{O_2}$	0.53	1.00	0.65	0.59	16.29%
$\boldsymbol{O_3}$	0.74	1.54	1.00	0.82	23.86%
$\boldsymbol{O_4}$	0.87	1.69	1.22	1.00	28.08%

As the results are shown in Table 4-6, the normalized sub-criteria evaluation matrix of the thermal quality R_1, the normalized sub-criteria evaluation matrix of the indoor air quality R_2, the normalized sub-criteria evaluation matrix of the lighting quality $R_{31}-R_{33}$, the normalized sub-criteria evaluation matrix of the acoustic quality $R_{41}-R_{44}$.

$$R_1 = \begin{bmatrix} 0.170, 0.424, 0.321, 0.062, 0.023 \\ 0.103, 0.473, 0.259, 0.138, 0.277 \\ 0.308, 0.339, 0.281, 0.054, 0.018 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.036, 0.112, 0.187, 0.455, 0.210 \\ 0.393, 0.237, 0.228, 0.098, 0.044 \\ 0.121, 0.339, 0.321, 0.161, 0.058 \end{bmatrix}$$

$$R_{31} = \begin{bmatrix} 0.183, 0.482, 0.268, 0.054, 0.013 \\ 0.053, 0.411, 0.295, 0.192, 0.049 \\ 0.152, 0.455, 0.210, 0.112, 0.071 \\ 0.188, 0.357, 0.259, 0.143, 0.054 \end{bmatrix}$$

$$R_{32} = \begin{bmatrix} 0.054, 0.143, 0.344, 0.295, 0.165 \\ 0.237, 0.384, 0.232, 0.080, 0.067 \\ 0.245, 0.192, 0.366, 0.157, 0.040 \end{bmatrix}$$

$$R_{33} = \begin{bmatrix} 0.290, 0.326, 0.299, 0.054, 0.031 \\ 0.473, 0.295, 0.134, 0.094, 0.004 \\ 0.455, 0.321, 0.161, 0.045, 0.018 \\ 0.460, 0.205, 0.188, 0.112, 0.036 \end{bmatrix}$$

$$R_{41} = \begin{bmatrix} 0.629, 0.290, 0.054, 0.018, 0.009 \\ 0.214, 0.295, 0.259, 0.152, 0.080 \\ 0.143, 0.393, 0.348, 0.098, 0.018 \\ 0.187, 0.670, 0.080, 0.054, 0.009 \end{bmatrix}$$

$$R_{42} = \begin{bmatrix} 0.357, 0.366, 0.121, 0.098, 0.058 \\ 0.813, 0.138, 0.054, 0.005, 0.000 \\ 0.634, 0.246, 0.089, 0.027, 0.004 \end{bmatrix}$$

$$R_{43} = \begin{bmatrix} 0.415, 0.188, 0.299, 0.080, 0.018 \\ 0.750, 0.205, 0.045, 0.000, 0.000 \\ 0.446, 0.366, 0.161, 0.018, 0.009 \\ 0.790, 0.054, 0.089, 0.045, 0.022 \\ 0.504, 0.192, 0.183, 0.063, 0.058 \\ 0.437, 0.353, 0.116, 0.054, 0.040 \end{bmatrix}$$

$$R_{44} = \begin{bmatrix} 0.473, 0.219, 0.187, 0.103, 0.018 \\ 0.397, 0.290, 0.197, 0.103, 0.013 \\ 0.232, 0.339, 0.214, 0.188, 0.027 \\ 0.442, 0.237, 0.201, 0.080, 0.040 \end{bmatrix}$$

The pairwise comparison results of the thermal quality assessment were given in Table 7. $A_1 = [0.4124, 0.2647, 0.3228]$ is the weighting coefficient evaluation matrix calculated from AHP method for thermal quality.

The result set of the comprehensive evaluation of thermal quality is as follows,

$$B_1 = A_1 \circ R_1 = [0.1968, 0.4095, 0.2916, 0.0795, 0.0886]$$

Similarly, the result set of the comprehensive evaluation of indoor air quality is:

$$B_2 = A_2 \circ R_2 = [0.2393, 0.2404, 0.2464, 0.1910, 0.0828]$$

The result set of the second hierarchy comprehensive evaluation of lighting quality is:

$$B_{31} = A_{31} \circ R_{31} = [0.1548, 0.4188, 0.2627, 0.1215, 0.0426]$$

$$B_{32} = A_{32} \circ R_{32} = [0.2010, 0.2827, 0.2911, 0.1454, 0.0803]$$

$$B_{33} = A_{33} \circ R_{33} = [0.4208, 0.2924, 0.1879, 0.0823, 0.0168]$$

$$B_3 = \begin{Bmatrix} B_{31} \\ B_{32} \\ B_{33} \end{Bmatrix} = \begin{bmatrix} 0.1548, 0.4188, 0.2627, 0.1215, 0.0426 \\ 0.2010, 0.2827, 0.2911, 0.1454, 0.0803 \\ 0.4208, 0.2924, 0.1879, 0.0823, 0.0168 \end{bmatrix}$$

The result set of the second hierarchy comprehensive evaluation of acoustic quality is:

$$B_{41} = A_{41} \circ R_{41} = [0.4068 \ \ 0.4048, 0.1223, 0.0513, 0.0169]$$

$$B_{42} = A_{42} \circ R_{42} = [0.5171, 0.2895, 0.0992, 0.0625, 0.0340]$$

$$B_{43} = A_{43} \circ R_{43} = [0.5923, 0.2370, 0.1265, 0.0289, 0.0152]$$

$$B_{44} = A_{44} \circ R_{44} = [0.3982, 0.2630, 0.1995, 0.1122, 0.0271]$$

$$B_4 = \begin{Bmatrix} B_{41} \\ B_{42} \\ B_{43} \\ B_{44} \end{Bmatrix} = \begin{bmatrix} 0.4068 \ \ 0.4048, 0.1223, 0.0513, 0.0169 \\ 0.5171, 0.2895, 0.0992, 0.0625, 0.0340 \\ 0.5923, 0.2370, 0.1265, 0.0289, 0.0152 \\ 0.3982, 0.2630, 0.1995, 0.1122, 0.0271 \end{bmatrix}$$

Referring to Table 12, the pairwise comparison and weighting coefficient evaluation of three sub-criteria of lighting quality was given. The weighting matrix A_3 is as follows:

$$A_3 = [0.2977, 0.5092, 0.1931].$$

The overall lighting quality C_l is:

$$C_l = A_3 \circ B_3 = [0.2297, 0.3251, 0.2627, 0.1261, 0.0568]$$

Referring to Table 17, the pairwise comparison and weighting coefficient evaluation of four sub-criteria of acoustic quality was given. The weighting matrix A_4 is as follows:

$$A_4 = [0.3355, 0.2755, 0.2031, 0.1860].$$

The overall acoustic quality C_a is:

$$C_a = A_4 \circ B_4 = [0.4733, 0.3126, 0.1312, 0.0612, 0.0232]$$

Referring to Table 18, the pairwise comparison and weighting coefficient evaluation of four main criteria of indoor environmental quality were given. The weighting matrix A is as follows:

$$A = [0.3177, 0.1629, 0.2386, 0.2808].$$

The result set of the first hierarchy comprehensive evaluation of IEQ is:

$$C = \begin{Bmatrix} B_1 \\ B_2 \\ C_l \\ C_a \end{Bmatrix} = \begin{bmatrix} 0.1968, 0.4095, 0.2916, 0.0795, 0.0886 \\ 0.2393, 0.2404, 0.2464, 0.1910, 0.0828 \\ 0.2297, 0.3251, 0.2627, 0.1261, 0.0568 \\ 0.4733, 0.3126, 0.1312, 0.0612, 0.0232 \end{bmatrix}$$

The overall indoor environmental quality Q is as follows:

$$Q = A \circ C = [0.2892, 0.3346, 0.2323, 0.1036, 0.0617]$$

In order to calculate the value of the overall assessment of indoor environmental quality in classrooms. The authors defined the evaluation index "Excellent" refers to score 95, "Good" refers to score 85, "Medium" refers to score 75, "Poor" refers to score 65, and "Very Poor" refers to score 30. These are mainly because the definition scores were depended on the mean score in the corresponding evaluation interval. Therefore, the evaluation index value set N defines:

$$N = [N_1, N_2, N_3, N_4, N_5] = ["Excellent", "Good", "Medium", "Poor", "Very\ \ Poor"$$

$$N = [95,85,75,65,30]$$

The overall assessment score of the IEQ in classrooms S is:

$$S = Q * N' = [0.2892, 0.3346, 0.2323, 0.1036, 0.0617] \begin{bmatrix} 95 \\ 85 \\ 75 \\ 65 \\ 30 \end{bmatrix} = 81.9274$$

Therefore, the overall assessment score of IEQ in PolyU classrooms is 81.9274, which refers to "Good."

Since the matrix A represents and weighting coefficient evaluation of four main criteria of indoor environmental quality. Therefore, the indoor environmental quality satisfaction formula is as follows:

$$O = 0.3177 O_1 + 0.1629 O_2 + 0.2386 O_3 + 0.2808 O_4 \quad (1)$$

5. Relationship between IEQ and environmental factors in classrooms

In addition to the subjective surveys in the university classrooms, objective measurements of indoor environmental quality were synchronously conducted in the mentioned classrooms. The detailed information about classrooms and instruments are shown in Table 1 and Table 3, respectively. During the survey, mean daily outdoor temperatures ranged from 24.6 °C to 35.8 °C. The outdoor relative humidity ranged from 60% to 86%.

In order to obtain the relationships between indoor environmental quality factors with the residential satisfaction in university classrooms, the regression analysis model was employed in a separate field. Several single parameters in each area were selected for analyzing the relationships between the quantitative and qualitative results. The underlying data (mean value) of the selected eight classrooms were given in Table 19. The overall satisfaction scores in the following sections were normalized. The regression analysis calculation and graphical representation were performed using MATLAB R2016a.

Table 19 The underlying data (mean value) of selected eight classrooms

Classroom	1	2	3	4	5	6	7	8
Temperature (°C)	19.0	20.9	23.1	25.0	25.9	27.0	28.1	30.0
Air velocity (m/s)	0.53	0.42	0.40	0.39	0.36	0.38	0.44	0.45
Relative humidity (%)	50.2	48.5	55.6	62.3	59.2	68.5	66.3	72.6
CO_2 concentration (ppm)	971	1641	521	554	843	1183	449	640
Illuminance level (lux)	533	309	919	645	505	458	724	239
L_{Aeq} (dB)	59.5	54.9	60.2	46.6	54.9	49.9	51.7	57.9
T_{30} (s)	0.41	0.35	0.49	0.43	0.41	0.39	0.64	0.44
STI (-)	0.72	0.86	0.65	0.76	0.77	0.79	0.71	0.75

5.1 Thermal environment

Referring to previous studies [63-65], the operative temperature, which was comprised of the convection and radiation, was used as an indoor temperature index. During the survey, the operative temperature in eight classrooms ranged from 19 °C to 30 °C. The indoor relative humidity ranged from 48.5% to 72.6%. The air velocity was 0.36m/s-0.53m/s. The overall satisfaction was calculated by subjective questionnaires in each classroom followed the mentioned FCE process (Sec. 4). The relationship between overall satisfaction (normalized) and the operative temperature was shown in Fig 3.

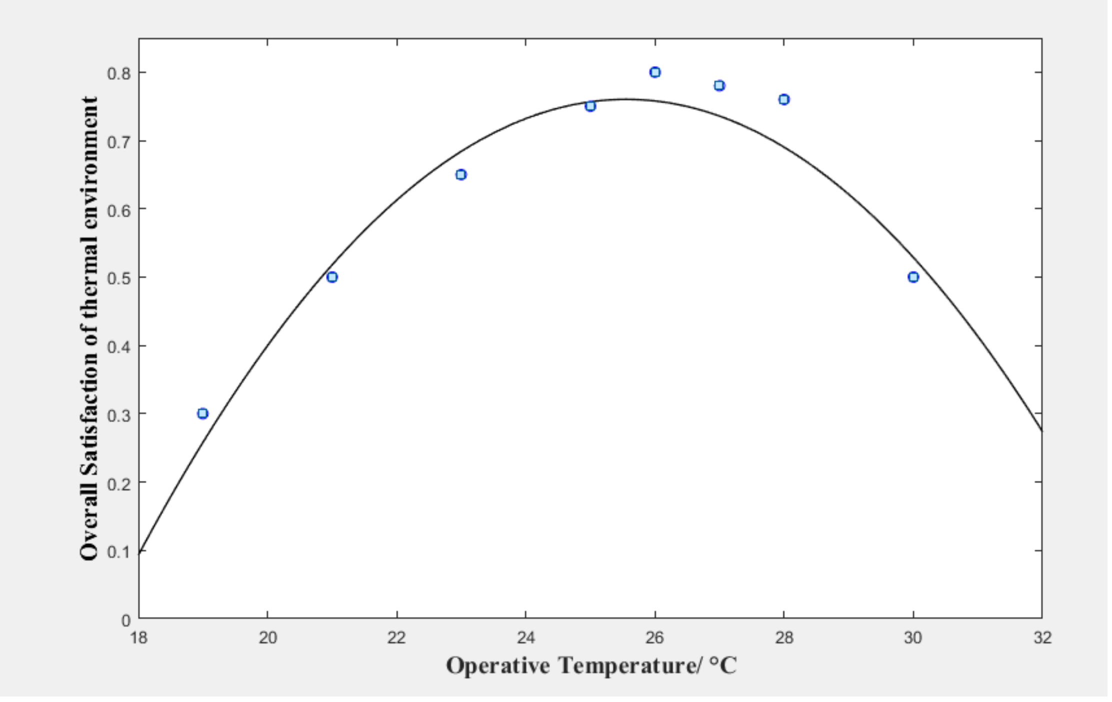

Fig 3 Relationship between thermal satisfaction and operative temperature

Fig. 3 shows the relationship between the overall satisfaction of the thermal environment and the operative temperature. Each dot represents the average value of the overall satisfaction at the corresponding operative temperature in a classroom. The corresponding polynomial equation is written as follows:

$$S_T = -0.0117{t_0}^2 + 0.5979t_0 - 6.878 \quad R^2 = 0.9509 \tag{2}$$

Where t_0 denotes the operative temperature, S_T is the normalized satisfaction of the thermal environment.

For the proposed polynomial equation, F-test was used for verifying the validation. The results show there are statistically significant differences between the overall satisfaction of the thermal environment and operative temperature ($F= 48.403$, $p<0.01$).

5.2 Indoor air quality

Many kinds of environmental parameters are factors affects the indoor air quality, such as $CO, CO_2, NO_x,\ NH_3, and\ O_3$ [66]. Since the target buildings in the current study are mainly used for studying and teaching. CO_2 As the primary production by the human body is considered the most essential factor for evaluating indoor air quality. During the survey, the concentration of CO_2 in eight classrooms ranged from 449 ppm to 1641ppm (parts per million). The relationship between overall satisfaction scores of IAQ and concentration of CO_2 are shown as follows:

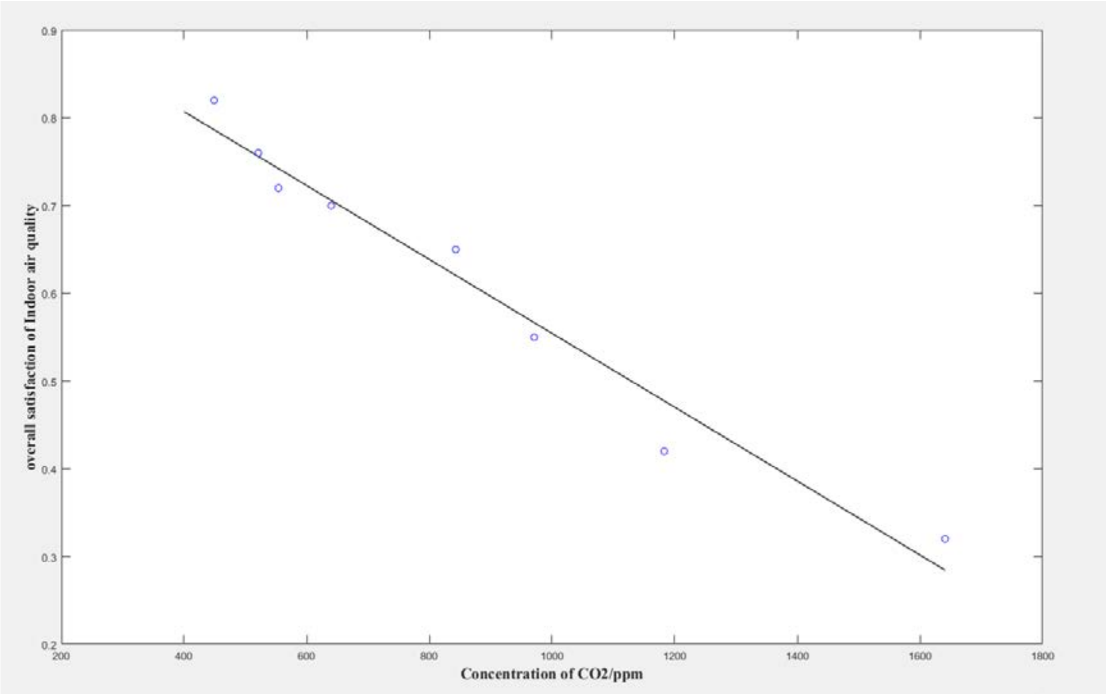

Fig 4 Relationship between indoor air satisfaction and CO_2 concentration

Fig. 4 shows the relationship between the overall satisfaction of the indoor air quality and the operative temperature. Each dot represents the average value of the overall satisfaction at the corresponding concentration of CO_2 in a classroom. The corresponding linear equation is written as follows:

$$S_I = -0.0004212C_{CO_2} + 0.9756 \quad R^2 = 0.9652 \tag{3}$$

Where C_{CO_2} denotes the concentration of CO_2, S_I is the normalized satisfaction of the indoor air quality.

For the proposed linear equation, F-test was used for verifying the validation. The results show there are statistically significant differences between the overall satisfaction of indoor air quality and CO_2 concentration (F=166.463, p<0.01).

5.3 Lighting environment

In the current study, the illuminance level is selected as the main parameter to evaluate the lighting environment in university classrooms. During the survey, the illuminance levels in eight classrooms ranged from 239 lx to 919 lx. The relationship between overall satisfaction scores of the lighting environment and illuminance level is shown as follows:

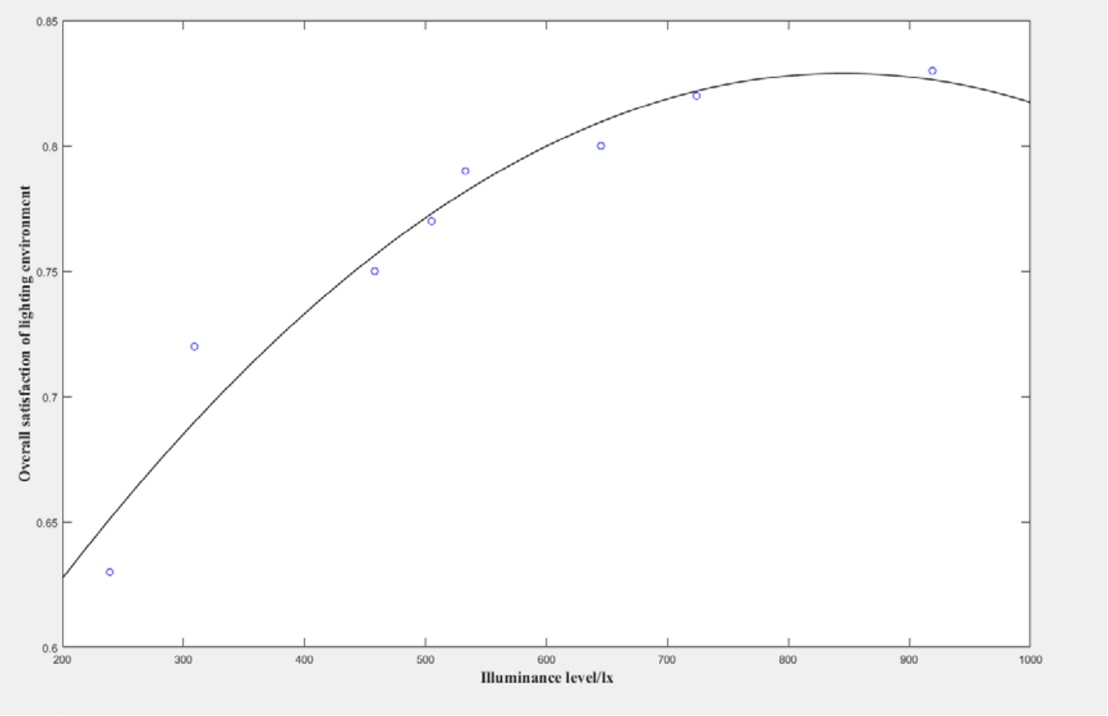

Fig 5 Relationship between lighting satisfaction and illuminance level

Fig. 5 shows the relationship between the overall satisfaction of the lighting environment and illuminance levels in university classrooms. Each dot represents the average value of the overall satisfaction at the corresponding illuminance level in a classroom. The corresponding polynomial equation is written as follows:

$$S_L = -4.838 \times 10^{-7}E^2 + 8.179 \times 10^{-4}E + 0.4833 \qquad R^2 = 0.9465 \qquad (4)$$

Where E denotes the illuminance level of the classroom, S_L is the normalized satisfaction of the lighting environment.

For the proposed polynomial equation, F-test was used for verifying the validation. The results show there are statistically significant differences between the overall satisfaction of the lighting environment and illuminance level ($F= 44.245$, $p<0.01$).

5.4 Acoustic environment

The classrooms in the case study were well decorated with acoustical treatments. Materials of the side surfaces are given in Table 1. Therefore, the main parameter that affects the acoustical environment is the background noise level. The subject survey for assessing the acoustical environment is to evaluate the noise sources. During the survey, the background noise levels in eight classrooms ranged from 46.6 dB to 60.2 dB. The reverberation time (T_{30}) ranged from 0.36 to 0.51. The speech transmission index (STI) ranged from 0.71 to 0.88. The relationship between overall satisfaction scores of the acoustical environment and background noise levels are shown as follows:

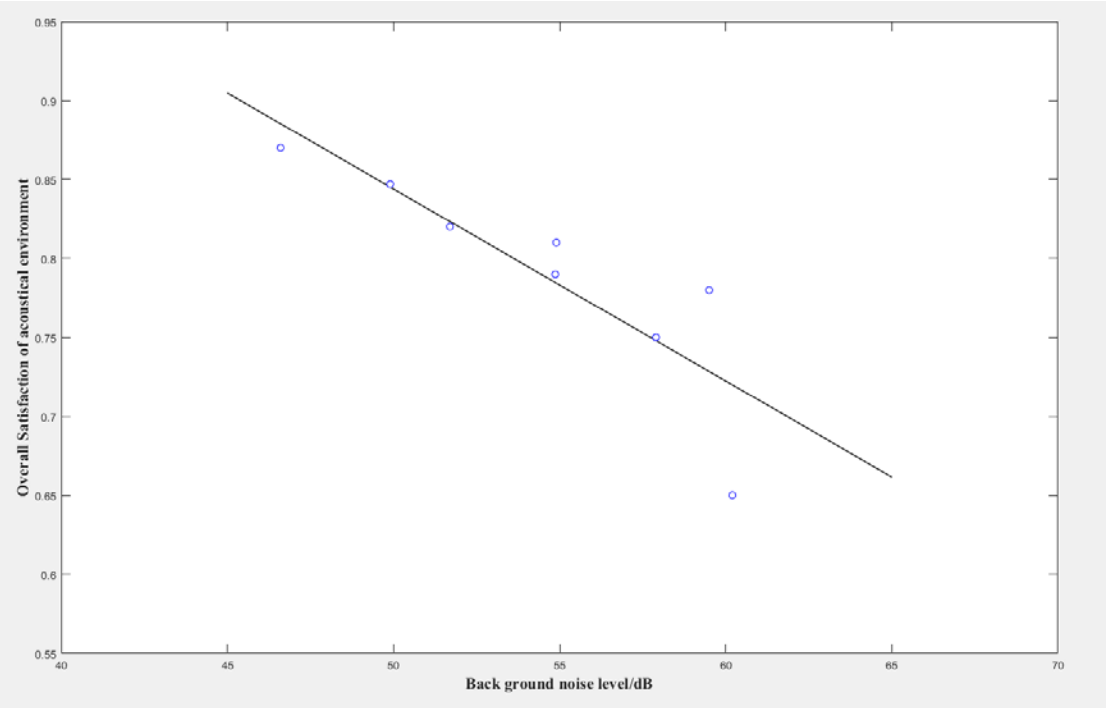

Fig 6 Relationship between acoustic satisfaction and background noise level

Fig. 6 shows the relationship between the overall satisfaction of the acoustical environment and background noise levels in university classrooms. Each dot represents the average value of the overall satisfaction at the corresponding background noise level in a classroom. The corresponding linear equation is written as follows:

$$S_A = -0.01216L_{Aeq} + 1.452 \quad R^2 = 0.7369 \tag{5}$$

Where L_{Aeq} denotes the A-weighted sound pressure level of the background noise, S_A is the normalized satisfaction of the acoustical environment.

For the proposed linear equation, F-test was used for verifying the validation. The results show there are statistically significant differences between the overall satisfaction of the acoustical environment and background noise level (F=16.804, p<0.01).

5.5 Relationship between indoor environmental quality and various parameters

To obtain the final relationship between indoor environmental quality and various parameters, a combination equation is integrated from Eq. (2-5) to Eq. 1.

$$O = 0.3177 \times (-0.0117{t_0}^2 + 0.5979t_0 - 6.878) + 0.1629 \times (-0.0004212C_{CO_2} + 0.9756) + 0.2386 \times (-4.838 \times 10^{-7}E^2 + 8.179 \times 10^{-4}E + 0.4833) + 0.2808 \times (-0.01216L_{Aeq} + 1.452) \tag{6}$$

The meaning of the above equation is that, in a particular indoor environment, the overall satisfaction of indoor environmental quality can be predicted by the four representative parameters. This is helpful for those authorities or architects as references in a design stage. Besides, the proposed assessment methods can be employed in other regions to evaluate the indoor environmental quality.

5.6 The acceptable range of each environmental factor

Referring to the China Standard GB 50019-2003, GB/T 18883-2002, GB 50034-2004, and GBJ 118-1988 [66-69], each environmental factor is suggested to be at an acceptable range in buildings. The standards suggested that the acceptable range of temperature is between 22 °C and 28 °C for air conditioning in summer, the acceptable range of CO_2 concentration should be lower than 1000 ppm, the acceptable level of illumination is above 300 Lux, and the acceptable level of noise is below 50 dB. In the current paper, since the subject questionnaire is based on the FCE evaluation method, the acceptable option for respondents to select corresponds to "Medium." The corresponding satisfaction score is 70, which normalized 0.7 in the prediction formulas. Therefore, in this study, the acceptable range of temperature is between 23.3 °C and 27.8 °C, the acceptable range of CO_2 concentration should be lower than 654.3 ppm, the acceptable level of illumination is above 329 Lux, and the acceptable level of noise is below 61.77 dB.

6. Findings and discussions

6.1 The significance of second hierarchy alternatives in the assessment model

Referring to the mentioned 224 questionnaire survey, thermal environment quality is an essential factor for respondents in university classrooms. The next is acoustic environment quality, lighting environment quality, and indoor air quality, respectively. As for the second hierarchy criteria, the values of the column of the weightings related to the proposed IEQ model by multiplying weightings related to the criterion by the weighting of the quality of the alternative. The results are shown in the following bar chart.

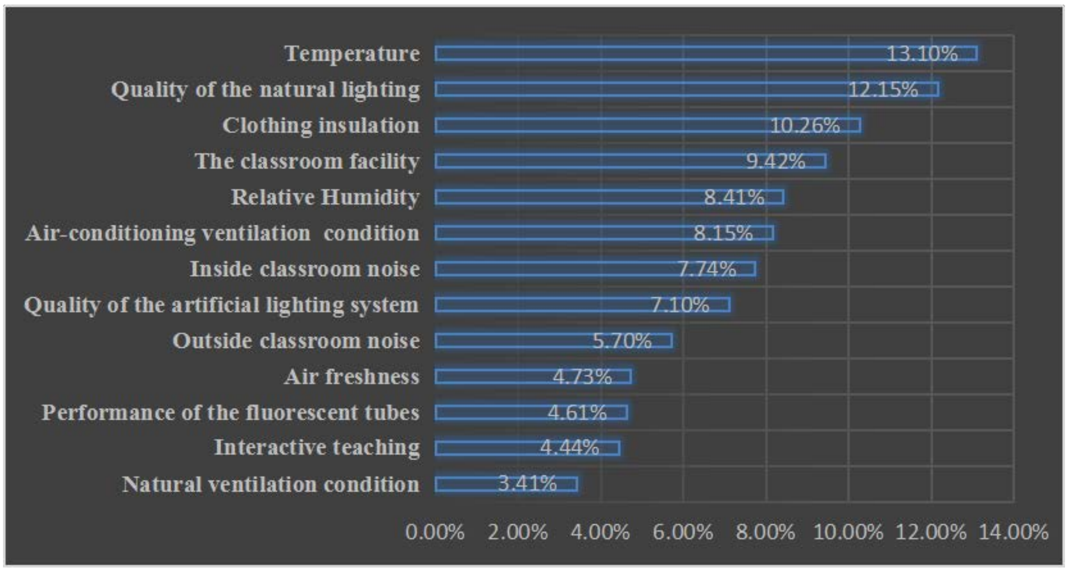

Fig 7 AHP results: bar chart of the second hierarchy criteria weightings

Fig.7 illustrates the weightings of second hierarchy alternatives ranked related to the IEQ assessment model. These findings show that the temperature of classrooms, natural lighting quality in classrooms, and students' appropriate clothes are the most critical factors to affect the feelings of the respondents in university classrooms. The reason for these findings is that in Hong Kong, the temperature is always high, nearly all read round. Students and teachers care more about the temperature and their clothing inside classrooms. Besides, Hong Kong is one of the most densely populated cities; high-rise buildings are a common type of buildings, including university buildings. Therefore, the natural lighting condition in university classrooms is another essential factor for respondents.

Furthermore, results also show that air freshness of the classrooms, the fluorescent tubes' performance, interactive teaching style, and natural ventilation conditions are with lower values of weightings in the questionnaires. The reasons for these findings are that classrooms at PolyU have a good quality of air freshness and fluorescent tubes. As for natural ventilation condition, it is mainly because that classrooms in Hong Kong are more rely on the HVAC systems. The interactive teaching style is acceptable for students so that it is not an essential factor in the survey.

6.2 The sub-criteria alternatives evaluation results based on the maximum membership principle

In the Fuzzy set theory, several defuzzification methods are included in consulting fuzzy problems. In the mentioned FCE evaluation model process, the weighted average method was employed in calculating the evaluation scores. The maximum membership principle is another defuzzification method, which is widely used for its simplify and intuition. The maximum membership principle is also known as the height method, which can be given by algebraic expression as:

$$u(z^*) \geq u(z) \ \ for \ \ all \ \ z \in Z$$

Where z^* is the output point (defuzzified value). In the current study, the evaluation results of each sub-criteria are intuitive for users to analyze. For instance, in the acoustic environment assessment survey, "Excellent" was chosen in most sub-criteria except for O_{412}, O_{413}, O_{414} and O_{443}. These results can easily be considered to enhance the achievement of a high-quality acoustic education environment. In the lighting environment assessment survey, most respondents chose "Good" in assessing natural and artificial lighting system quality, "Excellent" in assessing fluorescent tubes' performance. However, the amount of daylight (O_{321}) and direct solar radiation (O_{323}) are less dissatisfied compared to other sub-criteria. These results are useful for improving the lighting environment for university authorities. The most interesting sub-criteria in the FCE assessment survey is natural ventilation conditions in classrooms. Near half of the respondents (45.53%) selected "Poor" to express the dissatisfaction of the factor. While in the AHP comparison survey, they think it is less important than the other two factors for indoor air quality. The reason was mentioned in the formal part, that natural ventilation condition highly depends on the outdoor climate condition. The specific location of Hong Kong is classified as a Subtropical monsoon climate with high temperature and high relative humidity nearly all year round [70].

6.3 Comparison with other studies in prediction formulas

In this paper, two parts of the prediction models are proposed. One is predicting overall satisfaction from the individual factor satisfaction. The other is introducing the prediction formulas to present the relationship between environmental factors and individual results.

Various weightings schemes and different regression functions are the main factors in assessing the overall prediction formulas. A summary of the previous studies is shown in the following Table 20 for comparison.

Table 20 Summary of prediction models with weighting schemes in previous studies

Studies	Respondents	Analysis method	Prediction model
Cao et al. (2012) [64]	500 respondents in Beijing and Shanghai	Multivariate linear regression	$S_O = 0.0075 + 0.316S_T + 0.118S_I + 0.171S_L + 0.224S_A$
Astolfi & Pellerey (2008) [57]	852 students from secondary school in Turin (Italy)	Pearson's coefficient with overall satisfaction	Renovated classrooms(702): S_T: 0.5, S_I: 0.32, S_L: 0.29, S_A: 0.39 Nonrenovated classrooms(150): S_T: 0.28, S_I: 0.31, S_L: 0.25, S_A: 0.5
Fassio et al. (2014) [71]	17 occupants in a university classroom in Roma (Italy)	Multivariate linear regression	$S_O = 0.02S_T + 0.12S_I + 0.56S_L + 0.31S_A$ (9.45 am) $S_O = 0.33S_T + 0.10S_I + 0.38S_L + 0.18S_A$ (11.30 am)
		Multivariate logistic regression	$S_O = 0.33S_T + 0.16S_I + 0.25S_L + 0.26S_A$ (9.45 am) $S_O = 0.30S_T + 0.12S_I + 0.30S_L + 0.28S_A$ (11.30 am)
Wong et al. (2008) [72]	293 occupants in offices in Hong Kong	Multivariate logistic regression	$1 - \frac{1}{1 + \exp(15.02 + 6.09S_T + 4.88S_I + 3.7S_L + 4.74S_A)}$
Buratti et al. (2018) [74]	928 university students in Italy	Ask directly by students	$S_O = 0.35S_T + 0.3S_L + 0.35S_A$

Ncube & Riffat (2012) [63]	68 occupants in the UK	Multivariate linear regression	$S_O = 0.3S_T + 0.36S_I$ $+0.16S_L + 0.18S_A$
Chiang & Lai (2002) [73]	12 experts in Taiwan	AHP method	$S_O = 0.208S_T + 0.29S_I$ $+0.164S_L + 0.203S_A$ $+0.135S_{EMF}$
The current study	224 respondents in university classrooms in Hong Kong	FCE method	$S_O = 0.3177S_T + 0.1629S_I$ $+0.2386S_L + 0.2808S_A$

Several previous studies were listed in Table 20, in which different weighting schemes and regression functions were proposed. The data were collected in various regions and were analyzed using different statistical methods. Therefore, direct comparisons are difficult to be performed in results. However, it is possible to compare the weighting distributions in each study. In this paper, a new multi-criteria assessment model of indoor environmental quality criteria is developed based on the fuzzy comprehensive evaluation method (FCE). The analytic hierarchy process (AHP) method is used to calculate the weightings of the secondary layer index. The Multi-criteria FCE method combines with the weightings from the AHP method. The fuzzy set theory deals with ambiguous or not well-defined situations. The AHP leads from simple pairwise comparison judgments to priorities arranged within a hierarchy. The AHP cannot take into account uncertainly when assessing and tackling a problem effectively. However, the fuzzy comprehensive evaluation method can tackle fuzziness or the problem of vague decision-making more efficiently by using fuzzy scales with lower, median, and upper values. This can be contrasted with the AHP's crisp 9-point scale and synthesis of the relative weights using fuzzy sets, membership functions, and fuzzy members.

It is found that the weighting of the thermal environment is higher than other factors in most studies. Similar results are also observed in the current study. As for the other indoor environmental factors, there are no conclusive results for indoor environment comfort rating in field studies.

Table 21 Summary of prediction formulas for evaluating single parameters in previous studies

Studies	Respondents	Prediction formulas
Cao et al. (2012)[64]	500 respondents in Beijing and Shanghai	$S_T = -0.0063{t_0}^2 + 0.287t_0 - 2.934$
		$S_I = -0.0002C_{CO_2} + 0.244$
		$S_L = -5 \times 10^{-7}E^2 + 0.0011E - 0.106$
		$S_A = -0.0230L_{Aeq} + 1.382$
Ncube & Riffat (2012)[63]	68 occupants in the UK	$S_T = 100 - PPD$
		$S_I = 100 - 395e^{-15.15{C_{CO_2}}^{-0.25}}$
		$S_L = -176.16X^2 + 738.4X - 690.29$ $\{X = \ln(\ln(lux))\}$
		$S_A = 100 - 2(\text{Actual}_{SPL} - \text{Design}_{SPL})$

Wong et al. (2008) [72]	293 occupants in offices in Hong Kong	$S_T = 1 - \frac{1}{PPD}$ $S_I = 1 - 0.5\left(\frac{1}{1+\exp(3.118 - 0.00215C_{CO_2})} - \frac{1}{1+\exp(3.23 - 0.00117C_{CO_2})}\right)$ $S_L = 1 - \frac{1}{1+\exp(-1.017 + 0.00558E)}$ $S_A = 1 - \frac{1}{1+\exp(9.54 - 0.134L_{Aeq})}$
Guo et al. (2017) [75]	76 participants in Qingdao (China)	$S_T = -0.1394{t_0}^2 + 6.843t_0 - 84.130$ $S_L = -9.206 \times 10^{-6}E^2 + 0.012E - 4.573$ $S_A = -0.101L_{Aeq} + 6.011$
Huang et al. (2012)[65]	120 subjects in offices in Beijing	$S_T = -0.0108{t_0}^2 + 0.5541t_0 - 6.8587$ $S_L = -0.7844I^2 + 1.8886I - 0.497$ $S_A = -0.0524L_{Aeq} + 2.6$
The current study	224 respondents in university classrooms in Hong Kong	$S_T = -0.0117{t_0}^2 + 0.5979t_0 - 6.878$ $S_I = -0.0004212C_{CO_2} + 0.9756$ $S_L = -4.838 \times 10^{-7}E^2 + 8.179 \times 10^{-4}E + 0.4833$ $S_A = -0.01216L_{Aeq} + 1.452$

A summary of prediction equations among single environmental factors and satisfaction scores were listed based on several previous studies in Table 21 as the data in each study was collected in various regions and different satisfaction evaluation methods. Similarly, it is difficult to compare directly with the prediction equations.

However, the acceptable range of every single factor can be discussed and compared. The acceptable range of the selected study is summarized in Table 22.

Table 22 Summary of the acceptable range of environmental factors in previous studies

Studies	**The acceptable range of environmental factors**			
	Temperature	C_{CO_2}	**Illuminance**	L_{Aeq}
Cao et al. (2012)[64]	22 ~ 28 °C	$\leq 1200\ ppm$	100~2100 lx	$\leq 58\ dB$
Wong et al. (2008)[72]	24 ~ 26 °C	Not given	$\geq 500\ lx$	$\leq 60\ dB$
Guo et al. (2017)[75]	21.5 ~ 27 °C	Not given	$\geq 250\ lx$	$\leq 65\ dB$
Huang et al. (2012)[65]	20.9 ~ 30.4 °C	Not given	$\geq 300\ lx$	$\leq 49.6\ dB$
The current study	23.3 ~ 27.8 °C	$\leq 654.3\ ppm$	$\geq 329\ lx$	$\leq 61.77\ dB$

It is found that the acceptable range of CO_2 concentration is obviously lower than the other studies and China Standard GB/T 18883-2002 mentioned in Sec. 5.5. As we know that if the concentration is too high, people may feel tired, and their productivity during work and study will be negatively affected. The low acceptable range of CO_2 concentration may due to the small-sized university classrooms with full students are normal statuses in Hong Kong.

7. Future work and limitations

In the current study, several single environmental factors that were considered as the most significant impact on the corresponding sub-environmental satisfaction for analysis. The prediction formulas were proposed to describe the relationships between sub-environmental satisfaction and the single environmental factors in Eq (2-5). This idea roots in principal component analysis in the statistical field. The proposed method is an overall satisfaction assessment model for considering the most significant sub-environmental factors. The influences of other environmental factors were not included in the proposed prediction formulas. Therefore, the integrated Eq. (6) for describing the relationship between indoor environmental quality and various parameters that were needed to add a correction. The limitations mentioned above are uncertainties in the prediction formulas. The proposed prediction models and prediction formulas can provide applicability to the indoor environmental quality assessments and the impact of IEQ aspects. Furthermore, the interplay between the environmental factors was not considered in the current work. It is a valuable project to study the multisensory interactions of the four environmental factors on indoor environmental quality. Besides, the relationships between indoor environmental quality and the combined effects of environmental factors should be investigated in future work.

8. Conclusion

In this study, indoor environmental quality (IEQ) is co-determined by various environmental factors (Thermal, indoor air, lighting, and acoustics). Studies of IEQ and human satisfaction assessment are needed to consider the comprehensive influence of the four mentioned factors. The proposed fuzzy comprehensive evaluation (FCE) models are efficient methods to avoid the overall satisfaction results absolutely influenced by one single factor in extremely poor conditions (i.e., too hot or too noisy). Besides, the weighting schemes are calculated by the analytic hierarchy process (AHP) layer by layer. These conditions are essential to transfer the qualitative questionnaires into quantitative data. Besides, a set of prediction formulas are proposed to illustrate the relationship between respondents' satisfaction scores and single environmental factors. These single environmental factors are selected as the representative parameters which have the most significant impacts on the corresponding sub-environment (thermal, indoor air, lighting, and acoustics).

The proposed model is effective for assessing the overall satisfaction in university classrooms. It can help authorities manage the proper treatment and improve the indoor environmental quality. The methods can also be employed in other universities and schools. It is also useful for indoor environment design based on the proposed prediction formulas. Besides, the proposed prediction models and prediction formulas are effective approach for assessing the impact of IEQ aspects. This study also aims to understand how sub-factors such as temperature affect each IEQ aspect separately and to investigate the effects of the physical environment and residents' adaptive behaviors on their subjective feelings about those sub-factors. The results also indicated the relationship between environmental factors and indoor environmental quality. This result is a fundamental work to quantify the overall indoor environmental quality. It will also be possible to find and benchmark the key parameters with these questionnaire data. Therefore, guiding the building-efficiency design without eroding occupants' satisfaction with the overall environment could be achieved.

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References

[1] S. Abbaszadeh, L. Zagreus, D. Lehrer, C. Huizenga "Occupant satisfaction with indoor environmental quality in green buildings." Proc. Healthy Build. Lisbon, Port. 3 (2006), pp. 365-370.

[2] A.P. Jones "Indoor air quality and health." Atmos. Environ. 33 (28) (1999), pp. 4535-4564.

[3] A. Leaman "Dissatisfaction and office productivity." Facilities, 13 (2) (1995), pp. 13-19.

[4] L.T. Wong, K.W. Mui and T.W. Tsang "An open acceptance model for indoor environmental quality (IEQ)." Build. Environ. 142 (2018), 371-378.

[5] S. Vilcekova, L. Meciarova, E.K. Burdova, J. katunska, D. Kosicanoca, and S. Doroudiani "Indoor environmental quality of classrooms and occupants' comfort in a special education school in Slovak Republic." Build. Environ.120 (2017) pp.29-40

[6] H.Z. Wu, Y. Wu, X.Y. Sun, and J. Liu "Combined effects of acoustic, thermal, and illumination on human perception and performance: A review." Build. Environ.169 (2020) 160593.

[7] N. Djongyang, R. Tchinda, and D. Njomo "Thermal comfort: a review paper." Renew. Sustain. Energy Rev., 14 (9) (2010), pp. 2626-2640.

[8] H. Zhang, E, Arens, C. Huizenga, and T. Han "Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts." Build. Environ.45 (2010), pp.389-398.

[9] H. Zhang, E. Arens, C. Huizenga, and T. Han "Thermal sensation and comfort models for non-uniform and transient environments, part III: whole-body sensation and comfort." Build. Environ. 45 (2010), pp. 399-410.

[10] K.W. Tham "Indoor air quality and its effects on humans—a review of challenges and developments in the last 30 years." Energy Build. 130 (2016), pp. 637-650.

[11] R. Kosonen, F. Tan "The effect of perceived indoor air quality on productivity loss." Energy Build. 36 (2004), pp. 981-986.

[12] P. Xue, C.M. Mak, H.D. Cheung, and J.Y. Chao "Post-occupancy evaluation of sunshades and balconies' effects on luminous comfort through a questionnaire survey." Build. Serv. Eng. Res. T. 37 (1) (2016), 51-65.

[13] P. Xue, C.M. Mak, and Y. Huang "Quantification of luminous comfort with dynamic daylight metrics in residential buildings." Energy Build. 117 (2016), pp. 99-108.

[14] M.B.C. Aries "Human lighting demands: healthy lighting in an office environment." Technische Universiteit Eindhoven, Eindhoven (2005)

[15] D. Yang, C.M. Mak, "An assessment model of classroom acoustical environment based on fuzzy comprehensive evaluation method," Appl. Acoust. 127 (2017), pp. 292-296.

[16] E.L. Zhang, Q.M. Zhang, J.J. Xiao, L. Hou, and T. Guo "Acoustic comfort evaluation modeling and improvement test of a forklift based on rank score comparison and multiple linear regression." Appl. Acoust. 135 (2018), pp. 29-36.

[17] P.H.T. Zannin, C.R. Marcon "Objective and subjective evaluation of the acoustic

comfort in classrooms." Appl. Ergon. 38 (2007), pp. 675-680.

[18] S. Torresin, G. Pernigotto, F. Cappelletti, and A. Gasparella "Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works." Indoor Air, 28 (4) (2018), pp. 525-538.

[19] W.Y. Yang, H.J. Moon "Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment." Build. Environ. 148 (2019), pp. 623-633.

[20] W.Y. Yang, H.J. Moon "Combined effects of sound and illuminance on indoor environmental perception." Appl. Acoust. 141 (2018), pp. 136-143.

[21] Y.M. Jin, H. Jin, and J, Kang "Combined effects of the thermal-acoustic environment on subjective evaluations in urban squares." Build. Environ. 168 (2020), 106517.

[22] P. Xue, C.M. Mak, and Z.T. Ai "A structured approach to overall environmental satisfaction in high-rise residential buildings." Energy Build. 116 (2016), pp. 181-189.

[23] S.X. Kang, D.Y. Ou, and C.M. Mak "The impact of indoor environmental quality on work productivity in university open-plan research offices." Build. Environ. 124 (2017), pp. 78-89.

[24] A. Merabtine, C. Maalouf, A.A.W. Hawila, N. Martaj, and G. Polidori "Building energy audit, thermal comfort, and IAQ assessment of a school building: A case study." Build. Environ. 148 (2018), pp. 62-76.

[25] C. Buratti, P. Ricciardi "Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort

conditions." Build. Environ. 127 (2018), pp. 23-36.

[26] J. Kim, R. de Dear "Nonlinear relationships between individual IEQ factors and overall workspace satisfaction." Build. Environ. 49 (2012), pp. 33-40,

[27] M. Frontczak, S. Schiavon, J. Goins, E. Arens, H. Zhang, and P. Wargocki "Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design." Indoor Air, 22 (2) (2012), pp. 119-131.

[28] M. Frontczak, R.V. Andersen, P. Wargocki "Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing." Build. Environ. 50 (2012), pp. 56-64.

[29] Y.A. Horr, M. Arif, A. Kaushik, A. Mazroei, M. Katafygiotou, E. Elsarrag. "Occupant productivity and office indoor environmental quality: a review of the literature." Build. Environ. 105 (2016), pp. 369-389.

[30] Z. Wang. A field study of the thermal comfort in residential buildings in Harbin Build. Environ. 41 (2006), pp. 1034-1039.

[31] L. Li, P. Wargocki, and Z. Lian "Quantitative measurement of productivity loss due to thermal discomfort." Energy Build. 43 (2011), pp. 1057-1062

[32] N. Djongyang, R. Tchinda, and D. Njomo "Thermal comfort: a review paper." Renew Sustain Energy Rev, 14 (2010), pp. 2626-2640.

[33] P.O. Fanger. "Thermal comfort, analysis and application in environmental engineering." Danish Technical Press, Copenhagen (1970)

[34] ISO 7730 Ergonomics of the Thermal Environment Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria International Organization for Standardization, Geneva (2005)

[35] R. Yao, B. Li, and J. Liu "A theoretical adaptive model of thermal comfort adaptive predicted mean vote (aPMV)" Build. Environ. 44 (2009), pp. 2089-2096.

[36] C. Buratti, P. Ricciardi. "Adaptive analysis of thermal comfort in university classrooms: correlation between experimental data and mathematical models." Build. Environ. 44 (2009), pp. 674-684.

[37] R. Kosonen, F. Tan "The effect of perceived indoor air quality on productivity loss." Energy Build. 36 (2004), pp. 981-986.

[38] P. Wargocki, D.P. Wyon, J. Sundell, G. Clausen, and P.O. Fanger "The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity." Indoor Air, 10 (2000), pp. 222-236.

[39] Sundell J, Levin H, Nazaroff WW, et al. "Ventilation rates and health: multidisciplinary review of the scientific literature." Indoor Air. 21(3) (2011), pp.191-204.

[40] S. Fraga, E. Ramos, A. Martins, M.J. Sarmúdio, G. Silva, J. Guedes, E.O. Fernandes, H. Barros "Indoor air quality and respiratory symptoms in Porto schools." Rev. Port. Pneumol. 14 (2008), pp. 487-507.

[41] M. Winterbottom, A. Wilkins "Lighting and discomfort in the classroom." J. Environ. Psychol. 29 (2009), pp. 63-75

[42] T. Kruisselbrink, R. Dangol, and A. Rosemann. "Photometric measurements of lighting quality: an overview." Build. Environ. 138 (2018), pp. 42-52

[43] S.M. Yacine, Z. Noureddine, B.E.A. Piga, E. Morello, and D. Safa. "Towards a new model of light quality assessment based on occupant satisfaction and lighting glare indices." Energy Procedia, 122 (2017), pp. 805-810.

[44] L. Bellia, G. Spada, A. Pedace, and F. Fragliasso "Methods to evaluate lighting quality in educational environments." Energy Procedia, 78 (2015), pp. 3138-3143.

[45] F. Leccese, G. Salvadori, M. Rocca, C. Buratti, and E. Belloni "A method to assess lighting quality in educational rooms using analytic hierarchy process." Build. Environ. 168 (2020), 106501.

[46] P. Xue, C.M. Mak, H.D. Cheung. "The effects of daylighting and human behavior on luminous comfort in residential buildings: a questionnaire survey." Build. Environ. 81 (2014), pp. 51-59.

[47] C.M. Mak, Y.P. Lui "The effect of sound on office productivity." Build. Serv. Eng. Res. T. 33 (2012), pp. 339-345.

[48] H.M. Wong, C.M. Mak, and Y.F. Xu "A four-part setting on examining the anxiety-provoking capacity of the sound of dental equipment." Noise Health 13 (2011), pp. 385-391.

[49] C.M. Mak "Development of a prediction method for flow-generated noise produced by duct elements in ventilation systems." Appl. Acoust. 63 (2002), pp. 81-93.

[50] W.M. To, C.M. Mak, and W.L. Chung "Are the noise levels acceptable in a built environment like Hong Kong?" Noise Health 17 (2015), pp. 429-439.

[51] S. Hygge "Classroom experiments on the effects of different noise sources and sound levels on long-term recall and recognition in children." Appl. Cognit. Psychol. 17 (2003), pp.895-914.

[52] E. Sala, L. Rantala, "Acoustics and activity noise in school classrooms in Finland." Appl. Acoust. 114 (2016), 252-259.

[53] J. John, A.L. Thampuran, B, Premlet "Objective and subjective evaluation of acoustic comfort in classrooms: A comparative investigation of vernacular and modern school classroom in Kerala." Appl. Acoust. 104 (2016), 33-41.

[54] P.H.T. Zannin, D.P.Z. Zwirtes "Evaluation of acoustic performance of classrooms in public schools." Appl. Acoust. 70 (2009), 626-635.

[55] D. Yang, C.M. Mak "An investigation of speech intelligibility for second language students in classrooms." Appl. Acoust. 134 (2018), 54–59.

[56] J.X. Peng "Chinese speech intelligibility at different speech sound pressure levels and signal-to-noise ratios in simulated classrooms." Appl. Acoust. 71 (2010), pp. 386-390.

[57] A. Astolifi, F. Pellerey "Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms." J. Acoust. Soc. Am. 123 (1) (2008), pp. 163-173.

[58] W.C. Yang, K. Xu, J.J. Lian, L.L. Bin, and C. Ma "Multiple flood vulnerability assessment approach based on fuzzy comprehensive evaluation method and coordinated development degree model." J. Environ. Manage. 213 (2018), pp. 440-450.

[59] G.Z. Zheng, K. Li, W.T. Bu, and Y.J. Wang "Fuzzy comprehensive evaluation of

human physiological state in indoor high temperature environments." Build. Environ. 150 (2019), pp. 108-118.

[60] L. Wu, X.L. Su, X.Y, Ma, Y. Kang, and Y.N, Jiang "Integrated modeling framework for evaluating and predicting the water resources carrying capacity in a continental river basin of Northwest China." J. Clean. Prod. 204 (2018), pp. 366-379.

[61] Y. Zhang, R.H. Wang, P.F. Huang, X.L, Wang, and S.H, Wang "Risk evaluation of large-scale seawater desalination projects based on an integrated fuzzy comprehensive evaluation and analytic hierarchy process method." Desalination, 478 (2020), pp. 114286.

[62] C.M. Mak, W.M. To, T.Y. Lai, and Y. Yun "Sustainable noise control system design of building ventilation systems." Indoor. Built. Environ. 24(1) (2015), pp. 128-137

[63] M. Ncube, S. Riffat "Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study." Build. Environ. 53 (2012), pp. 26-33.

[64] B. Cao, Q. Ouyang, Y.X, Zhu, L. Huang, H.B. Hu, and G.F. Deng "Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai." Build. Environ. 47 (2012), pp. 394-399.

[65] L. Huang, Y.X, Zhu, Q. Ouyang, and B. Cao "A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices." Build. Environ. 49 (2012), pp. 304-309.

[66] Indoor air quality standard (GB/T 18883-2002), General administration of quality supervision, inspection and quarantine of the People's Republic of China, Ministry of Health of the People's Republic of China, Ministry of Environmental Protection of the People's Republic of China, Beijing, China [in Chinese].

[67] Code for design of heating, ventilation, and air-conditioning (GB 50019–2003), Ministry of housing and urban-rural development of the People's Republic of China and general administration of quality supervision, inspection and quarantine of the People's Republic of China, Beijing, China [in Chinese].

[68] Standard for lighting design of buildings (GB 50034-2004), Ministry of Housing and Urban-Rural Development of the People's Republic of China and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing, China [in Chinese].

[69] Code for design of sound insulation of civil buildings (GBJ 118-1988), General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, Beijing, China [in Chinese].

[70] Climate of Hong Kong – Hong Kong Observatory. https://www.hko.gov.hk/en/cis/climahk.htm

[71] F. Fassio, A. Fanchiotti, and R. Vollaro "Linear, non-linear and alternative algorithms in the correlation of IEQ factors with global comfort: a case study." Sustainability, 6 (11) (2014), pp. 8113-8127.

[72] L.T. Wong, K.W. Mui, P.S. Hui "A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices." Build. Environ. 43 (1) (2008), pp. 1-6.

[73] C.M. Chiang, C.M. Lai "A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan." Build. Environ. 37 (2002), pp. 387-392.

[74] C. Buratti, E. Belloni, F. Merli, P. Ricciardi "A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates." Build. Environ. 139 (2018), pp. 27-37

[75] T. Guo, S. Hu, and G. Liu "Evaluation model of specific indoor environment overall comfort based on effective-function method." Energies, 10 (10) (2017), 1634

[76] C.M. Mak, J. Yang, "A prediction method for aerodynamic sound produced by closely spaced elements in air ducts." J. Sound Vib. 229 (3) (2000), pp.743-753.

[77] K. Huang, J. Song, G. Feng, et al. "Indoor air quality analysis of residential buildings in northeast China based on field measurements and longtime monitoring." Build. Environ. 144 (2018), pp. 171-183.

[78] J. Liu, X. Dai, X. Li, et al. "Indoor air quality and occupants' ventilation habits in China: seasonal measurement and long-term monitoring." Build. Environ. 142 (2018), pp. 119-129.

[79] L. Lei, W. Chen, Y. Xue, W. Liu. "A comprehensive evaluation method for indoor air quality of buildings based on rough sets and a wavelet neural network." Build. Environ. 162 (2019), pp. 106296.