Investigation and influence of indoor air quality on energy demand of office buildings

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Abstract: - In office buildings occupants do high intensity intellectual work in eight hours. Quality and quantity of completed tasks are elementary influenced by indoor comfort, particularly thermal environment and indoor air quality. Investigation of indoor air quality has brief history, although it is getting more important issue nowadays. At Department of Building Service Engineering and Process Engineering, research work has been carried out as industrial assignments as well as tenders, sponsored by Hungarian Scientific Research Fund. For indoor air quality examination a laboratory state has been developed. Several materials have been evaluated concerning emission rate and its effect on indoor air quality. In the course of research, naive panels have been adopted, using Fanger (-1;+1) and Hedonic scale. Improved indoor air quality require increased fresh air rate, hereby energy demand of building become higher. Therefore we have dealt with energy demand influenced by indoor air quality as well.

Key-Words: - Indoor air quality, fresh airflow rate, HVAC system

1 Introduction

To evaluate indoor air quality two basic methods are generally used in international researches: investigation with trained panel or naive panel. During the last years several measurements have been made with naive panels in our laboratory, with seven different test groups (2000-2005), 32-in each of them 55 test persons. The goal is to evaluate the accuracy of test persons as well as test group, moreover to estimate pollutant emission of indoor materials using olf-decipol system and Hedonic scale. We tested the goodness-of-fit of the old-box measurement results to the normal distribution.

Measurements have been conducted in the Air Quality Laboratory of the Department of Building Services Engineering at the Budapest University of Technology and Economics with the participation of 32-55 university students aged between 22 and 25. First the olfactory sense of the measuring team was tested with the olf-box, then the pollutant emission of various indoor used materials, perceptible to humans, was examined.

By design of HVAC systems, it shall be a main issue to ensure required indoor environment. Design condition can be established by standard values of parameters of thermal comfort, indoor air quality as well as acoustic environment. In Hungarian standard MSZ CR 1752 three level of comfort is specified, each can be classified according different level of dissatisfaction. However it should be realized, that higher indoor environment standards can be met with increasing financial investments, because up-market equipments need to be installed into the system.

Designers, contractors commonly have to handle a problem that investors prefer higher level of comfort but investment cost should be as low as possible.

This paper is about indoor air quality, primarily required fresh airflow rate. This can be established considering human respiration and/or indoor air quality.

2 Methods

2.1. Laboratory measurements

At Budapest University of Technology and Economics investigations have been done using naïve panels, .with 7 examination teams, i.e. 310 participants in total. Team members were students.

2.1.1. Investigation with unknown acetone sample

When developing the olf-decipol system, Professor Fanger and his team linked the value of the decipol scale to the given concentration of a typical gas, evaporated acetone. It is therefore possible to produce any air quality using air quality standards.

For the measurement an olf-box has been created, which contains air quality standards the equivalent of 1, 5, 10, 20 decipol (decipolmeter) and the unknown pollution source.

Components of the air quality standard are the sampling funnel, fan, mixing space, and acetone source. Vented air mixes in the mixing space with acetone vapour from the acetone source. Subjects evaluate the acetone-air gas mix perceived through the sampling funnel. In order to the air quality standard we used low emission materials such as glass and stainless steel. Different air qualities can be produced by adjusting the number and size of openings on the aluminium plate, which is close off the acetone source.

During the investigation subjects estimated 8 different unknown values with the help of the standards (Table 1.). We examined with one-sample t-tests the null-hypothesises that the expectation of the measurement data can be equal to the adjusted hypothetical acetone level. The date of measurements and number of subjects are contained in Table 2.

The results of the Kolmogorov-Smirnov goodness-of-fit tests are summarized in Table 3. Among the 56 samples only 6 shows not too strong fitting to the normal distribution, so the application of the t-test seems to be reasonable. (In the cells of the Table 3. the asymptotic significance levels of the goodness-of-fit tests can be seen.) First we tested the normality of the samples with Kolmogorov-Smirnov test. If the sample fits well to the normal distribution, then the zest statistic $T_n = \sqrt{n} \cdot \sup_{x \in R} \left| F_n(x) - \phi_{m,\sigma}(x) \right|$ follows the so called Kolgomorov distribution. In the formula Fn(x) is the empirical distribution function of the sample, $\phi_{m,\sigma}(x)$ is the hypothetical normal distribution function, m the mean, σ is the standard deviation.

2.1.2. Examination of indoor used materials

We investigated influence of indoor used material on indoor air quality with different method. We measured the emission of indoor used material (olf) with naiv panel. We compared the materials by hedonic scale.

Examination state can be seen in Figure 1. It was constructed under inspiration from several international published professional papers. In design it should be taken into consideration that low emission materials have to be used. That is way a glass chamber have been applied with stainless steel flow deflector units. The examined pollutant source is placed into the 50x50x80cm sized glass chamber. The structure of the samples ensures that only the exposure across the effective surfaces is measured. Other surfaces are covered with an aluminium tape. Airflow across the chamber is developed by a fan (12V) installed on the one side. Ventilated air is exhausted across a sample cone. Test person is judged the emission by smell, in a subjective way. Airflow can be controlled by DC power supply. Set value is 2,9 m^3/h. By the examination the test person evaluate the quality of the exhausted air. Chamber is covered so the sample can be seen. It is important that evaluation shall be made before the adaptation occurs. Examined materials are commercial trades.

Examined materials have been represented with a sample plate in size of 40 x 40 cm. Thus exposure can be occurred across the surfaces exclusively. Measured emission rates are listed in Table 4. The emission was evaluated on an ungraded and Hedonic scale. Values measured of Hedonic scale for different indoor used materials are shown in Figure 2.

Graded results from the Hedonic and Fanger scale can be seen in Table 5., where 1 for the least source strength and 8 for the greatest one. By evaluation of common results no significant differences have been found. In fact tendency in results are similar.

Normality test can be provided by graphically and by statistical hypothesis testing. Graphically, normal distribution of sample realization is checked by Probability-Probability (P-P) and Quantile-Quantile (Q-Q) plots, and by a bell curve adapted for the histogram.

P-P plot: a point chart of the empirical, calculated from the sample, and the hypothetic distribution function both completed with linear regression. Adaptation can be said proper, if points are “twisted” around the line.

Histogram with bell-curve: normal density function for sample average and standard deviation are fitted to histogram calculated from the sample. By adequate fitting columns of the histogram are fulfil area under bell-curve properly.

If samples are fitting to normal distribution fairly, homogeneity test can be carried out correctly by deviation analysis, even in case of low sample number.

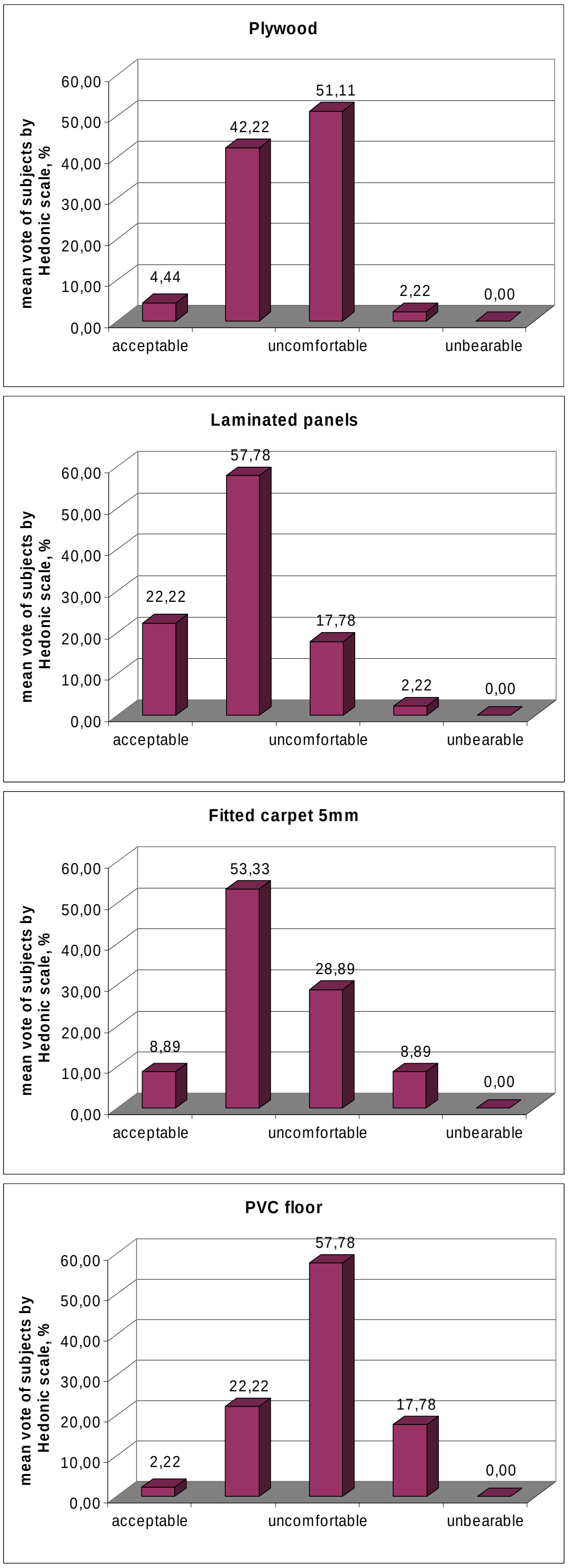
Producing normality tests of measuring results, distribution functions, P-P plots and box-plots have been made by SPSS 15.0 software. Distribution function, P-P plot and bo-plot of 1th sample of measuring team No.:VIII. can be seen in Figure 2. Based on P-P plot, measuring results are fitting to the regression line properly.

Two or more statistical sample are called homogeneous, if they are originated from the same probability – distribution, i.e. they had the same distribution function. Depending on the number of the samples, and taking into consideration of the correlation between the samples, different methods shall be used during statistical analysis.

If normality assumptions of analysed samples are fulfilled, homogeneity can be verified with so-called parametrical probes. In this case, a proper decision can be made even at low sample number. If there are no previous assumptions regarding distribution, non parametrical probes shall be used. Thus higher sample number is required to perform a proper decision about homogeneity.

Homogeneity test of measuring results regarding indoor

material emission has been performed by Friedman method.
Test results of measuring team No.VII. are listed in Table 6.



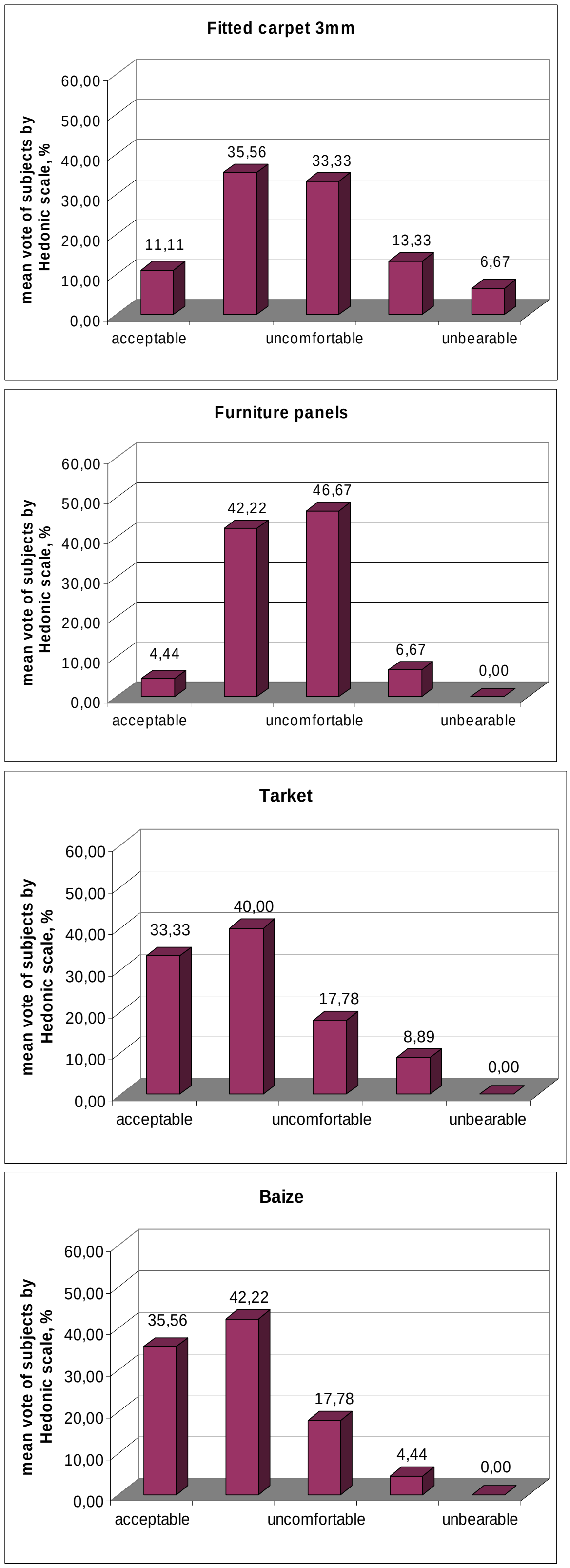


Figure 2. Measurement results of the Hedonic scales

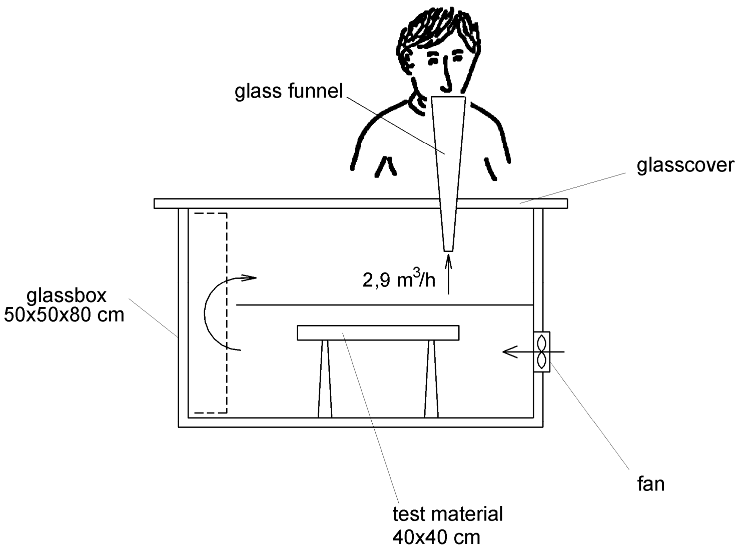


Figure 1.
Measuring of pollutant emission of interior building materials

Table 5.
Measured pollutant emission of different materials

Material	rank of ungraded scale	rank of Hedonic scale
plywood	6	7
laminated panels	2	2
fitted carpet 5mm	4	4
PVC floor	8	8
fitted carpet 3mm	5	5
furniture panels	7	6
tarket	1	3
baize	3	1

Table 6.
Results of Friedman test
Measuring team No.VII.

Ranks

	Mean Rank
Sample 1.	4,28
Sample 2.	3,97
Sample 3.	3,30
Sample 4.	4,22
Sample 5.	5,06
Sample 6.	5,51
Sample 7.	5,37
Sample 8.	4,30

Test Statistics(a)

N	45
Chi-Square	30,295
df	7
Asymp. Sig.	,000

a Friedman Test

2.2. Investigation of indoor air quality

In enclosures, designed for human occupancy, amount of fresh air and perfect ventilation are essential. Fresh air is required to ensure breathing and perfect indoor air quality.

2.2.1. Fresh airflow for breathing

Assumptions of occupants' metabolism are oxygen inhaling and carbon-dioxide exhaling. Carbon dioxide concentration in exhaled air is higher than in environmental air. Thus indoor CO_2 concentration is increasing.

From hygienic point of view, indoor air quality was examined by Max von Pettenkofer in the middle of 18th century. In a paper, published in 1858, he evaluated indoor air quality by CO_2 concentration. He demonstrated that indoor air compounds in flats, classrooms and auditoria are different from outdoor air. Outdoor carbon dioxide concentration is 0,03-0,04 % (300-400 ppm). He measured 0,09% CO_2 concentration in flats, and even significantly higher CO_2 level in auditoria. He established 0,1 %(1 000 ppm) maximal CO_2 concentration as a criterion of "good air". It is called Pettenkopfer number by professional literature.

According the former Hungarian design practice, design was based on fresh airflow for breathing. Requirements used to be established by fresh air ration (per person).

For intellectual activities 30 m^3/h fresh air shall be supplied for each occupants. By former regulations this value used to be 20 m^3/h per capita considering 20 l/h human CO_2 exposure, in case of 400 ppm outdoor and 1400 ppm indoor CO_2 concentration. German regulations (DIN) give another respect of calculation; fresh airflow rate can be calculated by the area of the enclosure as well. German standard values are listed in Table 7.

2.2.2. Indoor air quality requirements

Science of indoor air quality theory is a profession with considerably short history. Indoor air quality is a common concept of all non thermal parameters of indoor air which have impact on human well-being. Indoor air quality is primarily affected by different type of gaseous pollutants (gases, vapours, odours). Generally in Hungarian indoor air quality issues have not significant impact on design process yet. Considering indoor air quality, higher fresh airflow rate is required. Calculation can be carried out by two independent methods:

- by theory of Prof. Fanger, using olf/decipol units (*perceived air quality*),
- according permitted concentration level of dominant pollutant(s) (*health issues*).

By perceived air quality concept total effect of different sources (occupants, building, HVAC systems) is taken into consideration. Design data can be collected from professional references. Results of our investigations are collected in Table 8. Two cases are compared: single effect of occupancy (source strength: 0,1 olf/m^2, rate of occupancy 10 m^2 / person) and total effect of occupants, building and HVAC systems as pollutant sources. Heading of the table is separated by the different level of dissatisfactory in accordance the comfort categories.

According the results and reference data measurement can be carried out in given building interior materials accordingly. Presented results also confirmed that higher level of perceived indoor air quality requires remarkable more fresh air. Consequently it requires improved capacity of HVAC system, which results higher investment and maintenance costs.
Design with respect of health requirements can be made considering standard concentration level of dominant pollutant(s), such as carbon dioxide, formaldehyde, TVOC, radon, smoke, etc. From indoor air quality point of view carbon dioxide concentration in the indoor air is an essential criterion. Permitted concentration levels according indoor environment categories are listed in Table 9., where Δc is for acceptable increase of carbon dioxide concentration.
Design of enclosures with human occupancy based on healthy requirements should not be confused with health protection aspects for design of industrial halls.

3 Conclusion

3.1. Laboratory measurements

We carried out the measurements with seven independent teams. These results are utilizable as gauging raw data during design. Based on the analysis of measurement results, the following important conclusions can be made:
a. Near to 90% of the goodness-of-fit tests verify the normality of the samples derived from olf-box measurement.
b. The results in decipol system have been in accordance with values from Hedonic scale.
c. Test persons have been disposed to overestimate the low intensity odours and underestimate the high intensity odours. (Figure 5.)
We have developed a laboratory measurement method to study different indoor materials, which are commonly used in Hungary. With the help of the constructed measuring state we have determined the emission of plywood, laminated panels, fitted carpet, furniture panel, PVC floor, tarket and baize.
In the course of statistical evaluation we have done normality test of samples. Measuring results have been properly corresponded with normal (Gaussian) distribution. It have made possible to perform a homogeneity test with low sample number. Friedman tests have demonstrated, that it had not been significant similarity between measured samples, thus they have been independent from each other.
The measurement results provide basic data for dimensioning. The evaluation of emission figures has shown that our results nearly met the values, published in international researches.

3.2. Investigation of indoor air quality

According former Hungarian standards required fresh airflow rate for human respiration is 30 m^3/h. By calculated data increase of required fresh airflow rate can be established according to the selected comfort category (A, B or C). As fresh airflow rate is increasing, energy demand of HVAC system become higher. Table 10. and Figure 6. contains the rates of fresh air increment in case of different indoor environment category.

Economical aspects can be evaluated based on investments and maintenance costs. As it can be seen from the results, higher comfort level can be achieved with 2-3 times more fresh air. It can be supplied a HVAC system with 2-3 times higher capacity. Consequently investments and maintenance costs become more significant as well. Maintenance costs can be reduced using proper design of the building structure and the building service systems, e.g. using outside shading, heat recovery, enthalpy control, free-cooling systems, cooling energy storage. The most advantageous solutions can be selected analyzing given cases.

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Table 1.
Value of acetone samples

	Sample No. 1.	Sample No. 2.	Sample No. 3.	Sample No. 4.	Sample No. 5.	Sample No. 6.	Sample No. 7.	Sample No. 8.
Dp	12,78	6,32	25,1	3,77	21,5	8,81	12	13,15

Table 2.
Measuring teams

Measuring team	Date	Number of test persons
I	9.-12. 2000.	55
II	6. 2001.	32
III	9.-10. 2001	42
IV	10.-12. 2002.	45
V	11.-12. 2003	51
VI	11.-12. 2004	40
VII	10.-11. 2005	45

Table 3.
The asymptotic significance levels of the one-sample Kolmogorov-Smirnov tests

Measuring team	Sample No. 1.	Sample No. 2.	Sample No. 3.	Sample No. 4.	Sample No. 5.	Sample No. 6.	Sample No. 7.	Sample No. 8.
I.	0,18	0,219	0,665	0,252	0,229	0,365	0,379	0,601
II.	0,479	0,893	0,5	0,368	0,929	0,684	0,37	0,974
III.	0,883	0,487	0,146	0,445	0,044	0,146	0,573	0,304
IV.	0,009	0,07	0,327	0,346	0,137	0,13	0,177	0,134
V.	0,005	0,003	0,04	0,111	0,955	0,324	0,648	0,414
VI.	0,768	0,024	0,541	0,932	0,932	0,498	0,887	0,470
VII.	0,11	0,09	0,721	0,207	0,175	0,421	0,79	0,934

Table 4.
Intensity of indoor used materials as pollution source

Number	Name	Measuring team	Votes mean	Votes SD	Mean +Conf.	Mean -Conf.	PD %	G olf/m^2
1	plywood	IV	0,09	0,35	0,19	-0,01	34,18	0,73
2	laminated panels	IV	0,39	0,48	0,53	0,25	9,63	0,10
3	fitted carpet 5mm	IV	0,16	0,41	0,28	0,04	26,41	0,47
4	PVC floor	IV	-0,12	0,38	-0,01	-0,23	61,15	2,27
5	fitted carpet 3mm	IV	0,04	0,53	0,19	-0,12	40,34	0,99
6	furniture panels	IV	0,04	0,44	0,17	-0,09	40,34	0,99
7	tarket	VII	0,33	0,53	0,49	0,17	12,76	0,04
8	baize	VII	0,19	0,57	0,36	0,02	23,45	0,20

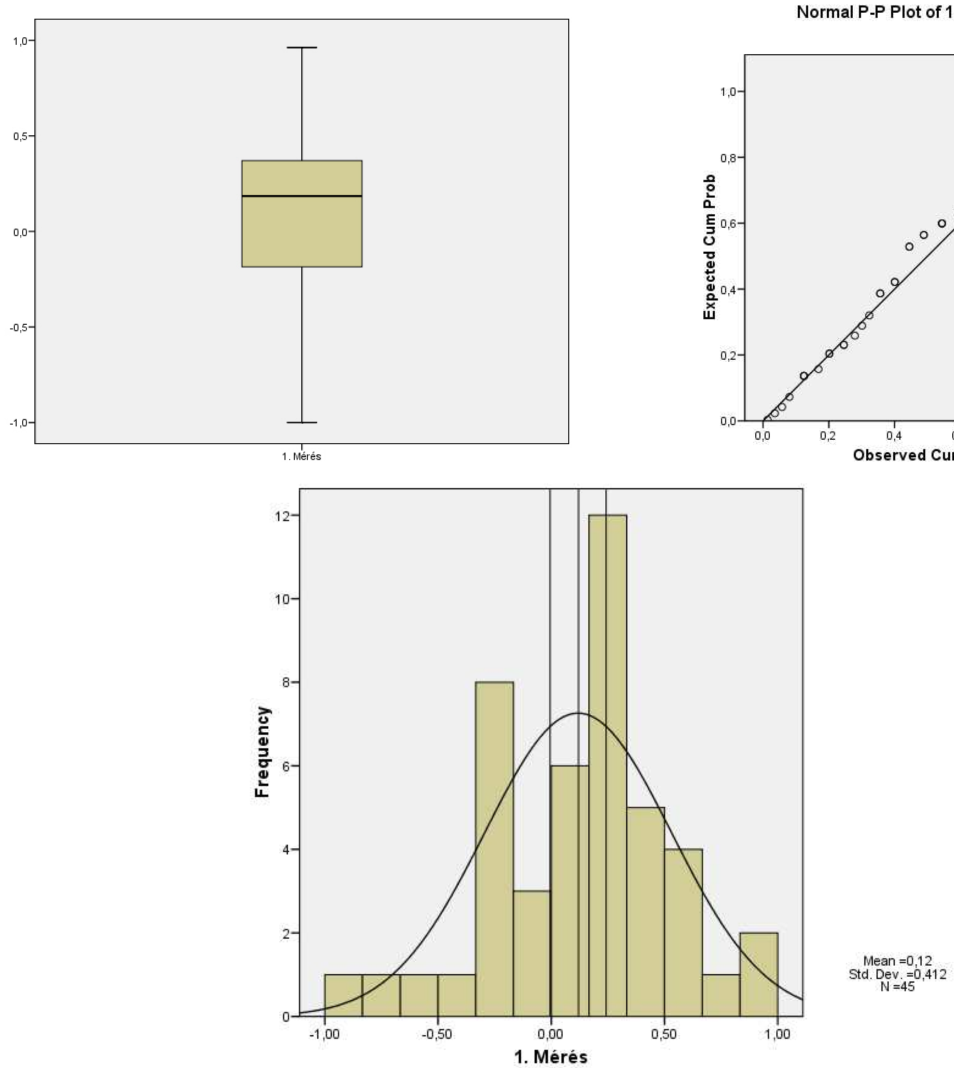

Figure 4. Normality test
1th sample, measuring team No. VII. (45 participants) 2005. X.-XI.

Table 7.
Required fresh air according DIN 1946/2

Enclosure	Example	Per capita m^3/h	Per area $m^3/m^2,h$
Workspaces	Single office Landscape office	40 60	4 6
Leisure area	Concert hall Theatre Conference room	20	10-20
Educational area	Reading room Classroom Lecture hall	20 30	12 15

Table 8.
Required fresh air according perceived air quality

Occupant		Only occupants (0,1 person/m^2)			Occupant + building + HVAC (building + HVAC = 0,2 olf/m^2)		
		$\dot{V}$, m^3/h, per capita					
Activity	olf	c_b = 1,0, ≤15%	c_b = 1,4, ≤20%	c_b = 2,5, ≤30%	c_b = 1,0, ≤15%	c_b = 1,4, ≤20%	c_b = 2,5, ≤30%
Level: 120W	1	45	30	15,6	135	90	46,8
Level: 150W	1,5	68	45	23,5	158	105	54,8
20% smoker	2	90	60	31,3	180	120	62,6
40% smoker	3	135	90	47,0	225	150	78,3
Smokers	6	270	180	94	360	240	125,3

Table 9.
Comfort categories according permitted level of $C0_2$ concentration

Category	**Δc;ppm**	**c_i ;ppm***	**V m^3/h, per person**
A	460	900	43,9
B	660	1 100	30,3
C	1 190	1 630	16,8

*** Note:** outdoor $C0_2$ concentration level: 440 ppm

Table 10.
Increasing energy demand according comfort categories

Cathegory	**A**	**B**	**C**
CO_2 concentration	1,46	1,0	0,56
IAQ only occupants	1,5	1,0	0,52
IAQ occupant+building+HVAC	4,5	3,0	1,56

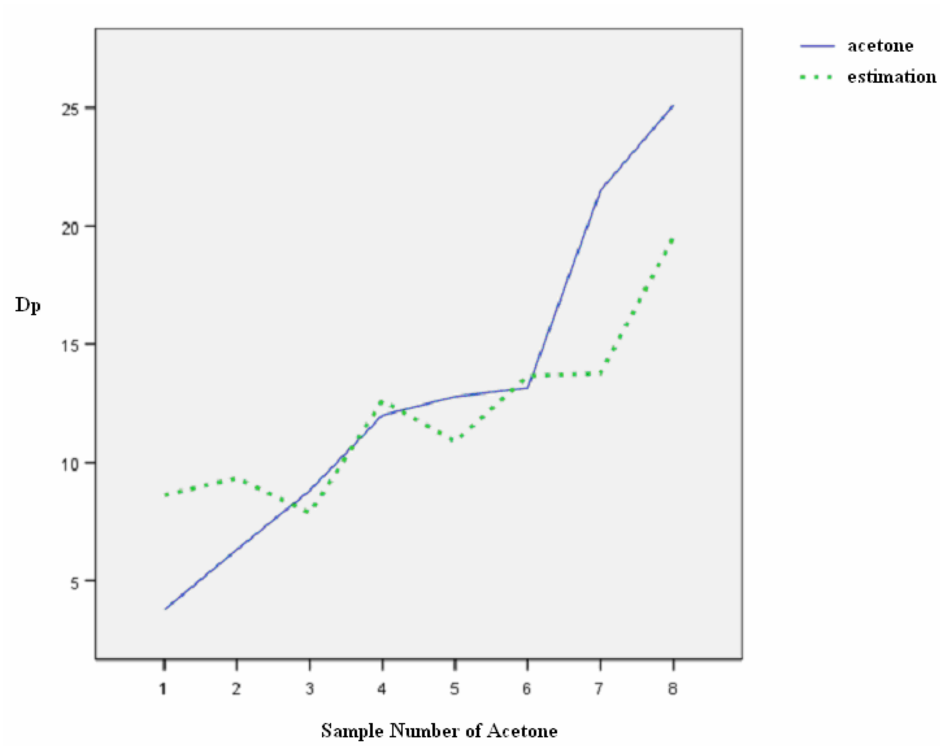

Figure 5. The actual and estimated acetone intensity (naive panels).

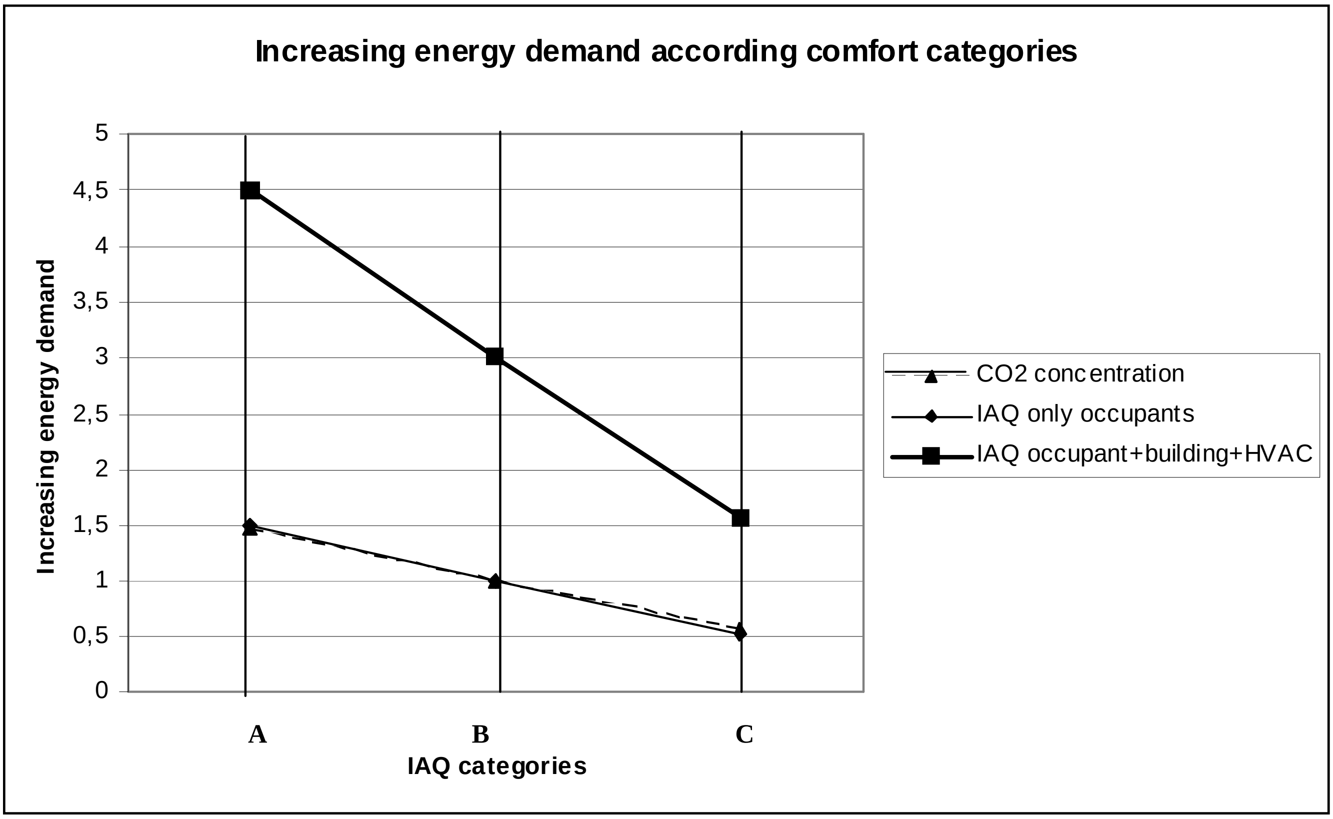

Figure 6. Increasing energy demand according comfort categories