A Comparative Study of three Mathematical Models for Predicting the Indoor Environment Quality (IEQ) in Research Office

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Abstract
Indoor environment quality is considered as an important indicator of sustainable development of structures, and it can be used to reflect the occupants' comfort level in buildings. However, it is difficult to evaluate the impact of physical parameters on the occupants' comfort in individual level because of the coexistence of parameters and their interactions with each inhabitant. The objective of this research is to find out the most suitable mathematical model to predict the occupants' comfort in research office by comparing three different IEQ models: Iordache's IEQ model, Wong's multivariate-logistic model and Ncube's IEQ model. The data were collected by combining physical measurement with subjective survey. The entire experiment was carried out in a research office in Japan Advanced Institute of Science and Technology, with a sample of 12 participants (6 sub-groups). And data were collected twice a week for each sub-group during the three-week experiment. The relevant physical environment parameters from the collected data were brought into three mathematical models to calculate the corresponding thermal index, indoor air quality (IAQ) index, acoustic index and visual index. Meanwhile, Actual Mean Votes and Actual Percentage of Satisfaction (APS) were calculated by analyzing the questionnaire from subjective survey. By comparing the calculated indexes and the corresponding APS through the SPSS, the results showed that Iordache's IEQ model is best-fit comfort prediction for the research office.

Keywords: Indoor environment quality, Wong's multivariate-logistic model, Iordache's IEQ model, Ncube's IEQ model

Background

Indoor environment quality is considered as an important indicator of sustainable development of structures, and it can be used to reflect the occupants' comfort level in buildings. Comfort is a composite mental response of occupants to indoor physical environment based on their physiological and psychological state (Wong L.T., Mui K.W., & Hui P.S., 2008). Comfort can be divided into many parts, among which the four basic components are thermal comfort, IAQ comfort, acoustic comfort and visual comfort. Mui et al. point out that the occupants' comfort in buildings depends on many environment parameters, like air temperature and relative humidity (K.W. Mui, W.T. Chan, & J. Burnett, 1999). In addition, relevant literature shows that indoor environment has a direct impact on occupants' health and work productivity, such as bad indoor environment can cause long-term health problems, reduce happiness index, and reduce their work efficiency (Alhorr Y. et al., 2016), (Feige A. et al., 2013), (Kridlova Burdova E., Vilcekova S., & Meciarova L., 2016).

According to the statistical data from ASHRAE, researchers need to spend 80% to 90% of their research time in the research office (*ASHRAE,* 2012). Burdova et al. (2016) pointed out that good indoor environment can improve researchers' comfort and their research performance. Therefore, it is important that indoor environment must meet the requirements of comfort.

However, in the actual environment, it is difficult to evaluate the impact of individual physical environment parameters on the occupants' comfort separately. This is mainly due to the coexistence of many of these parameters and their interaction with each inhabitant (Budaiova Z. & Vilcekova S., 2015). Therefore, relevant comprehensive mathematical models are proposed, such as Wong's multivariate-logistic model, Iordache's IEQ model and Ncube's IEQ model (Wong L.T. et al., 2008), (Mihai T. & Iordache V., 2015), (Ncube M. & Riffat S., 2012). These mathematical models are used to comprehensively evaluate the co-effects of multiple physical environment parameters on the occupants' comfort in buildings.

There is still some imperfection of those models, where the impact of building use is not considered. Some studies have shown that the weight of related environmental parameters is different among buildings with different uses (Lee Y.S. & Guerin D.A., 2010), (Malmqvist T., 2008). Studies have shown that acoustic parameters are the most important factors to affect comfort in research environment (Wong L.T. et al., 2008), (Lee M.C. et al., 2012). Since the above mathematical models are based on data from office and residential buildings, their applicability in the research facilities has not been fully tested.

Research Objective

In this research, physical measurement and subjective survey are used to collect the data from the participants. After the data collection, three different comprehensive mathematical models are compared to achieve the following objectives:

a. Find out the most suitable mathematic model that best predict the IEQ for the research facilities.
b. Find the inner correlation between thermal, IAQ, visual and acoustic indexes.

Mathematical Model

Three different mathematical models were examined in this research, which are Wong's multivariate-logistic model, Iordache's IEQ model and Ncube's IEQ model (Wong et al., 2008), (Mihai T. & Iordache V., 2015), (Ncube M. & Riffat S., 2012).

A. Wong's multivariate-logistic model

Wong's multivariate-logistic model is developed based on the subjective evaluation about indoor environmental condition from 293 occupants in a typical air-conditioned office in Hong Kong. The equation of Wong's multivariate-logistic model is listed from Eq.1 to Eq. 5:

$Thermal\ Index: \phi_1 = 1 - \frac{PPD}{100} \quad (Eq. 1)$
$IAQ\ Index: \phi_2 = 1 - \frac{1}{2}\left(\frac{1}{1+\exp(3.118-0.00215\zeta_2)} - \frac{1}{1+\exp(3.230-0.00117\zeta_2)}\right), 500 \leq \zeta_2 \leq 1800\ ppm \quad (Eq. 2)$
$Visual\ Index: \phi_4 = 1 - \frac{1}{1+\exp(-1.018+0.00558\zeta_4)}, 200 \leq \zeta_4 \leq 1600\ lux \quad (Eq. 3)$
$Acoustic\ Index: \phi_3 = 1 - \frac{1}{1+\exp(9.540-0.134\zeta_3)}, 45 \leq \zeta_3 \leq 72\ dBA \quad (Eq. 4)$
$Overall\ IEQ: \theta = 1 - \frac{1}{1+\exp(-15.02+\sum_{i=1}^{4} K_i\phi_i)}, K_1 = 6.09, K_2 = 4.88, K_3 = 4.74, K_4 = 3.70 \quad (Eq. 5)$

B. Iordache's IEQ model

Iordache's IEQ model is a multiple non-linear regression models developed based on the data from university classroom and professors' office in Romania. The equation of Iordache's IEQ model is listed from Eq.6 to Eq. 10:

$Thermal\ Index: I_{th} = \begin{cases} 28.57\theta_o - 514, & \theta_o \leq 21.5 \\ -28.57\theta_o + 800, & \theta_o \geq 24.5 \end{cases} \quad (Eq. 6)$
$IAQ\ Index: I_{IAQ} = 3.125Q_{air} - 12.5 \quad (Eq. 7)$
$Visual\ Index: I_v = 0.33E_{av} \quad (Eq. 8)$
$Acoustic\ Index: I_a = -3.33L_{pi} + 200 \quad (Eq. 9)$
$Overall\ IEQ: I_{IEQ} = \frac{1}{4}(I_{th} + I_a + I_v + I_{IAQ}) \quad (Eq. 10)$

C. Ncube's IEQ model

Ncube's IEQ model is a multiple regression model developed based on the surveyed input data from 68 occupants in two selected office buildings in UK. It is used to quick assess the environmental performance of the air-conditioned office alongside energy performance. The Equation of Ncube's IEQ Model is from Eq. 11 to Eq. 15.

$Thermal\ Index: TC_{index} = 100 - PPD \quad (Eq. 11)$
$IAQ\ Index: IAQ_{index} = 100 - PD_{IAQ}, where\ PD_{IAQ} = 395\times\exp(-15.15\times C_{CO_2}^{-0.25}) \quad (Eq. 12)$
$Visual\ Index: L_{index} = -176.16x^2 + 738.4x - 690.29, x = \ln(\ln(\ln(illumminance))) \quad (Eq. 13)$

$$Acoustic\ Index: AC_{index} = 100 - PD_{ACc}, where\ PD_{ACc} = 2\times(Actual_{SoundPressureLevel} - Design_{SoundPressureLevel}) \quad (Eq. 14)$$

$$IEQ_{index} = 0.30TC_{index} + 0.36IAQ_{index} + 0.18AC_{index} + 0.16L_{index} \quad (Eq. 15)$$

Research Methodology

A. Introduction of controlled office

In this research, physical measurement and subjective survey were used to collect the data from the participants in a controlled office environment at Japan Advanced Institute of Science and Technology in Japan. The total floor area of the controlled office is 36m^2, with the clear ceiling height of 2.17m. The envelop of this controlled office is constructed using heat-insulating materials, and covered by sound insulation board. In addition, the window shadings are also installed to avoid the interference of the nature light. One set of air conditioner with ventilation function is installed at the center of the ceiling to provide constant thermal and IAQ condition for the office. The illumination condition is controlled by six sets of LED lights on the ceiling, together with two desk lamps. The acoustic condition is adjusted by playing the video of discussion with related topic to the participants. The plan view of the controlled office is in Figure 1.

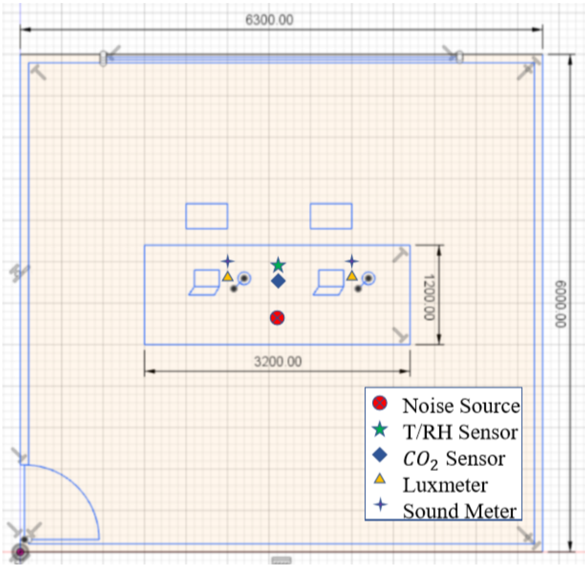

Figure 1: Plan View of the Controlled Office

B. Experiment Process

In this experiment, the independent variable is the indoor air temperature (22°C, 24°C, 26°C), illumination level (300lux, 550lux) and background noise level (40dBA, 70dBA). 12 researchers are recruited and divided into 6 sub-groups, where the researchers in each sub-group are in the similar research area. For each sub-group, the participants need to attend three sets of experiment and each last for 130 minutes to prevent the influence of the fatigue. During each set of experiment, the office condition is changed for 4 times and the temperature remains constant. Each participant needs to conduct their own research work during the 2-hour experiment. The participants can communicate with each other about their research during the noisy condition, while they need to keep quiet during the quiet condition. The flow chart of each set of experiment is listed in Figure 2.

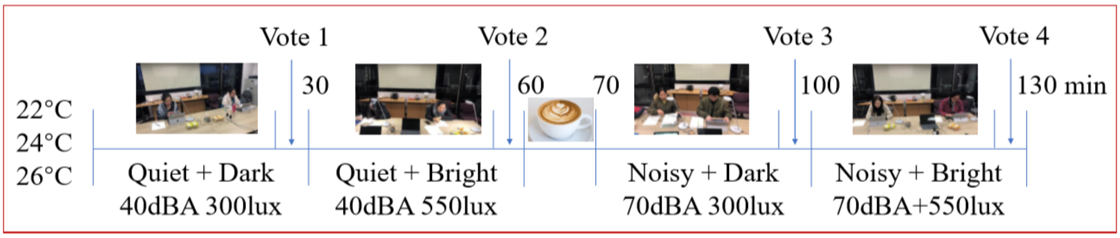

Figure 2: Experiment Procedure for each set of Experiment

C. Physical Measurement and Questionnaire

Several physical environment parameters are recorded in the experiment process. For thermal comfort, indoor air temperature, relative humidity and air velocity are recorded. For IAQ part, the concentration of indoor carbon dioxide is recorded. For acoustic comfort part, average background noise level and reverberation time are recorded. And for visual comfort part, luminance of office desk is recorded.

A specially designed questionnaire is distributed to the sample population in order to assess their comfort level about the office. It includes three sections: general information, environment preference and environment sensation & satisfaction. 7-point ASHRAE scale is used for rating the occupants' sensation and satisfaction, while 3-point McIntyre scale is adopted for choosing the preference about the environment (Zomorodian Z.S., Tahsidoost M., Hafezi M., 2016). Check list is also used in the questionnaire for selecting the clothing insulation and recording their activity.

D. Comparative Study

After data acquisition, the relevant environmental parameters are brought into three mathematical models to obtain the corresponding thermal index, IAQ index, acoustic index and visual index.

Meanwhile, Actual Mean Votes and Actual Percentage of Satisfaction (APs) are calculated by analyzing the questionnaire from subjective survey, where the APS value is used to represent the actual occupants' comfort. The comparative analysis is conducted with the help of the SPSS. Through comparing the calculated indexes and the corresponding APS value, the optimal mathematical model for research office is found out.

Results and Discussion

A. Physical Environment Parameters

Table 1 shows all the measured physical environment parameters for each environment condition, which includes the indoor air temperature, relative humidity, concentration of indoor carbon dioxide, illuminance level at the office desk and average background noise level. Because of the heat-insulating materials around the walls and window shading, no direct solar radiation was inputted and thus the mean radiation temperature can be approximately equal to the indoor air temperature measured in the controlled office.

	Air Temperature (°C)	Relative Humidity (%)	CO2 (ppm)	Illuminance (lux)	Noise (dBA)
22+Dark+Quiet	21.8	20.3	680	289	43.3
22+Bright+Quiet	21.7	20.4	700	534	43.5
22+Dark+Noisy	21.8	20.3	693	295	72.1
22+Bright+Noisy	21.8	20.5	715	530	70.6
24+Dark+Quiet	24.5	21.5	743	301	42.3
24+Bright+Quiet	24.3	20.2	750	551	41
24+Dark+Noisy	24.3	20.1	770	303	70.8
24+Bright+Noisy	24.3	20.2	765	557	69.5
26+Dark+Quiet	25.8	19.3	690	288	40.8
26+Bright+Quiet	25.9	19.1	687	520	42.5
26+Dark+Noisy	26.2	19.2	715	293	68.9
26+Bright+Noisy	26.2	19.1	721	505	71.3

Table 1: Summary of Measured Physical Environment Parameters

B. Factor Analysis of actual Satisfaction

The thermal satisfaction vote, IAQ satisfaction vote, visual satisfaction vote and acoustic satisfaction vote were used for factor analysis using SPSS, in order to calculate the weight coefficient of each IEQ index for actual results.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.623
Bartlett's Test of Sphericity	Approx. Chi-Square	50.389
	df	6
	Sig.	.000

Table 2: KMO and Bartlett's Test of Actual Satisfaction

The KMO value is 0.623, which falls into the range between 0.6 to 0.7. The significance value from Bartlett's test of sphericity is 0.000, less than 0.01, which means that the sample data is normally distributed. From the results of KMO and Bartlett's test, the entire sample set is appropriate for factor analysis and there exists a meaningful relationship among thermal, IAQ, visual and acoustic indexes.

From the communalities list, the extracted variance of four components are all above 0.4. This indicates that it is acceptable conduct factor analysis and majority information can be remained with acceptable loss.

According to Total Variance Explained List, it can be found that only one initial eigenvalue is larger than 1. Even though the first component only contributes to 43.374% to total variance, it is used to explain the entire data information.

	Initial	Extraction
Thermal_Satisfaction	1.000	.456
Visual_Satisfaction	1.000	.529
Acoustic_Satisfaction	1.000	.496
IAQ_Satisfaction	1.000	.658

Extraction Method: Principal Component Analysis.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.739	43.474	43.474	1.739	43.474	43.474
2	.968	24.201	67.674			
3	.698	17.439	85.113			
4	.595	14.887	100.000			

Extraction Method: Principal Component Analysis.

Table 3: Communalities List and Total Variance Explained List

The component score coefficient is obtained by normalization of the component matrix. And the weight of four indexes are obtained by unifying the component score coefficient (Table 4). Therefore, The weight coefficient for thermal index is 0.227, for visual index is 0.249, for acoustic index is 0.239 and for IAQ index is 0.284. Therefore, the actual IEQ equation is as Eq.16:

$$Acutal\ IEQ = 0.227 \times Thermal\ Satisfaction + 0.249 \times Vis\square al\ Satisfaction + 0.239 \times Acoustic\ Satisfaction + 0.284 \times IAQ\ satisfaction \quad (Eq. 16)$$

	component matrix	component score coefficient	weight of index
Thermal	0.597	0.453	0.227
Visual	0.655	0.497	0.249
Acoustic	0.629	0.477	0.239
IAQ	0.747	0.566	0.284

Table 4: Component Matrix, Component Score Matrix and Weight of Indexes

C. Comparison among Three Mathematical Models

According to the results in Table 5, it indicates that all three models are not accurate for the prediction of thermal satisfaction at low temperature. This is because the thermal satisfaction index in Wong's and Ncube's IEQ Model is developed according to Fanger's Thermal Comfort Model, without considering the influence of actual outdoor temperature on thermal satisfaction. In addition, Iordache's Model does not consider the effect of relative humidity on thermal satisfaction.

As for the prediction of the visual satisfaction, Iordache's IEQ model simulates well under low illuminance condition, while Ncube's IEQ model and Wong's IEQ model provide better simulation under high illuminance condition.

In the prediction of acoustic satisfaction, the deviation between the predicted results of Iordache's IEQ model and the acutual results is small, while the other two IEQ models predict much higher satisfaction rate than the actual results.

For IAQ comfort, the experiment results indicate that all three models are not accurate in predicting the IAQ satisfaction. This is because none of the three models consider the influence of other variables on IAQ satisfaction. The results show that the participants give lower IAQ scores under high temperature and high noise conditions.

	Thermal				IAQ				Acoustic				Visual			
	Actual	Wong	Iordache	Ncube	Actual	Wong	Iordache	Ncube	Actual	Wong	Iordache	Ncube	Actual	Wong	Iordache	Ncube
22+Dark+Quiet	33.33	93.00	100.00	93.00	83.33	96.01	70.19	79.67	58.33	97.67	55.81	83.40	41.67	64.47	47.685	60.50
22+Bright+Quiet	41.67	92.00	100.00	92.00	83.33	95.81	70.19	79.23	58.33	97.61	55.15	83.00	66.67	87.68	88.11	71.73
22+Dark+Noisy	58.33	93.00	100.00	93.00	75.00	95.88	70.19	79.38	8.33	46.97	10.64	25.80	58.33	65.23	48.675	60.96
22+Bright+Noisy	66.67	93.00	100.00	93.00	66.67	95.65	70.19	78.90	16.67	51.99	15.63	28.80	66.67	87.44	87.45	71.62
24+Dark+Quiet	83.33	93.00	100.00	93.00	75.00	95.34	70.19	78.30	50.00	97.96	59.14	85.40	66.67	65.98	49.665	61.40
24+Bright+Quiet	83.33	94.00	100.00	94.00	75.00	95.26	70.19	78.16	66.67	98.28	63.47	88.00	66.67	88.67	90.915	72.17
24+Dark+Noisy	83.33	94.00	100.00	94.00	66.67	95.03	70.19	77.74	8.33	51.32	14.97	28.40	66.67	66.23	49.995	61.54
24+Bright+Noisy	91.67	94.00	100.00	94.00	75.00	95.09	70.19	77.84	16.67	55.65	19.29	31.00	66.67	89.00	91.905	72.33
26+Dark+Quiet	66.67	88.00	62.89	88.00	58.33	95.91	70.19	79.45	66.67	98.33	64.14	88.40	66.67	64.34	47.52	60.42
26+Bright+Quiet	58.33	87.00	60.04	87.00	66.67	95.94	70.19	79.52	66.67	97.91	58.48	85.00	75.00	86.81	85.8	71.34
26+Dark+Noisy	66.67	85.00	51.47	85.00	58.33	95.65	70.19	78.90	16.67	57.63	21.29	32.20	58.33	64.97	48.345	60.80
26+Bright+Noisy	66.67	85.00	51.47	85.00	58.33	95.58	70.19	78.77	16.67	49.65	13.30	27.40	66.67	85.83	83.325	70.90

Table 5: Summary of the Satisfaction of Actual Results and 3 IEQ Models

According to the T-test comparison (Table 6), there is no statistical difference between the prediction by Iordache's Model and the actual IAQ satisfaction, acoustic satisfaction and visual satisfaction. However, there is statistical difference between the prediction of thermal satisfaction and the actual statistical results, and the prediction of IEQ is affected.

The results also showed that Iordache's IEQ Model is best-fit comfort prediction for research office by comparing the calculated indexes and the corresponding APS. However, Iordache's IEQ Model still needs to be adjusted. First of all, the equation of each comfort index only consider the physical environmental parameters in its own aspects, without considering the impart of other variables. Secondly, the weight of all four comfort indexes should be adjusted according to different types of room usages.

	t	df	Sig. (2-tailed)
Actual_Thermal - Iordache_Thermal	-2.445	11	0.033
Actual_IAQ - Iordache_IAQ	-0.020	11	0.985
Actual_Acoustic- Iordache_Acoustic	-0.075	11	0.941
Actual_Visual - Iordache_Visual	-0.860	11	0.408
Actual_IEQ - Iordache_IEQ	-3.119	11	0.010

* Correlation is significant at 0.05 level (2-tailed)

	IEQ			
	Actual	Wong	Iordache	Ncube
22+Dark+Quiet	55.55	91.25	68.42	80.34
22+Bright+Quiet	63.67	95.81	78.36	81.33
22+Dark+Noisy	51.06	49.06	57.37	69.54
22+Bright+Noisy	54.65	73.32	68.32	71.45
24+Dark+Quiet	68.77	91.54	69.75	82.16
24+Bright+Quiet	72.75	96.42	81.14	83.41
24+Dark+Noisy	56.44	55.61	58.79	71.29
24+Bright+Noisy	62.69	78.18	70.35	72.37
26+Dark+Quiet	64.23	88.70	61.18	73.06
26+Bright+Quiet	66.78	94.34	68.62	72.17
26+Dark+Noisy	50.21	48.99	47.82	59.91
26+Bright+Noisy	52.28	58.66	54.57	58.74

Table 6: Comparison Result between Iordache's IEQ Model and Actual Result

D. Correlation Analysis

In the questionnaire, thermal satisfaction, IAQ satisfaction, acoustic satisfaction and visual satisfaction are scored from 1 to 7, where 1 represents total dissatisfaction and 7 represents total satisfaction. For the correlation analysis, the thermal satisfaction vote, IAQ satisfaction vote, visual satisfaction vote and acoustic satisfaction vote are analyzed using SPSS and the total sample size is 144. The results are shown in Table 7 and Table 8.

	Mean	Std. Deviation	N
Thermal_Satisfaction	3.94	1.102	144
IAQ_Satisfaction	4.14	1.227	144
Visual_Satisfaction	4.04	1.384	144
Acoustic_Satisfaction	3.30	1.449	144

Table 7: Average Mean Vote for Thermal, IAQ, Visual and Acoustic Satisfaction

		Thermal_Satisfaction	IAQ_Satisfaction	Visual_Satisfaction	Acoustic_Satisfaction
Thermal_Satisfaction	Pearson Correlation	1	.223**	.300**	.124
	Sig. (2-tailed)		.007	.000	.047
	N	144	144	144	144
IAQ_Satisfaction	Pearson Correlation	.223**	1	.273**	.382**
	Sig. (2-tailed)	.007		.001	.000
	N	144	144	144	144
Visual_Satisfaction	Pearson Correlation	.300**	.273**	1	.161
	Sig. (2-tailed)	.000	.001		.034
	N	144	144	144	144
Acoustic_Satisfaction	Pearson Correlation	.124	.382**	.161	1
	Sig. (2-tailed)	.047	.000	.034	
	N	144	144	144	144

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8: Correlation Analysis among Thermal, IAQ, Visual and Acoustic Satisfaction

According to Table 7, the mean value of thermal satisfaction vote is 3.94 with standard derivation of 1.102. For IAQ comfort, the mean value of IAQ satisfaction vote is 4.14 with standard derivation of 1.227. As for Visual comfort, the mean value of visual satisfaction is 4.04 with standard derivation of 1.384. And for acoustic comfort, the mean value of acoustic satisfaction is 3.30 with standard derivation of 1.449.

The result of correlation analysis is listed in Table 8. The results showed that the Pearson correlation factor between thermal and IAQ satisfaction is 0.223, between thermal and acoustic satisfaction is 0.124, between IAQ and visual satisfaction is 0.273 and between visual and acoustic satisfaction is 0.161, which all fall into the range of 0.1 to 0.3. The significance value of the above four pairs are all below 0.05. Therefore, there is weak correlation for the above four pairs under 95% confidence level and correlation is positive.

As for the pair of thermal and visual comfort, the Pearson correlation factor is 0.300. For the pair of IAQ and acoustic comfort, the Pearson correlation factor is 0.382. They both fall into the range of 0.3 to 0.5. Both significance value are less than 0.05, which means the correlation between IAQ and acoustic as well as between IAQ and acoustic are moderate and positive under 95% confidence level.

From the results of correlation analysis, there is positive correlation among thermal satisfaction, IAQ satisfaction, visual satisfaction and acoustic satisfaction. The correlation is from weak to moderate. This shows that when developing the mathematical model for individual index, it needs to consider the influence of all physical environment parameters from all four aspects. This is also an important reason why the three mathematical model has deviation from the actual results.

Conclusion

The results indicated that there is positive inner relationship among thermal, IAQ, visual and acoustic satisfaction. However, the correlation is from weak moderate. The results also showed that Iordache’s IEQ Model is best-fit comfort prediction model for research office by comparing the calculated indexes and the corresponding APS through the SPSS. However, Iordache’s IEQ Model still needs to be adjusted. First of all, the equation of each comfort index only considers the physical environment parameters in its own aspect, without considering the impart of other variables.

Secondly, the weight of all four comfort indexes should be adjusted according to different types of room usages.

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