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Research Project Preport

LTW.02 Indoor Environment Quality and Sleep quality in Residential Building

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Abstract

The relationship of the indoor environment quality (IEQ) and the sleep quality in Hong Kong residential building is going to be discussed. The acceptance of occupant in four parameters will be investigated under the sleeping condition: thermal comfort, indoor air quality, background noise level, and illumination level. Besides, the interview of occupants is self-report with their sleep quality and acceptance with environment. Total 30 occupants evaluate in 15 bedrooms. Overall IEQ acceptance predict sleep quality from result change due to change of environment conditions. Also, this study examined the comfortable sleeping environment condition. The result of this research find that background noise level has strong correlation with sleep efficiency and sleep latency. In addition, occupants prefer cooler sleeping environment with relatively higher clothing value. However, IAQ and visual comfort are less effect of IEQ and sleep quality acceptance since these are controllable before sleeping.

1. Introduction

According to the article UBS Prizes and Earnings 2015, Hong Kong is the longest working hour in the world in which the weekly average working hours is 50.1. The most of HongKonger requires to work more than 9 hours per day, which causes their imbalanced work-life time. Beside the working hours, sleep quality is also one of the consideration since people hold a lot of time for sleeping on weekdays. Sleep quality is important for maintaining health and daytime performance. The sleeping environment performance is one of the key factors to contribute the sleep quality. Hence, this research is conducted the relationship of Indoor environmental quality and sleep quality in residential building in Hong Kong.

2. Literature Review

The good environmental performance of residential building is maintained acceptance of IEQ by user [1]. Studies concern the acceptance of indoor environment quality in office [2] and residential building [3] in Hong Kong. Besides, other studies related of learning performance [4] or working product [5] with IEQ.

Based on the article of results, it showed that the operative temperature is required up to 29°C [3] conducted by the participant. The result is not related to the concentration of carbon dioxide. Also, Chau (2010) compare theoretical, which using CFD software simulated, and survey study of thermal comfort in sleeping at summer in Hong Kong. The result show that Hong Kong people feel relatively low indoor air temperature. The comfort air temperature is 28.8°C and below 24 °C in mathematical and questionnaire survey respectively. [6] Also, relative humidity was 52.16% in sleeping environment. [6] It have a difference of thermal comfort temperature since external factors had affected the result, for example, covering with quilt (high clothing value). High clothing value (clo) caused better insulation of human body and environment so occupants could not determine thermal comfort accurately.

Then, the visual acceptance keep constant at 50lx. [3] The aural comfort would be drop when noise level up to 70dBA. [3] The result of visual and aural comfort reflect the environment at daytime in living room. There are limited research about visual and aural comfort in sleeping environment.

In addition, the most important effect of human comfort is thermal and aural environment. However, the least effect is indoor air quality in residential building. [3] As a reference, those factors are chosen for consideration, includes the concentration of carbon dioxide, lighting and background noise level. Also, the questionnaire and the physical measurement will be undergoing in this research to assist whether the operative temperature related to the sleep quality.

3. Objectives

The objective of this study is to investigate the influence of indoor environmental quality (IEQ) in sleep quality in Hong Kong residential buildings, to find out the relationship of environmental conditions and sleeping habits, and to study the correlation between sleeping environmental acceptance and sleeping efficiency.

4. Methodology

In this study, the field measurement and subjective interview are selected for analysis. The field measurement will be carried out at the place of occupant's residences. That place prefer to be chosen as the major reason is to assure the results more accurate and to reflect how the different kinds of environmental condition influence to the living environment actually, rather than setting up a sleeping room for testing.

On the other hand, 30 occupants participate in field study from around 15 bedrooms in Hong Kong from 24th October 2017 to 25th January 2018. Based on the lack of manpower, the interview will be preferred due to the small sample instead of having large sample of questionnaire. By having the face-to-face interview to the participants, their response about the environmental acceptance (IEQ) and sleep quality tend to be more direct and accurate that can maintain the quality of data.

In normal, the interview will be conducted during the user using. However, in this field measurement, since participants were sleeping, the result could not be collected with interview. Hence, the interview is needed to be hold after the user had been waken up and within one hour as the fresh memory is still remain on the mind of interviewees.

4.1 Field Measurements

There are four aspects of IEQ measurement: thermal comfort, indoor air quality (IAQ), background noise level and illumination level. Thermal comfort is classified into two categories: environmental (air temperature, mean radiant temperature, relative humidity and air velocity) and personal (metabolic rate and values of clothing). The effectiveness of ventilation in IAQ could be reflected by the concentration of CO₂. It is because the human sensation would be decreased during sleeping, aural and visual comfort are measured from illumination level and background noise level.

(a) Thermal Comfort

The practice of air-conditioning system design is 25.5°C, 50%RH, which is the most comfortable environment. [9] The low velocity measuring equipment is chosen for consideration, which is the most desirable situation by setting air velocity as 0.15m/s. The mean radiant temperature is calculated by globe temperature with equation (1). The operative temperature would be influenced by equation (1) and air temperature, and then using equation (2) for further analysis. The sensation of room temperature by human will be affected by the clothing values(clo) and metabolic rates (met). The metabolic rate (met) of sleeping is taken as 0.7, 40W/m² from ASHRE 55. [9] The clothing value will be affected by the sleeping cover and mattress because of thermal and moisture insulation from human.

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\epsilon D^{0.4}} \times (T_g - T_a) \right]^{\frac{1}{4}} \quad (1)$$

$$T_{op} = C_{op} T_a + (1 - C_{op}) T_r; \quad C_{op}(constant) = \begin{cases} 0.5; & V_a < 0.2 \\ 0.6; & 0.2 \leq V_a < 0.6 \\ 0.7; & 0.6 \leq V_a \end{cases} \quad (2)$$

, where T_{mrt} = Mean Radiant Temperature (°C) T_g = Black globe temperature (°C)
 T_{op} = Operation temperature (°C) T_a = Air Temperature (°C)
 V_a = Air Velocity (m/s)
 ϵ = Emissivity of Black Ball (0.95 for standard globe)
 D = Diameter of Black ball = 0.75 m (from instrument operation manual)

Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) are two indices based on Fanger's comfort equation in ISO 7730. [10] The PMV predicts the average thermal comfort of most people. The PPD is a quantitative measure of dissatisfaction with heat in a group of people under specific thermal conditions. The application of PMV examined acceptance of occupants from interview and chamber, which consider six parameters of thermal comfort.

In addition, Bayesian thermal comfort model [7] applied in thermal comfort assessment. It compares the actual percentage dissatisfied in this study's survey and predicted percentage dissatisfied in Fanger's model. The actual percentage dissatisfied had estimated by suitable posterior, based on sample size and acceptable error.

(b) Indoor Air Quality (IAQ)

The indoor air quality is measured by the ventilation condition. The concentration of Carbon dioxide is the only aspect to be considered under IAQ in this study. Although there are no special standard about conc. CO₂ provided from residential building, the standard of conc. CO₂ for offices and public area are less than 1000ppm. If it is over 100ppm, it may has a bad effect to people's health. [1] The main source of CO₂ is from respiration. Since the concentration of CO₂ is not high, so the equipment is suitable to be selected a lower upper limit, which up to 2500ppm. The other IAQ particulates and carbon dioxide are not easy to be distinguished from people during sleeping, therefore dust and particulates are not considered in this study.

(c) Aural and Visual Comfort

Recently, there are many studies about how the lighting effect sleep quality from biology aspect. In the study, it assumed that occupants are not require any light during sleep, hence, the illuminance level is the only aspects to be considered. In aural comfort, noise problem may be interferes residents getting to sleep while noise is a random frequency sound for human relax and easy to fall asleep. However, if sound pressure level is too high, sleep quality would be decreased and even cannot sleep. The background noise level is measured to examine the maximum sound level acceptance.

4.2 Subjective Survey

The structure of interview questions is shown in Table 1 with question types and flow. First, the background information question refer to Pittsburgh Sleep Quality Index (PSQI) that guide interviewee to pay attention in interview. [8] There are two main type of assessment scale of IEQ acceptance; rating scale and dichotomous scale. Second, seven-point acceptability of ASHRAE design is used to measure thermal comfort in order to analyze the sensation of operative temperature. [9] IAQ, noise and Sleep quality are measured with a similar scale 'very bad', 'bad', 'natural', 'good', 'very good' because the result of different aspects can compare with each other for the remaining part of interview.

Table 1. The structure of interview question

Part of interview question	Types	Description
Background information	Factual	Sleeping quantity and habits for occupant
Thermal Comfort	Yes/ No Rating	Acceptance of thermal comfort with different time Overall satisfaction of thermal comfort
Indoor Air Quality (IAQ)	Yes/ No Rating	Acceptance of indoor air quality Overall satisfaction of IAQ
Lighting and Noise	Yes/ No, Rating	Acceptance and influence of sleeping by any light and noise
Sleep quality and overall IEQ	Rating Yes/ No	Determine occupant sleeping problem in measurement and overall satisfaction of sleep quality

4.3 Overall indoor environment quality (IEQ) and Sleep Quality acceptance

Depend on the binary latent response as assumption since occupants always prefer certain environmental and sleep quality conditions. IEQ model was applied in this study to calculate the overall IEQ acceptance. It finds out the correlation of individual IEQ component and overall acceptance. Multivariate logistic regression equation (3) use for overall indoor environment quality in residential building, which four aspects showed under a value. [2] The acceptance of thermal comfort, IAQ, aural and visual comfort shows in equation (4) [2]. The regression constants (C_i) determined from the result.

$$\phi_0 = 1 - \frac{1}{1 + \exp(k_0 + \sum_{i=1}^4 k_i \phi_i(\zeta_i))} \quad (3)$$

$$\phi_j = 1 - \frac{1}{1 + \exp(C_{0,j} + C_{1,j} \zeta_j)} \quad (4)$$

, where ϕ_0 = overall IEQ acceptance
 ϕ_1 = thermal comfort acceptance
 ϕ_j = acceptance of IAQ, Lighting and Background noise level and sleep quality
 ζ_1 = thermal vote ζ_2 = Carbon dioxide concentration (ppm)
 ζ_3 = illumination level (lux) ζ_4 = background noise level (dBA)
 ζ_5 = time to fall asleep (mins)
 C_j = regression constants of different aspect

5. Result and Discussion

Total 30 occupants with in the age range of 18 to 70 participated the field measurement and interview. Due to the measurement undergone in winter, this study considers addition value of clothing value(C_L), based on $C_L = 1\text{clo}$ in winter room condition and addition clothing value(C_L) from cover and mattress. The value is shown in table 2. In addition, this table summarised the acceptance and unacceptable sleeping condition. The result is similar with result of residential building in Hong Kong [3], which most occupants (26 out of 30) voted 'Acceptable' with overall IEQ. For individual aspect of IEQ, the different of other three elements are not significant ($p \geq 0.05$, t-test), except Background noise level(ζ_4) ($p \leq 0.0002$).

Table 2. Summary of Indoor environment quality in surveyed 15 bedrooms

	Parameter								
	T_a (°C)	T_r (°C)	R_h (%)	V_a (ms^{-1})	T_{op} (°C)	ζ_2 (ppm)	ζ_3 (lx)	ζ_4 (dBA)	C_L (clo)
'Acceptable' IEQ (N=26)									
Average	23.77	23.69	60.94	0.28	23.73	620.02	8.66	40.66	1.69
SD	2.82	2.87	7.18	0.13	2.84	126.00	5.50	11.83	0.66
Minimum	19.01	18.97	41.80	0.12	18.99	377.47	3.90	24.00	1.00
Maximum	27.10	26.95	71.57	0.54	27.03	860.97	21.00	65.00	3.00
'Unacceptable' IEQ (N=4)									
Average	22.62	22.40	54.53	0.30	22.51	546.36	12.77	65.75	1.38
SD	1.66	1.76	3.55	0.18	1.70	71.88	6.02	2.99	0.25
Minimum	21.10	21.10	50.30	0.20	21.10	504.46	7.46	63.00	1.00
Maximum	24.99	24.99	59.00	0.56	24.99	654.00	21.42	70.00	1.50
p-value (t-test)	0.44	0.39	0.09	0.80	0.41	0.27	0.18	0.0002	0.55

5.1 Thermal comfort

The PMV is used for mathematical expression in the thermal comfort model, which show my study result, residential building [3] and chamber studies at figure 1. The result of this study is same with the residential building study, which the condition of 'very hot' (+3) or 'very cool' (-3) is not occur obviously during sleeping. Figure 1. show the relationship of thermal vote ζ_1 and PMV index. Both results are within 'cool' (-2) to 'natural' (0) in PMV index and thermal vote. Compare with chamber test and other results in Hong Kong, this study has different outcome that the occupants are less thermal sensitive. Occupants would less sensitivity in non-air-conditioned flat contrast with air-conditioned building [14]. Since the field measurement undergone at winter, 'Slightly warm' and 'warm' also not occur. In addition, the thermal vote is 'shift' to cooler side in sleeping environment so it was concerned occupants prefer cold sleeping environment.

Bayesian thermal comfort model apply to small size samples since Fanger's thermal model was statistically insignificant in field measurement and the number of sample not large enough to be a new model. [7] The number of posterior and error of posterior of this study base on Wong, Mui and Cheung's research. Based on consideration of result reliability, the accepted error and shape factor of this study assumed 0.1 and 2 respectively in Bayesian thermal. [7] Figure 2 showed predicted percentage dissatisfied (PPD) against Fanger's PMV of this study. Compare with Figure1, this curve of posterior's predicted percentage dissatisfied shift to cooler side obviously. It illustrated that occupants like colder environment during sleep.

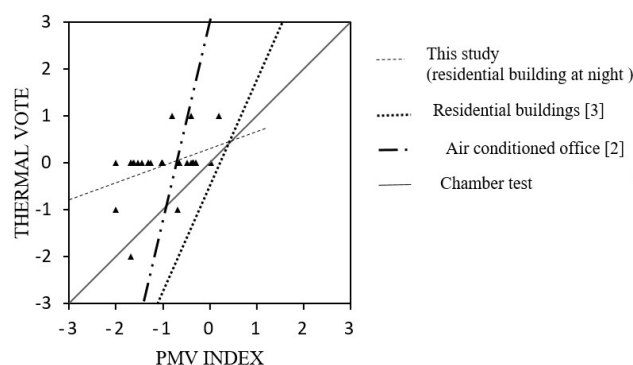


Figure 1. Predicted and measured thermal sensation vote from previous study in Hong Kong and this study

Table 3. Actual percentage dissatisfied by Bayesian model

Vote	k	n	k/n	PPD shape factor =2
0	0	11	0	0.0538
-1	0	11	0	0.0773
-2	1	8	0.125	0.3892

k= Number of dissatisfied of Thermal comfort
n= Total number of sample

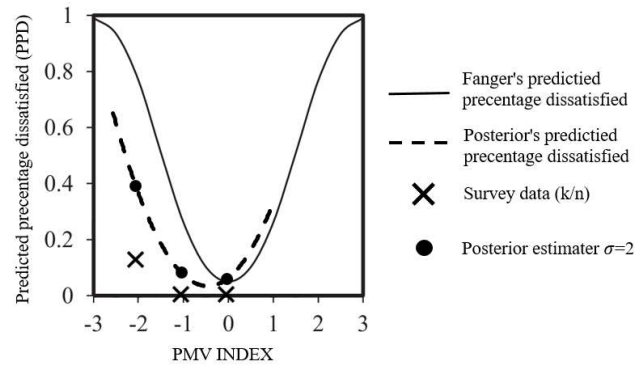


Figure 2. Predicted percentage dissatisfied (PPD) against Fanger's PMV

5.2 Aural environment

The survey assessment result showed non-accepted aural environment had 7 occupants. The measured range of background noise level is 24 to 70dBA. Under T-test calculation in Figure 3, the distribution of acceptance and non-acceptance showed. The different of these two types are considering to be very significant, which have 27dBA different. The mean accepted noise level is 37dBA (like as silent room or whisper) and non-accepted level is 64dBA. Occupant are highly feel discomfort which the noise level is over 60dBA.

Figure 4 showed logistic regression between of this aspect's acceptance and background noise level. Occupants accepted if noise level is lower than 52dBA. Noise level larger than 65dB, that is similar a normal sound level at conversations, are totally dissatisfied. Sound level form 52 to 65dBA would decrease acceptance proportionally. These 7 dissatisfied samples mainly come from two family's flats that locate at low level of residential building or ground floor of village house. The opening of room reduces the sound reduction index of wall partition. Both flats face to traffic roads and open windows as natural ventilation so the main source come from traffic noise. There is uncontrollable of noises since noise come from outside activities, compare with another three components. Therefore, it causes notable unacceptance of aural environment during sleeping.

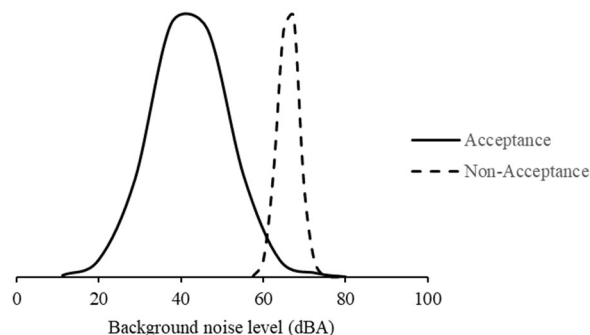


Figure 3. Distribution of Acceptance and non-acceptance of noise level

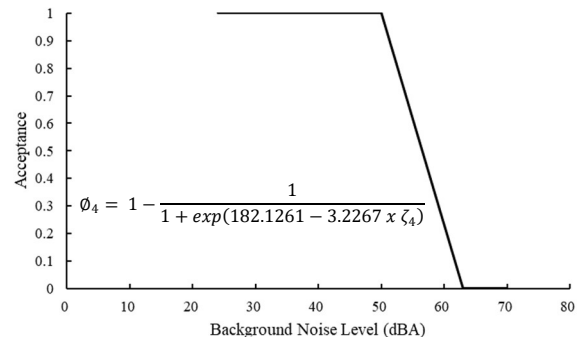


Figure 4. Acceptances of noise level in sleeping condition by logistic regression

5.3 Indoor air quality, visual environment and Overall IEQ acceptance

The measured range of illumination level and carbon dioxide concentration is 3.9-21.42 lux and 377-860 ppm respectively with all satisfied from Table. 2 and 5. Therefore, it lacks dissatisfied data to calculate acceptance of individual and overall IEQ acceptance. Table 4. The low horizontal illumination level occurs in sleeping environment since occupants like sleep in dark environment. The result is similar with Americans sleep environment study that suggest people sleep in dark bedroom [12]. High illumination level cause bad sleep quality in theory [12]. However, the measured lighting level is low level so sleep health barriers do not have data in this study. In addition, it is wide acceptance range of carbon dioxide level. Also, it collected 'Neutral' and 'Good' in IAQ five-point acceptability only. The occupants are open window or bedroom door for fresh air supply and without heavy CO₂ generation activities, for example cooking and smoking, hence it keeps at low level (<1000ppm) and accepted in all measurement.

Table 4 showed the logistic regression coefficient of each measured components and overall IEQ acceptance, which apply in equation (4) and (3) respectively. It studies the relationship of human acceptance and environmental components independently. It only considers the acceptance of thermal comfort and aural environmental in overall acceptance ϕ_0 . It is statistically significant in overall and aural environment acceptance and survey data. However, the result of thermal comfort acceptance is not notable ($p > 0.05$).

Table 4. Regression coefficients of IEQ logistic regression

i	Variable	$C_{0,i}$	$C_{1,i}$	$C_{2,i}$	p-value
0	ϕ_0	-0.2878	1.3268E-08	21.8330	0.0009
1	ϕ_1	7.6080	3.0756	-	0.1325
4	ϕ_4	182.1261	-3.2257	-	<0.0001

The vote acceptance of IEQ assessment base on 4 parameters had summarised in table 5 that acceptable and unacceptable represent 1 and 0 respectively. No occupants dissatisfied in IAQ and Visual environment; little dissatisfied in thermal comfort ($N=1$). Equation (5) show the calculation of survey acceptance ϕ_0 in 4 cases only, which number of non-acceptance people divided by total sample number. Table 6 explains less importance of thermal comfort in sleeping environment since acceptance of cases $j=2$ and 4 are 1 nearly. Noise is obvious effect of overall acceptance. 20% of overall IEQ acceptance reduce (see Table 6) when noise problem occurs in sleeping environment.

$$\phi_{0,j} = \left(\frac{N_{\phi_{0,j}=1}}{N} \right); j = 1 \dots 4 \quad (5)$$

Table 5. Vote acceptance of IEQ

IEQ	Votes	Thermal ϕ_1		IAQ ϕ_2		Visual ϕ_3		Aural ϕ_4	
		0	1	0	1	0	1	0	1
0	4	0	4	0	4	0	4	4	0
1	26	1	25	0	26	0	26	3	23
Total	30	1	29	0	30	0	30	7	23

Table 6. Overall IEQ acceptance

Case j	Survey samples (N)	Survey acceptance (ϕ_0)	Contributor		
			ϕ_1	ϕ_4	Predicted acceptance
1	0	-	0	0	0.785
2	1	1	0	1	0.954
3	7	0.429	1	0	0.785
4	22	1	1	1	0.954

5.4 Sleep quality and phenomenon

Beside of that overall IEQ acceptance, the air and operative temperature of survey relatively lower than another season ($19.01^\circ\text{C} \leq T_a \leq 27.1^\circ\text{C}$; $18.99^\circ\text{C} \leq T_{op} \leq 27.03^\circ\text{C}$); also, the metabolic rate of sleeping (0.7met) is lower than daytime activities. However most of occupants accepted thermal environment, the clothing value of occupants sleeping cover and wearing had study in Figure 5. It is inversely proportional of operative temperature and clothing value. The clothing value of this study is higher than other residential building [3] because of different measured season and time. According to Figure 5, Occupants prefer cover blanket (clothing value= 1clo) body during sleep even room temperature above 25°C since they reported that it not only for thermal comfort, also is a sleep habit. Therefore, clothing value in sleep environment usually have larger value than daytime environment in Hong Kong.

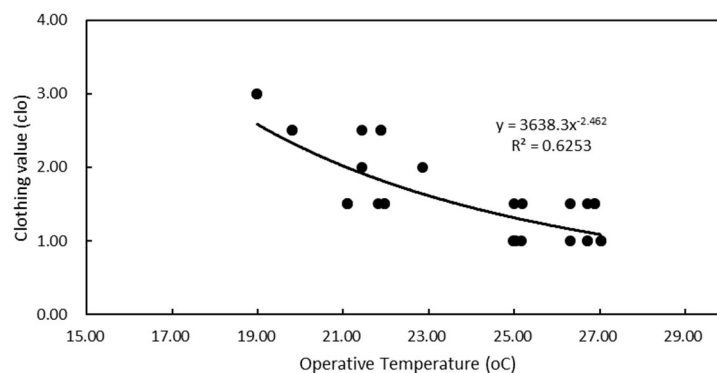


Figure 5. Relationship of Clothing value(clo) and Operative temperature

Base on the rating scale of sleep quality which similar the thermal and IAQ rating is not significant, the sleeping efficiency had applied that is measurable parameter. Sleeping Efficiency is the ratio of time of people spent asleep

and total amount of time spent in bed by Nation Sleep Foundation [11]. Second, the time required to fall asleep is another aspect of sleep quality that is the transition times length of people by wake to asleep. It compares with occupants' sleep day and field measured day so occur sleep latency or not. Table 7 summaries this two aspects and noise level of accepted and non-accepted sleep quality. It has obvious difference of all parameters with p-value less than 0.05.

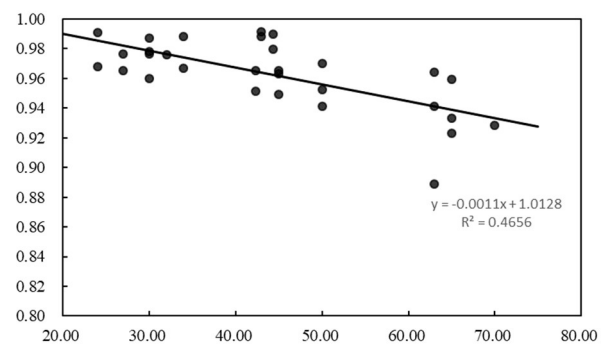
The Sleeping efficiency (<74%) mean bad sleep quality [11] but this result of this study is both higher than this benchmark (see table 7). However, noise level inversely proportional of sleeping efficiency occurred in Figure 6. When the noise level below 35dBA, sleep efficiency is at highest level steadily. The value would decrease and fluctuate during level above 40dBA. For over 60dBA, the efficiency decrease rapidly and had difficult predicted sleep quality. Because of noise environment, sleep latency and more awakenings times lead to asleep time reduced.

The vote of acceptance of sleep quality is similar with overall IEQ acceptance, few occupants dissatisfied (N=4). Figure 7 show the logistic regression equation and results of (a) time to fall sleep and (b) background noise level. The data of time ≥ 30 minutes, the measured background noise levels are larger than 60dBA in Figure 7(a). Occupants began to have the opportunity not to receive sleep quality while the noise greater than 55dBA in Figure 7(b). Both Figure 7(a) and (b) give the same result. For those occupancy which unacceptance with sleep quality are all dissatisfied of aural environment since the high noise level cause sleeping disturbances and annoyance.

$$\text{Sleeping Efficiency} = \frac{\text{Total time spent asleep}}{\text{Total amount amount of time spent in bed}} \quad (6)$$

Table 7. Summary of Sleep quality and Noise level

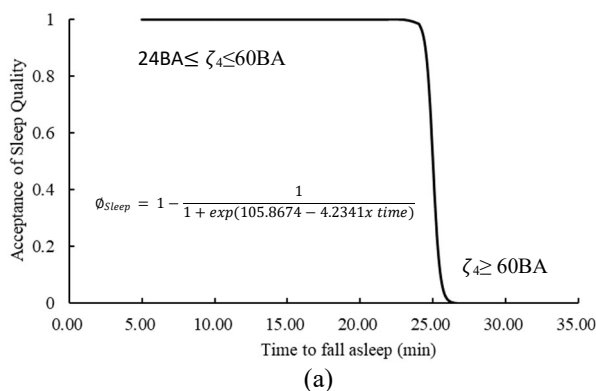
	Parameter		
	Sleeping Efficiency	Time to fall asleep (min)	Noise Level (dBA)
'Acceptable' Sleep quality (N=26)			
Average	0.97	12.69	40.66
SD	0.02	5.52	11.83
Minimum	0.94	5.00	24.00
Maximum	0.99	20.00	65.00
'Unacceptable' Sleep quality (N=4)			
Average	0.92	30.00	65.75
SD	0.02	0.00	2.99
Minimum	0.89	30.00	63.00
Maximum	0.93	30.00	70.00
p-value	1.04E-05	7.6214E-05	0.00027



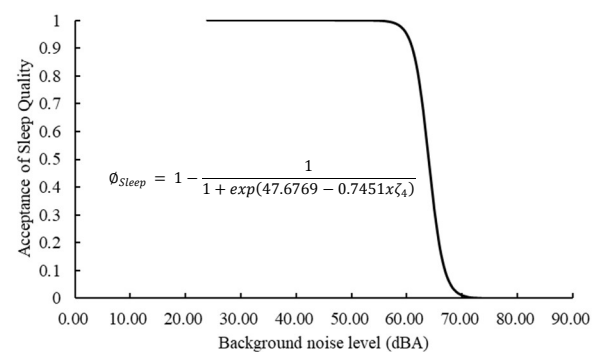
x-axis: Background noise level;

y-axis: Sleeping Efficiency

Figure 6. Relationship of noise level and sleeping efficiency



(a)



(b)

Figure 7. Logistic regression of acceptance sleep quality (a) considering time to fall sleep; (b) considering background noise level

6. Conclusion

This study determined the relationship of IEQ and sleep quality in Hong Kong residual building. It combines the physical measurement and interview with 30 persons for examine sleep quality and acceptance in thermal comfort, indoor air quality, illuminance level and background noise level. Through the rating question is quantify the

feeling of persons under interview. The predicted mean vote, overall IEQ acceptance and sleep quality can compared each other by graph analysis. Thermal comfort and background noise level have the most significant effect on human's sleep quality. IAQ and visual comfort can be control manually, for example opening the window and turn off lighting. Therefore, results of these parameters are all accepted. On the other hand, Occupants tend to cover blankets or quilt without consider the room temperature thus higher clothing value measured. Sleep latency and noise level are directly proportional of each other, and background noise level, which larger than 50dBA, is the main aspects to affect the sleep quality.

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I, Tsang Sze Man, Student No. 1600 certify that this paper is all my own work unless where referenced or acknowledged.

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