INDOOR ENVIRONMENTAL QUALITY AND PERFORMANCE IN OFFICE BUILDINGS

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Abstract

In general, employers should provide satisfying indoor environmental quality to ensure higher performance and productivity of their employees. Physical, chemical, biological, physiological and social factors are the main factors affecting users' comfort, performance and well-being. This paper aimed at investigation of indoor environmental quality, performance and comfort of employers in selected office building. This study was conducted during the heating and non-heating season. Occupants were requested to evaluate their subjective and objective performance. Subjective performance was carried out by questionnaires related to perceived indoor environment quality. Objective performance was conducted by simulated works consisting of three types of tasks such as text transcription, arithmetic counting and short-term memory task. Concurrently the measurements of physical parameters (temperature, relative humidity, noise and intensity of light) and chemical factors (total volatile organic compounds, carbon dioxide and particulate matters) were carried out for purpose the determination of their occurrence and comparison it with subjective evaluation of respondents. The average overall performance of users in the heating season was 84.4% and in the non-heating season was 98.3%. The highest performance was the last job on short-term memory, the lowest average overall performance was in math problems. Most users have made mistakes in the role of the transcription text. According to factor analysis the high correlation was found between air temperature and concentration of total volatile organic compounds as well as between concentration of carbon dioxide and total volatile organic compounds.

Keywords: indoor environmental quality, performance, comfort, office building

1 INTRODUCTION

Energy consumption of buildings depends significantly on the criteria used for the indoor environment and building design and operation. The environmental factors that define the indoor environmental quality are: thermal comfort, indoor air quality, acoustic comfort and visual comfort [1].

Providing optimal, or at least comfortable environment that can satisfy a majority of occupants is deemed to be important, and has been the primary goal of conventional facilities management practice, particularly in the context of commercial office environments in which individual occupant's control over their surrounding environments is usually restricted. However, indoor environments deemed satisfactory by a certain occupant group may not be satisfactory to another [2].

The preservation of indoor environmental quality (IEQ) is key to the well-being and productivity of office occupants [3]. The study [4] showed strong associations of the overall IEQ votes with the environmental parameters. It was also revealed that all IEQ complaints had similar impact on learning performance and there was a good correlation between learning performance and the number of complaints. To aid design needs, empirical expressions for approximating the impact of unsatisfactory IEQ on learning performance loss were proposed.

In study [5] using the survey parameters for office building stocks of Hong Kong, the distribution profiles of office environmental quality and the associated thermal energy consumption were determined by Monte Carlo simulations. The air conditioned offices were benchmarked according to the overall occupant acceptance of IEQ via an empirical expression of the IEQ index correlating with thermal comfort, indoor air quality, aural and visual comfort. Study [6] analyzes the subjective and objective measurements of indoor environment quality (IEQ) from four parts: thermal environment, indoor air quality, visual and acoustic environment. The result indicates that green buildings possess significantly higher satisfaction level than conventional buildings, and the actual performance of green buildings basically achieve the design goal of IEQ.

This paper deals with the indoor environmental quality, performance and comfort of employers in selected office building during the heating and non-heating season.

2 MATERIALS AND METHODS

Investigated office building (Fig. 1) was built in 1977, and was renovated in 1995. It is a nine storey building, with basement, located in the centre of Kosice. The bearing system consists of a concrete skeleton with longitudinal support system. The ceiling structure consists of reinforced concrete prestressed panels with thickness of 250 mm. External walls consist of concrete panels with thickness of 300 mm. The building envelope is insulated with contact insulation system. The flat roof is covered by modified asphalt strips with slate sanding. Internal walls are built of brick. The ceilings consist of reinforced concrete. Supplying of building by heat is provided by centrally. Heating in offices is ensured by radiators. In the building is not provided mechanical ventilation and cooling of office space.

Figure 1. View of building

Monitored office is located on the first floor (Fig. 2 and 3). The walls in experimental room are made of brick, the ceiling is made of reinforced concrete. Walls and ceiling of the room were plastered and painted with white paint 10 years ago. The floor is covered with synthetic carpet across the surface of the experimental room, the carpet was laid 10 years ago. The room can be characterized as an office with three jobs, with a floor area of 27.6 m^2 (5.2 x 5.3 m), light room height is 4 m. In the office was 10 years old office furniture, office chairs and desks, as well as computer equipment and two printers. The external walls with two windows are oriented to the north. The room was illuminated by daylighting and artificial lighting without direct solar irradiation of users. Users are able to open and close windows, as well as enable or disable downlights for experimental measurements. During the monitoring the office was occupied by three users with an average age of 38.7 years, non-smokers who performed administrative works in sedentary state.

Figure 2. Monitored office

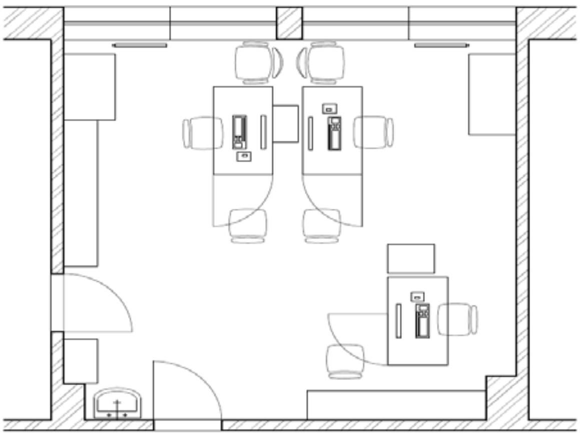

Figure 3. Floor plan

3 RESULTS

The building measurements were taken in the winter season of the year (two measurements) and summer season of the year (two measurements) in the same office.

3.1 The objective measurement of physical and chemical factors indoors in summer season

Indoor environment parameters measured during the two days in the summer season of the year are summarized in Tab. 1. In the tables are highlighted an average values of parameters which did not meet the recommended values.

Table 1. Measured values of indoor air quality factors in summer season

Parameter	1. day		2. day	
	Mean	SD	Mean	SD
Air temperature (°C)	24.3	0.5	21.2	0.3
RH (%)	**23.8**	2.1	45.0	1.0
Operative temperature (°C)	23.8	0.6	**20.5**	0.1
Air velocity (m/s)	0.05	0.02	0.04	0.03
Illuminance (lux)	276.0	137	557.0	246
Sound pressure level (dB)	**60.8**	3.6	**56.1**	4.5
Total PM (μg/m^3)	106.1	28	174.1	46
PM_{10} (μg/m^3)	**88.9**	20	**158.6**	39
$PM_{2.5}$ (μg/m^3)	12.4	2.0	16.5	3.2
CO_2 (mg/m^3)	1555.0	233	**2232.0**	300
TVOC (μg/m^3)	128.4	46	183.5	19

The average value of relative humidity at first day was compared with Decree of the Health Ministry no. 259/2008 Coll. The operative temperature was calculated from the measured values of the mean radiant temperature and air temperature. The average values of operational temperature were in the range of acceptable values (Decree no. 259/2008 Coll.) The optimal value for the summer season is from 23 to 27°C for class work 1 by Decree no. 259/2008. During the second day, this requirement was not met. The average value of the air velocity in the monitored room met the permissible value. The level of light intensity on 1.day fulfils the requirement for the lowest allowable illumination in interior space with sufficient ambient light (in office lights were turned off during the measurement). The level of light intensity in the second day met the requirement for the lowest allowable illumination for interior space with an associated lighting (during measurement, the office lights were turned on). The average value of sound pressure levels exceeded the maximum level. The maximum permissible limit for the concentration of particulate matter PM_{10} was exceeded. CO_2 concentration satisfied the requirements for the recommended value in the first day, during the second day average value of CO_2 exceeded the recommended value. The average level of concentration of TVOC satisfied the requirements for the recommended value during both days.

3.2 Factor analysis

In Table 2, the correlation matrix for the building in the summer season is highlighted for correlation coefficients greater than 0.5; less than -0.5. This indicate group of variables that have a high correlation with each other.

Table 2. The correlation matrix for the summer period

	θ_o	RH	CO_2	TVOC	$PM_{2.5}$	PM_{10}	TPM
θ_o	1.00	-0.10	**0.70**	**0.78**	**0.64**	-0.05	-0.09
RH	-0.10	1.00	**0.50**	0.33	0.13	-0.11	-0.09
CO_2	**0.70**	**0.50**	1.00	**0.94**	**0.77**	-0.05	-0.09
TVOC	**0.78**	0.33	**0.94**	1.00	**0.83**	-0.04	-0.09
$PM_{2.5}$	**0.64**	0.13	**0.77**	**0.83**	1.00	-0.01	-0.06
PM_{10}	-0.05	-0.11	-0.05	-0.04	-0.01	1.00	**0.99**
TPM	-0.09	-0.09	-0.09	-0.09	-0.06	**0.99**	1.00

Furthermore, the factor analysis is necessary to determine the eigenvalues of the correlation matrix R, in order to determine the number of factors standing in the background. Eigenvalues and the percentage of variance are shown in Table 3. Table 3 shows that we have two eigenvalues (of the Kaiser test was chosen for R eigenvalues of the matrix R which are greater than 1). The total percentage of variance is 77.6%.

Table 3. Eigenvalues and percentage of variance of the reduced correlation matrix

	Eigenvalues	% of total variance	Cumulative eigenvalue	% of cumulative
1	3.453516	49.33594	3.453516	49.33594
2	1.980809	28.29727	5.434325	77.63321

The next step in factor analysis is the rotation of factors - varimax rotation. Results for rotation factors are summarized in Table 4. The first factor is positively correlated with temperature, humidity, CO_2 concentrations and TVOC, concentration of particulate matter $PM_{2.5}$. After the rotation the first factor accounts 3.42 of the total variance, the total variance of the seven variable is 34.2%. The second factor is positively correlated with concentration of PM_{10} and the amount of particles, negatively correlated with the moisture. The second factor represents 20.1% of the total variance.

Table 4. Factors for rotation

	Factor 1	Factor 2
θ_o	0.810918	-0.021258
RH	0.332694	-0.166915
CO_2	0.960916	-0.057039
TVOC	0.980273	-0.038913
$PM_{2.5}$	0.875244	0.006633
PM_{10}	-0.006281	0.997016
TPM	-0.050036	0.992973
Variance	3.421164	2.013161

3.3 The objective measurement of physical and chemical factors indoors in winter season

Indoor environmental parameters measured during the two days in winter season are summarized in Table 5. In the table are highlighted mean values which did not meet the recommended values.

The average value of relative humidity meet the permissible values according to Decree of Health Ministry no. 259/2008 Coll. The average value of operative temperature in the monitored days in the winter season were in the range of acceptable values (Decree no. 259/2008 Coll.). The optimal value for the winter season is 20 to 24°C for class work 1 by Decree no. 259/2008. During both days, this requirement was not met. The average value of the air velocity in the monitored room met the permissible value. The level of light intensity has met the requirement for the lowest allowable illumination in interior space with sufficient ambient light (during measurement, in the office or lights on). The average value of sound pressure levels exceeded the maximum level. The maximum permissible limit for the concentration of PM_{10} was exceeded.

Table 5. Measured values of indoor air quality factors in winter season

Parameter	1. day		2. day	
	Mean	SD	Mean	SD
Air temperature (°C)	26.1	0.6	25.4	0.3
RH (%)	35.8	1.2	31.0	1.0
Operative temperature (°C)	25.3	0.7	24.7	0.4
Air velocity (m/s)	0.05	0.03	0.01	0.02
Illuminance (lux)	453.0	162.0	269.0	221.0
Sound pressure level (dB)	59.0	6.9	53.1	6.8
TPM (μg/m^3)	131.6	31.0	85.4	34.0
PM_{10} (μg/m^3)	113.4	24.0	70.0	26.0
$PM_{2,5}$ (μg/m^3)	17.0	3.6	4.6	0.6
CO_2 (mg/m^3)	2599	254.0	1369	165.0
TVOC (μg/m^3)	94.0	15.0	268.0	88.0

CO_2 concentration satisfied the requirements for the recommended value in the second day during the first day of the average measured value of CO_2 concentration exceeded the recommended value. The average level of concentration of TVOC satisfied the requirements for the recommended value during the first day, second day average concentration of TVOC exceeded the recommended value.

3.4 Factor analysis

In Table 6 the correlation matrix in winter season are highlighted for correlation coefficients greater than 0.5.

Table 6. The correlation matrix for the cold period of the year in building

	θ_o	RH	CO_2	TVOC	$PM_{2.5}$	PM_{10}	TPM
θ_o	1.00	-0.17	0.39	-0.57	-0.42	-0.33	-0.31
RH	-0.17	1.00	0.69	-0.00	-0.14	-0.10	-0.09
CO_2	0.39	0.69	1.00	-0.50	-0.36	-0.54	-0.52
TVOC	-0.57	-0.00	-0.50	1.00	0.55	0.75	0.71
$PM_{2.5}$	-0.42	-0.14	-0.36	0.55	1.00	0.70	0.68
PM_{10}	-0.33	-0.10	-0.54	0.75	0.70	1.00	0.99
TPM	-0.31	-0.09	-0.52	0.71	0.68	0.99	1.00

This correlation is "large"). This indicate group of variables that have a high correlation with each other.

Furthermore, factor analysis is necessary to determine the eigenvalues of the correlation matrix R, in order to determine the number of factors standing in the background. Number and the percentage of variance are listed in Table 7. Table 7 shows that we have two eigenvalues (of the Kaiser test was chosen for R eigenvalues of the matrix R which are greater than 1). The total percentage of explanation for variance is 76.37%.

Table 7. Eigenvalues and percentage of explanation for variance of the reduced correlation matrix

	Eigenvalues	% of total variance	Cumulative eigenvalue	% of cumulative
1	3.891105	55.58722	3.891105	55.58722
2	1.455088	20.78697	5.346193	76.37419

The next step in factor analysis is the rotation of factors - varimax rotation. The results of the rotation factors are summarized in Table 8. The first factor is positively correlated with the concentration of TVOC, $PM_{2.5}$, PM_{10} and total PM, a negative correlation with the temperature, concentration of CO_2. After the rotation of the first element accounts for 3.69 of the total variance, of the total of the seven variable is 36.9%. The second factor of a positive correlation with the temperature, PM concentration, correlates negatively with humidity, concentration of CO_2. The second factor is 16.5% of the total variance.

Table 8. Factors for rotation

	Factor 1	Factor 2
θ_o	-0.647231	0.185712
RH	0.045656	-0.977163
CO_2	-0.515705	-0.766710
TVOC	0.873095	0.030519
$PM_{2.5}$	0.778960	0.116973
PM_{10}	0.913325	0.181782
TPM	0.895680	0.170094
Variance	3.692422	1.653771

3.5 Subjective assessment of the indoor environmental quality

Winter season

Users evaluated the perceived environment:

- Air temperature – heat
- Humidity – neutral
- Air - weak draft
- Air Quality - The strong smell
- Noise – acceptable
- Lighting – acceptable

According to the questionnaire, users stated that they had the symptoms of SBS - the feeling of dry eyes, eye pain, dry nose and throat (drowsiness, fatigue, headache - these symptoms sometimes occurred in users). According to the results of evaluation users satisfaction with color was evaluated as neutral, mildly dissatisfied to very dissatisfied; friendliness and location of workplace received similar assessments; with the aesthetics of the workplace they were somewhat satisfied (30%), somewhat dissatisfied (40%) and dissatisfied (30%); with the flexibility of the device users were slightly dissatisfied and unhappy; 60% of users were dissatisfied or very dissatisfied with the cleanliness and maintenance of the workplace. They evaluated the privacy as very satisfied (30%), neutral (40%) and dissatisfied (30%); position and arrangement of the workplace was evaluated as slightly dissatisfied, neutral and dissatisfied.

Summer season

Users evaluated the perceived environment:

- Air temperature – heat
- Humidity – neutral
- Air flow - no drafts
- Air Quality - strong smell
- Noise – acceptable
- Lighting – acceptable

According to the questionnaire, users stated that they experienced the symptoms of SBS - the feeling dry nose and eye irritation, eye pain, drowsiness, fatigue, slow reaction rate, difficulties in concentration.

According to the results of color, friendliness and workplace layout were evaluated similarly neutral and slightly dissatisfied; with the aesthetics of the workplace were somewhat dissatisfied (30%) and dissatisfied; with the flexibility of the device users were satisfied and somewhat satisfied; location workplace and workplace cleanliness and maintenance were evaluated similarly; privacy of users rated moderately satisfied and satisfied.

3.6 Performance testing of users

The results of performance evaluation of individual tasks for winter and summer period of the year are summarized in Table 9. The results showed that the average total and correct performance was higher in the summer season. In winter and summer season, the lowest average performance in the role of the counting numbers. The highest average performance was the last job in the short-term memory where users assign letters to symbols by the master. Most errors were reported in the role of the transcription of the text (where the number of errors is calculated as the difference between total and correct performance).

Table 9. Objective performance of users

Task	Winter season		Summer season	
	TP [%]	CP [%]	TP [%]	CP [%]
Text transcription	90.30	88.0	89.20	85.60
Counting	81.30	79.50	72.00	70.30
Assigning a letter to symbols	96.30	95.80	91.98	90.60
All tasks	84.40	87.80	89.30	82.20

TP - Total Performance

CP - Correct Performance

3.7 Subjective assessment of comfort and performance

Winter season: air temperature, humidity, feeling drafts and indoor air quality were evaluated as slightly discomfortable to discomfortable state; noise load users equally as mild discomfortable state.

Summer season: temperature, the lipid as mild to very discomfortable to discomfortable state; humidity as mild discomfortable and discomfortable state; perception drafts as discomfortable to very discomfortable state; indoor air quality users consistently rated as discomfortable state; noise exposure as mild discomfortable state; users rated lighting as comfortable and slightly discomfortable state.

Winter season: the impact of indoor environmental parameters on the perceived performance of the users like; lighting to improve their efficiency (25%); quality and indoor air temperature slightly decreases (25%) of their performance.

Warm Period: By users operating parameters of the indoor environment of neutral or reducing their perceived performance; only the effect of light users perceived as the slightly increased (50%) and increased (50%) of their performance. In the winter season all users evaluated factors as neutral in relation to their perceived performance. In the summer period users evaluated relaxation areas, greenery indoors and outdoors and contact with the exterior as positive impact (rising slightly) on their perceived performance.

3.8 Regression analysis

Analysis of interdependence between sensory evaluation parameters of the indoor environment and the subjective assessment of the impact of these parameters on the perceived performance of users was conducted using simple linear regression. Tightness linear regression characterizes the correlation coefficient R2. The tightness of the linear relationship and Thermo sensation illumination is high; for the perception of noise leakage was significant linear dependence; for the perception of humidity, air quality, wind tightness was zero.

The tightness of the linear dependence of the perception of temperature, humidity, and the sensation of drafts was high; the perception of the quality of air, noise and light leakage rate was zero.

4 CONCLUSION

Summer season

The average sound pressure level exceeded the maximum level of 21.6% during first day of monitoring and 12.2% in the second day. The average concentration of particulate matter PM_{10} during the monitored days exceeded the maximum value of 67.8% in first day and second of 217.2%. The recommended value for CO_2 concentration has been exceeded during the second day by 24%. In sensory evaluation, they rated as acceptable noise and all users of this state as mild discomfortable; more than half of users said that the noise burden slightly reduces their performance. In sensory evaluation, users rated air quality as discomfortable state (felt strong smell) and air quality reduce user performance.

Winter season

The average sound pressure level exceeded the maximum level by 18% in the first monitored day and 6.2% in the second day. The average concentration of particulate matter PM_{10} during the monitored days exceeded the maximum value by 126.8% on the first day and 40% in the second day. The recommended value for CO_2 concentration were exceeded during the first day by 44.4%. The recommended value for TVOC concentrations were exceeded during the second day by 34%. In sensory evaluation, users rated as acceptable noise and all users of this stave as mild discomfortable; thirds of users said that the noise burden reduces their performance. In sensory evaluation, users rated air quality as discomfortable state (felt strong smell) and air quality at third users slightly reduced their performance.

Effect of other factors on the perceived performance was judged to be neutral, respectively. It increases user productivity. The average overall performance of the users in the winter season of the year was 84.4%, in the summer season was 98.3%. The highest performance was the last work in the short-term memory, the lowest average overall performance was in math problems. Most users have made mistakes in the task of the transcription text. Some recent studies deal with indoor environmental quality (IEQ) in green and conventional office buildings. A study [3] investigates and compares the green and conventional office buildings in middle Taiwan on various aspects of indoor environmental quality during a period of active air-conditioning use. Results show, only about 10% of the respondents in the green building group were uncomfortable with the overall IEQ in their workplace, suggesting that in general the green buildings was able to deliver an indoor environment of comfort to their occupants. Thirteen percent of the occupants in the conventional building group voted "uncomfortable" to the overall IEQ. Although the ratios of uncomfortable votes were similar between both groups, more people (28%) were neutral to the overall IEQ in the conventional buildings than the percentage (15%) in the green buildings. The contrast between both groups was further enlarged in the "comfortable" category - only 59% of the respondents in the conventional building group sensed the IEQ as comfortable whereas 75% in the green building group claimed the same perception. Another study [7] concludes that (1) there was insufficient evidence to support their research hypothesis that green buildings are more comfortable than conventional buildings, particularly with respect to aesthetics, serenity, lighting, ventilation, acoustics, and humidity; and (2) there was evidence that thermal environments that are perceived to be warm cause a lower level of satisfaction among the occupants of a building. According to our study (1) the impact of indoor environmental quality on performance and user experience was confirmed by objective assessment, (2) high correlation between the air temperature and total volatile organic compounds, as well between the concentration of carbon dioxide and total volatile organic compounds was observed according to factor analysis, (3) influence of negative effects of environmental parameters on the perceived performance was confirmed in subjective assessment where users identified environment as discomfort, and finally (4) according to regression analysis, there is a correlation between sensory perception, environmental conditions and their impact on perceived performance [8].

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