Assessments of indoor environmental quality on occupant satisfaction and physical parameters in office buildings

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SUMMARY
The indoor environmental quality is of major interest for occupants in office buildings. This study is to identify the benchmarking values of physical parameters for indoor environmental quality (IEQ) of office buildings and explore the influences of outer climate conditions on the perceived IEQ. The recommended values from selected research articles are compared and classified in different hierarchies against thermal environment satisfaction level, air quality, illuminance and acoustic. A case study in five office buildings carried out in Switzerland is analysed from onsite physical measurements and occupant questionnaires. The results summarize the optimal ranges of selected physical parameters with three IEQ comfort levels. The differential and consistent outcomes in previous studies are verified. Outer climate parameters show potential correlations and influences with the satisfaction of IEQ aspects and weighting factors. In conclusion, it is lacking a standardized index and clear benchmarking values regarding both criteria requirements and local information.

PRACTICAL IMPLICATIONS
The recommended ranges of physical parameters from different classification schemes are applied in the case study and verified with the voting results of occupant satisfaction in the survey. Summarizing existing field studies from different countries. The idea of differentiating climate conditions is developed in this study.

KEYWORDS
Indoor environmental quality, Office building, Field measurement, Physical parameter, Occupant satisfaction

ABBREVIATIONS
IEQ, indoor environmental quality; IAQ, indoor air quality; PD, percentage of dissatisfaction; PS, percentage of satisfaction; SL, satisfaction level; +++, Class I; ++, Class II; +, Class III

1 INTRODUCTION
The indoor environmental quality is of major interest for occupants in office buildings. A key reason is a comfortable working environment that contributes to a better life with less sick leave days and high work satisfaction. These results in benefits for different stakeholders in society. It is commonly agreed that it is crucial to make the indoor environment as comfortable and healthy as possible to positively contribute to the well-being of employees (CEC, 2004; WHO, 2004).

A conventional understanding of IEQ includes at least four key aspects which are thermal environment, indoor air quality, acoustic and illuminance (Nilsson et al. 2003). These are also key factors required in many international standards as EN15251 (2007), ISO7730 (2005) and also in building certificates for example LEED, BREEAM, HQE, DGNB/SGNI. The target values and benchmarks of physical parameters in different IEQ aspects are defined to assure the basic requirements of human health and satisfaction. To further assess the quality of indoor environments different indicators, indexes, and classifications have been studied in research specifically addressing these four aspects (Chiang and Lai, 2002; Marino et al. 2012). Physical parameters and their ranges are mainly shown as benchmarks for different IEQ levels. In addition, subjective survey is carried out to explore the relations of perceived IEQ and physical environments and the complex interrelations of different IEQ aspects (Bluyssen et al. 2011; Mui and Chan, 2005; Huizenga et al. 2002). Weighting factors of different IEQ aspects are extracted from field studies as an important method for an overall assessment of IEQ (Bluyssen et al. 2011; Heinzerling et al. 2013; Cao et al. 2012).

However, it is observed that in the existing studies different assessing indexes and benchmarking values of physical parameters are provided. It needs to be tested on the consistency of ranking IEQ with different methods using case studies. Also, in the previous studies different results of weighting factors are calculated based on surveyed samples which contained specific individual and locally climatic zone information. Thus, another question is if climatic conditions have influence on the weighting factors of different IEQ aspects.

2 METHODS

Literature study, field study with physical measurement and subjective surveys are used as the main methods in this study. Fig. 1 shows the main framework of the research. Physical scope means the range of different IEQ parameters at a classified IEQ level. Subjective scope means the range of a perceived IEQ.

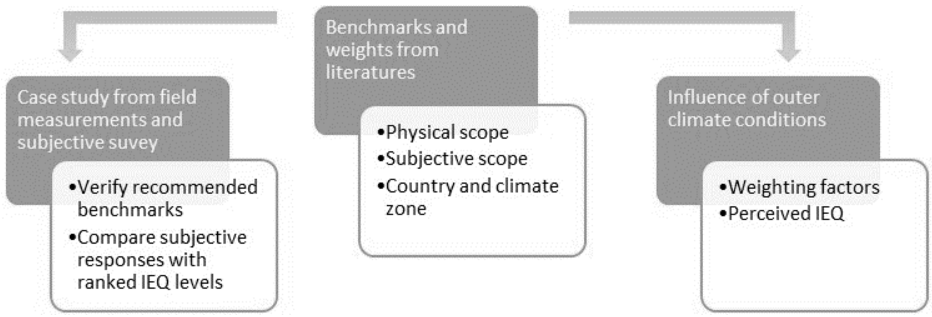


Figure 1: Outline of the research

2.1 Literature study

A literature review was carried out focusing on articles showing the results of physical benchmarks for different levels of IEQ or occupant satisfaction, weighting factors of the four aspects thermal environment, indoor air quality, acoustic and illuminance and climate conditions. The author concerned the papers showing both the physical benchmarks and clear IEQ categories. Finally five key papers were selected and analysed in detail (Chiang and Lai, 2002; Marino et al. 2012; Mui and Chan, 2005; Ncube and Riffat, 2012; Cao et al. 2012).

2.2 Field study

Five office buildings in the northern part of Switzerland were studied by both physical measurements and subjective surveys. Measurement period was one week in each season, winter between November to December and summer between July to August in 2012. During the periods questionnaires were filled in by the occupants in the buildings. The measurement and questionnaire were applied addressing a comprehensive set of physical parameters and questions on comfort and well-being. This paper analyses the data collection from air temperature, air velocity, background noise and illuminance, and with regards to the subjective votes of satisfactions of thermal comfort, air quality, noise and illuminance. Outdoor temperature and relative humidity were also collected. Table 1 shows the building information and questionnaire information.

Table 1. Building and questionnaire information

Building type	Ventilation type	Responses collected	Questionnaire
Office	Mechanical	Building no.1: 1167 no.2: 110 no.3: 103 no.4: 152 no.5: 50	Please indicate your degree of satisfaction with the following elements of your work area: air temperature, air movement, air quality, amount of lighting, amount of background noise. Very unsatisfactory – Somewhat unsatisfactory – neutral – Somewhat satisfactory – Very satisfactory (Unsatisfactory / Satisfactory)

3 RESULTS

3.1 Literature review results and classified levels with benchmarks

Under the umbrella of different IEQ categories used in the researches and regarding the physical parameters in different IEQ aspects of thermal, air quality, acoustic and lighting, Table 2 summaries the benchmarking values and indexes from the five studies found in this literature study. Because the index used in the studies is different with different IEQ category divided, a three-level scheme is proposed on top of these categories which are class I (+++), II (++) and III (+).

In the study of Chiang and Lai, 2002, detailed benchmarks of physical environment are provided and different score is used to rank IEQ. The score ranges from 100-20 corresponding to the field-measured results of physical parameters which are identified as key indicators from expert consultation and analytic hierarchy process method. The score-evaluation is a five interval scale with an interval of 20 scores in between. Score 60 are widely referred to the criteria of the recommended values and building codes for human health and comfort. In this study, the scores from 60 to 100 are analysed. The scopes of physical parameters of air temperature, air velocity, predicted mean vote, carbon dioxide, A weighted Leq, illuminance etc. are given at three levels of 100, 80 and 60.

A four scale environmental quality category is adopted in the study (Marino et al. 2012) and the index is recognized as “Level” here. The author further identify the values from the comfort targets reported in the ISO7730, EN 15251 regarding IAQ aspect, and CEN and EPA for illuminance and acoustic aspects respectively on the basis of comfort limits. Instead of air temperature, operative temperature is used with the other main physical parameters of carbon dioxide, A weighted Leq and illuminance showing at Level I, II and III. An IEQ equation is developed from the field measurements and subjective surveys in office buildings (Mui and Chan, 2005). The index of percentage of dissatisfaction (PD) is used to target IEQ at three levels of I-10%, II-20% and III-30%. The bound limits of each physical parameter are further calculated in this study according to the equations containing operative temperature, carbon dioxide, A weighted Leq and illuminance. In parallel, percentage of satisfaction (PS) is taken into account as the index in another study (Ncube and Riffat, 2012). The equations of PS on thermal environment, IAQ and illuminance are referred to the standards and previous studied models. For the acoustic, it is extracted by the author from the previous field data. Based on the equations, bound limits are achieved here for predicted mean vote, carbon dioxide and A weighted Leq. The aspect of illuminance is not found significantly related with the perceived IEQ. The last relevant reference comes from the field study using satisfaction level (SL) as an index which is a break scale from satisfied to just satisfied and just dissatisfied to dissatisfied (Cao et al. 2012). The bound limits are again calculated from the regression equations for operative temperature, carbon dioxide, A weighted Leq and illuminance.

Comparing these five studies with different evaluation schemes, the first difference is different indexes used including score, level, occupant dissatisfaction, satisfaction and satisfaction level. To further summarize the different levels defined in the studies, the ranking schemes are grouped into three classes based on the understandings of different indexes. The second is the benchmarking values showing different IEQ levels. Comprehensive parameters are defined in the score scheme. The common physical parameters used are air temperature (operative temperature), carbon dioxide, A weighted Leq and illuminance.

3.3 Verify benchmarks by case studies

In the case studies, physical parameters of air temperature, air velocity, carbon dioxide, background noise level and illuminance in the work area were collected. The mean value of physical parameters in each building is calculated for winter and summer respectively. The subjective survey of satisfaction level using seven point Likert scales are collected for the four IEQ aspects. Then the results are checked with the recommended benchmarks by five different ranking schemes shown in Table 2. The following verifications are carried out from two aspects:

a) Compare occupant satisfactions with IEQ categories ranked by the benchmarking values of physical parameters.
b) Compare the category results among the five ranking schemes.

From the subjective survey results in the five office buildings, the average values of occupant satisfactions are between just unsatisfied to just satisfied using a seven point Likert scale shown in Tab. 1. The correspondingly ranking classes using the physical benchmarks in Tab. 2 are between "+++" to "+". Fig. 2 takes the comparison results of acoustic as an example. The ranking classes using different schemes are marked in different colours as shown on the left axis. The actual satisfaction votes from the five buildings are shown in green colour on the right axis. It shows that satisfaction vote is at neutral and just satisfied levels, and the ranking class is between "+++" to "+" evaluating by different schemes of Score, Level, PD, PS and SL. Referring to the changing trends, Score and PD schemes have a mild ranking comparing with Level, PS and SL schemes. However, rankings by benchmarking values do not sufficiently correspond to the subjective satisfaction levels, for example with a class "+++" of Score and PD schemes, the satisfaction votes of acoustic vary between the five buildings from neutral to just satisfied and in the opposite even with differently ranked classes as "+" of Level scheme in building 1, and "+++" in building 3, acoustic can have the same satisfaction vote of neutral.

Regarding the physical parameters and different buildings, it interestingly observes that comparing with the aspect of thermal environment, ranking category by physical benchmarks doesn't comply well with the satisfaction vote of air quality, acoustic and illuminance, for example just satisfied happens in all the classes which indicates for these three IEQ aspects, some other indicators beyond the relevant physical parameters should have an influence.

Table 2. Benchmarks of indoor physical parameters based on comfort and health ("( )" means the boundary value is not included; "[ ]" means the boundary value is included; "S" means summer; "W" means winter; "S&A" means spring and autumn)

Comfort & Health		Class I / Very high quality/Very low dissatisfaction percentage/Satisfied				Class II / High quality/Low dissatisfaction percentage/Slightly satisfied					Class III / Medium quality/Medium dissatisfaction percentage/Just satisfied				
IEQ factors_Benchmark		Index				Index					Index				
		Score (100) (Chiang and Lai, 2002)	Level (I) (Marino et al. 2012)	Occupant dissatisfaction (≤ 10 %) (Mei and Chan, 2005)	Occupant satisfaction (≥ 90 %) (Ncube and Riffat, 2012)	Score (80) (Chiang and Lai, 2002)	Level (II) (Marino et al. 2012)	Occupant dissatisfaction (10 ~ 20 %) (Mei and Chan, 2005)	Occupant satisfaction (≥ 80 %) (Ncube and Riffat, 2012)	Satisfaction (slightly satisfied) (Cao et al. 2012)	Score (60) (Chiang and Lai, 2002)	Level (III) (Marino et al. 2012)	Occupant dissatisfaction (20 ~ 30 %) (Mei and Chan, 2005)	Occupant satisfaction (≥ 70 %) (Ncube and Riffat, 2012)	Satisfaction (just satisfied) (Cao et al. 2012)
Thermal environment	Air temp. (℃)	[24.0 ~ 26.0] (S) [19 ~24] (W) [23.0 ~ 25.0] (S & A)				[23.0 ~ 24.0) (S) (26.0 ~ 27.0] (S) [18 ~ 19) (W) (24 ~ 25] (W) [22.0 ~ 23.0) (S & A) (25.0 ~ 26.0] (S & A)					[22.0 ~ 23.0) (S) (27.0 ~ 28.0] (S) [17 ~ 18) (W) (25 ~ 26] (W) [21.0 ~ 22.0) (S & A) (26.0 ~ 27.0] (S & A)				
	Operative temp. (℃)		23.5 ~ 25.5 (S) 21.0 ~ 25.0 (W)				23.0 ~ 23.5 (S) 25.5 ~ 26.0 (S) 20.0 ~ 21.0 (W) 25.0 ~ 26.0 (W)	23.0 (S) [20.3 ~ 25.6] (W)		[19.1 ~ 26.4]		22.0 ~ 23.0 (S) 26.0 ~ 27.0 (S) 18.0 ~ 20.0 (W) 26.0 ~ 28.0 (W)	[22.0 ~ 23.0) (S) (23.0 ~ 24.3] (S) [19 ~ 20.3) (W)		[15.5 ~ 19.1) (26.4 ~ 30]
	Air velocity, m/s	≤ 0.15	< 0.15			(0.15 ~ 0.25]	0.15 ~ 0.18				(0.25 ~ 0.35]	0.18 ~ 0.21			
	Relative humidity, %	[45~60]				[40 ~ 45) (60 ~ 70]					[35 ~ 40) (70 ~ 80]				
	PMV	[-0.5 ~ 0.5]			[-0.5 ~ 0.5]	[-1 ~ -0.5) (0.5 ~ 1]			(0.5 ~ 0.8] [-0.8 ~ -0.5)		[-1.5 ~ -1.0) (1.0 ~ 1.5]			(0.8 ~ 1.1] [-1.1 ~ -0.8)	
Air quality	CO2, ppm	≤ 600 (8 h)	< 350 above outdoor concentration	≤ 577	≤ 290 above outdoor concentration	(600 ~ 800] (8 h)	350 ~ 500 above outdoor concentration	(577 ~ 824]	(290 ~ 665] above outdoor concentration		(800 ~ 1000] (8 h)	500 ~ 800 above outdoor concentration	(824 ~ 1178]	(665 ~ 1193] above outdoor concentration	[275 ~ 1220]
	CO (8 h)	≤ 2				(2 ~ 4.5]					(4.5 ~ 9]				
	PM10 , μg/m3 (24 h)	≤ 0.025				(0.025 ~ 0.05]					(0.05 ~ 0.15]				
	Formaldehyde (HCHO) (8 h)	≤ 8				(8 ~ 16]					(16 ~ 100)				
	VOC (8 h)	≤ 0.5				(0.05 ~ 0.1]					(0.1 ~ 0.3]				
Acoustic	A weighted Leq, dB	≤ 50	< 40	≤ 53	≤ 45	(50~ 53]	40 ~ 45	(53 ~ 55]	(45 ~ 50]	(45 ~ 49]	(53~ 56]	45 ~ 50	(55 ~ 58]	(50 ~ 55]	(49 ~ 60]
Lighting	Illuminance, lux	≥ 500	> 750	[626 ~ 1231]		[300 ~ 500)	500 ~ 750	[444 ~ 626) (1231 ~ 1413]		[463 ~ 1537]	[150 ~ 300)	300 ~ 500	[314 ~ 444) (1431 ~ 1543]		[112 ~ 463] [1537 ~ 1889]

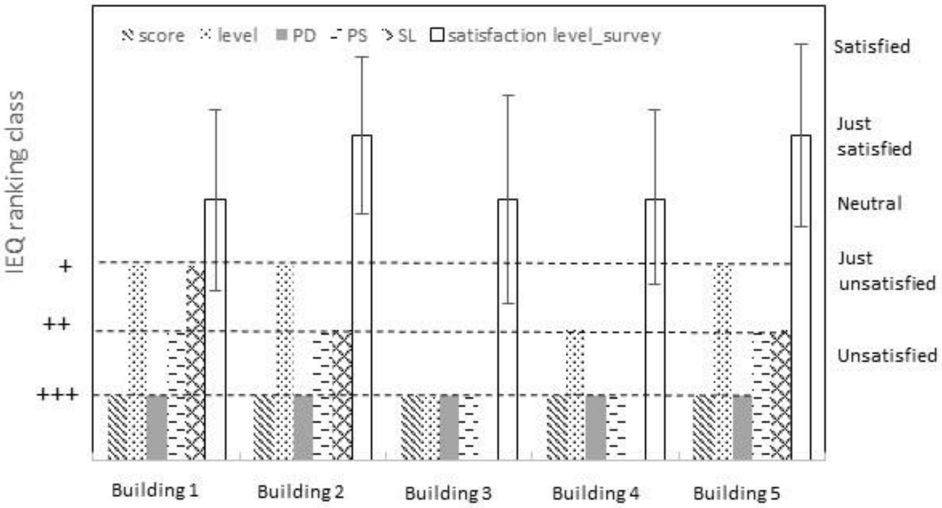
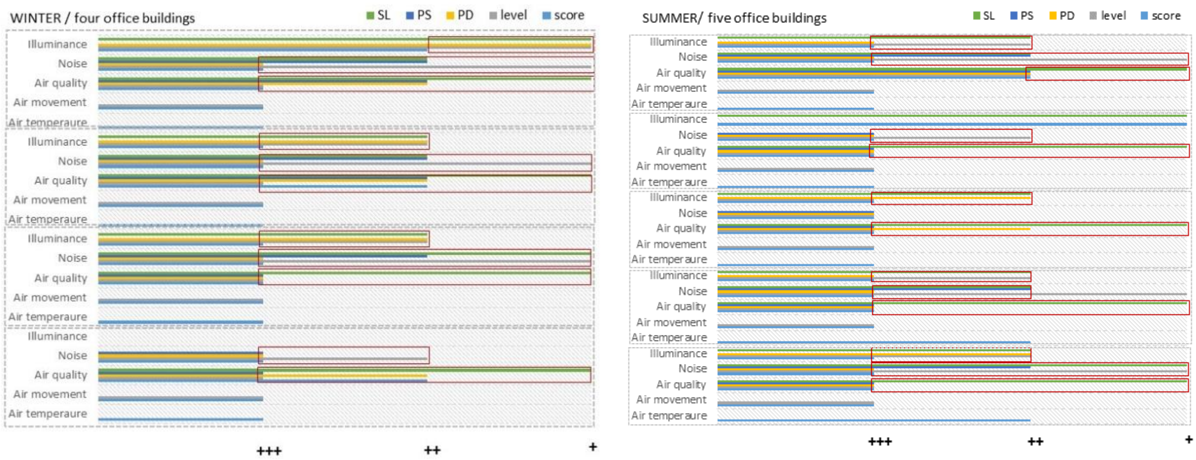


Figure 2. Occupant satisfaction votes versus IEQ ranking classes for the aspect of acoustic in summer condition (standard deviation bar is shown with the mean value of satisfaction votes)

Figure 3 shows the different ranking results for air temperature, air movement, air quality, noise and illuminance using different schemes of SL, PS, PD, Level and Score from the four office buildings surveyed in winter and five office buildings surveyed in summer. By marking the specific IEQ aspects in each building which show different outcomes of categories from the ranking schemes in a red rectangle, it is observed from the corresponding items on vertical axis that there is a bias among different schemes on the IEQ aspects of air quality, acoustic or illuminance in both seasons. The range can vary from one to two classes. As only one scheme addresses air temperature in this study, no bias exists. From the winter case, air quality can have two classes' difference, acoustic has one to two and illuminance only has one class's difference. From the summer case, the results of acoustic and illuminance are the same as winter case, while air temperature has one to two classes' difference. Air velocity are all ranked as "+++" with a physical scope lower than 0.15 m/s. Furthermore, combing the results in winter and summer the outcomes of IEQ ranking are highest in Score scheme and following with Level scheme, PS scheme, PD scheme and then the lowest in SL scheme.



a) Winter case b) Summer case

Figure 3. Comparisons of IEQ class by five different ranking schemes on the case study (+++ for class I, the top level; ++ for class II and + for class III, the medium level)

3.3 Weighting factors regarding climate conditions

To check the influence of outdoor climate on IEQ weighting factors, climate conditions are classified into four major climate zones: tropical, subtropical, temperate and cold. This method is simple to be used. In previous studies, weighting factors are mainly achieved by correlation and linear regression methods using the measured data from amount of field studies. Thus the climate zone information can be summarized through the locations where the field study carried out. The relative weights of the four IEQ aspects are summarized based on the studies (Bluyssen et al. 2011; Heinzerling et al. 2013; Cao et al. 2012; Ncube and Riffat, 2012; Mui and Chan, 2005; Chiang and Lai, 2012).

Relative sizes of weights are shown in Fig. 4 regarding the distribution of climate zones. The sum of weighting factors of the four aspects is one. The x-axis shows a trend with the climate zones from hot to temperate. With this trend, the weights of thermal, acoustic and IAQ are explored to increase or decrease as some trend too. These trends are further indicated by a trapezoid with dash lines. It shows that in temperate climate zone, comparing with subtropical climate zone, thermal comfort is weighted less while IAQ is weighted more. Acoustic is also weighted less as thermal comfort is in temperate climate zone. No obvious trend is found for illuminance. It seems that with the studies carried out in different climate zones, a single IEQ aspect as thermal, IAQ or acoustic is weighted differently in its importance to be addressed for the overall satisfaction.

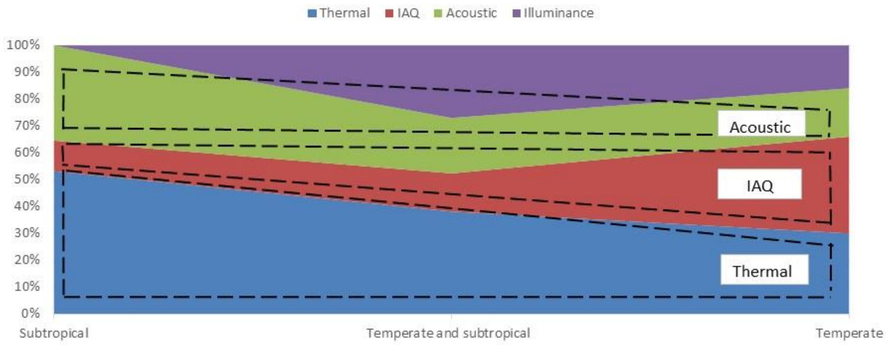


Figure 4. Stacked areas of weighting factors regarding climate zones

4 DISCUSSION

Regarding the results of the bias existing between IEQ ranking categories (see section 3.2), one possible reason might be that the bound limits of PS, PD and SL schemes are achieved from the field data regressions in which more specific conditions and individual characters may have influences. While the benchmarks from Score and Level schemes are mainly referred to the standards and guidelines which favor at a general level. In other words, an overestimation of IEQ ranking might happen when the benchmarks from these two schemes are used. A question for a future study will consider how local conditions influence the ranking of IEQ categories.

More results will be analysed in the near future regarding the correlations between outdoor conditions and IAQ and overall satisfactions.

5 CONCLUSIONS

Benchmarking values from physical environments are summarized and IEQ ranking schemes are further classified into three classes on top. A bias is found among different schemes from the case verification on the ranking results. It indicates that an overestimation might happen when the benchmarks from Score and Level schemes used for the IEQ assessment. A standardized index and scheme in IEQ category are lacking and the benchmarks are also needed to be clarified regarding both criteria requirements, local information and interrelations among IEQ aspects.

The relative weights are addressed differently in different climate zones. Especially when climate zone is changing from tropical to temperate, the weight of thermal comfort is decreasing as acoustic performs while which is opposite for air quality. It makes sense to further study the influence of outer climate conditions on perceived IEQ.

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