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THE EFFECTS OF WOODEN BUILDING MATERIALS ON THE INDOOR AIR QUALITY OF HOUSES

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Abstract: *Exposure to indoor chemical air pollutants has a great impact on our health because we spend most of our time inside buildings. Pollutant exposure levels inside buildings are likely due to pollutants from both indoor and outdoor sources. As a natural, biological material, wood emits various organic chemical substances, mostly volatile organic compounds (VOCs), very volatile organic compounds (VVOCs) and formaldehyde. When such emissions occur in indoor spaces, concentrations of these substances are higher than concentrations outdoors. Consequently, the level of emissions from building materials is of relevance in relation to their possible health effects. The current work shows the measurements of the indoor air concentration in a passive, low-energy, wooden, light frame house. Concentrations of volatile organic compounds (VOC) and formaldehyde were measured and compared and with the current international regulations of air pollutants. Six measurements were taken throughout one year. An active sampling device was used on the site. The results of the measurements showed the changing concentrations of air pollutants. Concentrations of 180 components were determined according to standards ISO 16000-6:2004. During the field measurements we detected the presence of formaldehyde (34µg/m3), BTX (35.51µg/m^3), and some materials in the terpene family, limonene (64.7µg/m^3), and alpha-pinene (297µg/m^3), in the indoor air. The concentration of the detected TVOC (Total Volatile OrganicCompounds) was 2150µg/m^3, which does not significantly differ from European average values. We determined the health risk of all measured substances according to the German standard using the Lowest Concentration of Interest (LCI) analysis. The conclusion of the present case study is that the total volatile organic compounds (TVOC) of the indoor air during the one-year measurements had been changed only slightly and they did not pose a health risk. The concentration of the TVOC was influenced by indoor temperature, indoor relative humidity and air exchange rate. Human activities and the furniture had the greatest impacts on the concentrations. The rate of the wooden clothing in each room had a great influence on the concentrations of alpha-pinene and 3-carene.*

Keywords: *IAQ; wooden building materials; VOCs*

INTRODUCTION

The global climate change and increasing energy requirements have led to the development of airtight, energy-saving buildings with very low air exchange rates. Because of the cheap mass-production the most common building materials are synthetic materials. The houses may become more and more comfortable and automatized, still the question arises: Do these technical improvements provide a healthy living-space for people? We spend 80-90% of our lives inside buildings [1]. Environmental health researchers have been investigating intensively the indoor air quality of newly built homes, existing homes and renovated homes [2] [3] [4]. The guidelines of WHO (World Health Organisation) categorize the harmful substances emitted by the sources [5]. In Germany the Committee for the Health Assessment of Building Materials (AgBB - Ausschuss zur gesundheitlichen Bewertung von Bauprodukten) first defined VOCs from the emission of building products in 2000. Now more than

180 different VOCs can be defined [6]. Because of the differences in factors such as climatic conditions, lifestyles, and construction habits the indoor environments can vary from region to region, and country to country.

However, despite this variation, many industrialized societies are facing a growing number of very similar indoor air quality problems. It is necessary to re-evaluate the way in which buildings are designed and constructed. By choosing the right building materials (low-emitting materials) andtechnologies (slow-tech, low-tech) can these adverse impacts on the indoor air quality be avoided. More in-situ measurements are needed, to get a wider view of the "health condition" of buildings and how they affect our health. People have the right to a healthy living environment. The Agenda 21 sais: "Support research and develop programmes for applying prevention and control methods to reducing indoor air pollution."[7].

There are some countries where the regulations of the indoor air quality define the building materials and the concentrations of air pollutants emitted from them. In the European Directive it is emphasized, that provisions should not only relate to building safety, "but also to health, durability, energy economy and other aspects important in the public interest" [8].

In Hungary there are no regulations regarding the maximal values of air pollutants emitted in the indoor air of residential buildings. There are regulated values for the working environment (MSZ 21461 1-2) [9].

Wood is one of the most environment-friendly raw materials. Wood cells contain high amount of carbon absorbed from the CO^2 component of the air. Wood as a raw material has a very low demandof energy during manufacturing compared to other materials such as metals or silicate based materials.[10]. Engineered wood products, such as oriented strand board (OSB) contain chemical materials in form of added adhesives or as surface treatment etc. These chemicals have significant emissions of volatile organic compounds (VOCs) that could pose a health risk especially in indoor spaces [11] [12].There are researches examining the beneficial effects of wood indoors [44] [45]. In a Norwegian studyresearchers made a comparison of wooden building materials and other synthetic building materials onthe basis of their ecological effect. The conclusion was that wood absorbs much less greenhouse gases and leaves much less waste behind. This conclusion stands only for natural wood, not for engineered wood products (e.g.: OSB) [13].

There are several studies about the emission of VOCs and formaldehyde from wood based composites, such as MDF, plywood, particleboards, etc [19-22]. Ze-Li showed in their study that the most emitted VOCs were terpenes, aldehydes, and aromatics. Pine wood plank had the highest VOCs(approximately 900 $\mu g/m^3$). Fresh particleboard showed the second highest value with 450 $\mu g/m^3$ [22].Manninena's study compared the emissions of VOCs from air-dried pine wood and heat-treated pine wood. Terpenes were clearly the main compound group in the air-dried wood samples, whereas aldehydes and carboxylic acids and their esters dominated in the heat-treated wood samples. The results suggest that if heat-treated wood is used indoors, emissions of monoterpenes are reduced compared to air-dried wood, but some irritating compounds might be released into indoor air. Significant chemical changes have occurred; volatile monoterpenes and other low molecular weight compounds have evaporated from the wood during the heat-treatment process when compared to air dried wood [23].

The emission of wood-based materials depends on the type of wood. Hard wood emits high concentrations of acetic acid and formic acid, while soft wood emits more terpenes (alpha-pinene, 3-carene, etc.) [24]. The age and the time of logging are another important influence factors. The reuse and recycling of waste wood is a growing field in many countries. The most critical point is still the presence of used adverse chemicals e.g. urea formaldehyde, phenol formaldehyde. To reduce the concentrations of these chemicals in engineered wood, there are studies made in the last fifteen years [25-28].

Song-Yung measured the emissions of particleboard from recycled wood-waste chips using polymeric 4,40-methylenediphenyl isocyanate (PMDI) and phenol-formaldehyde (PF) resins. The research showed that by increasing ratio of PMDI the concentration of emitted formaldehyde was lowering[25].

Sumin Kim used natural tannin as adhesive in wood-based flooring. They had to add PVAc to increase the bonding strength of tannin. The formaldehyde emission was lowered even by adding PVAc (Polyvinyl acetate), and more greatly reduced when UV curable urethane acrylate was coated [26]. The volcanic pozzoloan is another material added as scavenger to engineered wood, which reduced the emissions of formaldehyde [27].

In a newly-built wooden house the concentrations of the emitted air pollutants can be reduced with the "bake out" process. The inside temperature is raised to 32-40°C and kept it for a week. The extent of the reduction of air pollutants in the indoor air is about 60-90% [28].
Standardized emission testing using test-chambers are part of the national and international approval for construction materials, thus a lot of data exits for the emission from wood and wood-based composite boards. Weschler emphasises in his review, that still there are few studies analyzing the harmful substances in indoor air of existing houses [29].
The present study shows the measurements of the indoor air concentration in a passive, low-energy, wooden, light frame house. Concentrations of volatile organic compounds (VOC) and formaldehyde were measured and compared with the current Hungarian [9] and international regulations (WHO) of air pollutants [1]. We determined the health risk of all measured substances according to the German standard using the Lowest Concentration of Interest (LCI) analysis.

MATERIALS AND METHODS

The sampling was performed in a newly built, low-energy, frame-house [30]. The turnkey construction of the building was completed during summer. It has an area of 120m2, a ground floor and an attic room. Downstairs there are a hall, a living room + a kitchen, a room and a bathroom. From the living room there is a staircase leading up to the gallery, which opens into a room in the attic.
The structure of the building consists of wooden frames and wooden panels with Isocell insulation, which is rendered from the outside and covered with gypsum fibre panels inside (Table 1). The interior walls are covered with solid wood panels. The house is heated with circulating hot air combined with an airing system. The heat is derived from solar panels and stored in seasonal thermal storage system. In addition, the ground floor heating is supported by electric under-floor heating in winter.

Table 1. Outside wall layers (from outside to inside)

No.	Thickness		Description	Thermal conductivity W/mK
1	5	mm	Breathable render	0.6
2	60	mm	Fiber Insulation Panel THD NF 230	0.05
			KVH 60x160 mm spruce, truss frame	0.1
3	160	mm	with 160 mm ISOCELL in between	0.039
4	12	mm	MFP	0.13
			KVH 60x160 mm spruce, truss frame	0.1
5	160	mm	with 160 mm ISOCELL in between	0.039
6	15	mm	H15 gypsum fibre board	0.22
7	0.25	mm	ÖKO-NATUR vapour-stop paper	
8	30	mm	Planed and dried spruce, batten framework	-
9	05.dec	mm	impregnated plasterboard	0.24

Sampling was performed in the building and the samples were analysed by the laboratory of Wessling Hungary Ltd. An active sampling device was used on the site. During the sampling, in order to facilitate the accuracy of the laboratory tests the physical characteristics of indoor air had been set 24

hours before the sampling. Thus the sampling was performed in a stationary state. The air exchange rate was 2.51/h, which means that during the measurement the doors and windows were closed.
Two sampling tubes were connected to the active measuring device used in the sampling. The sampling tube was a 200 mg Tenax TA stainless steel tube, 90 mm long, for sampling the VOCs.
Suction duration: 60 min
Suction rate: 100 ml/min
Suctioned air volume: 6000 ml
Six measurements were taken throughout one year. The results of the measurements showed the changing concentrations of air pollutants. When we determined the VOC content of the samples taken from the indoor air we measured the concentrations of 180 components according to standards ISO 16000-6:2004 and ISO 16000-3:2001.

RESULTS AND DISCUSSION

In Table 2 we included the measured concentrations of those VOC components out of the 180 measurement results whose values were significantly greater than the detection limit and are present in each room. Presumably, these are the materials which determine the quality of indoor air in the building.

Table 2. Measured concentrations of VOCs above detection limit measured in all rooms

	1. Measurement	2. Measurement			3. Measurement			4. Measurement			5. Measurement			6. Measurement		
Time	december		january			february			march			june			july	
Temperature (C)	18		18			15			21			24			26	
Relative Humidity (%)	41		37			37			40			43			43	
Compound name	Indoor	1. Living room	2. Room	3. Attic	1. Living room	2. Room	3. Attic	1. Living room	2. Room	3.Attic	1. Living room	2. Room	3. Attic	1. Living room	2. Room	3.Attic
Formaldehid	34	11	4	10	130	10	23	32	21	49	41	35	51	32	24	40
Benzene	3,11	2,79	2	2,16	0,08	0,08	0,08	0,08	1,66	0,01	1,71	1,8	2,35	0,08	1,65	0,08
Toluene	11,6	4,92	4,78	5,09	5,16	4,74	6,13	4,97	6,85	19,7	34,4	37,1	38,4	4,86	3,36	6,21
Ethyl benzene	4,8	1,96	1,81	1,86	1,66	1,27	1,46	4,14	4,38	33	102	61,6	66,5	6,64	5,09	3,22
1,3-Xilol, 1,4-Xilol	20,8	8,59	7,57	8,23	6,72	5,36	5,31	11,6	12,5	104	76,8	90,5	96,8	7,09	5,14	4,19
Styrene	3,06	0,96	1,2	1,32	0,08	0,08	0,08	3,52	4,98	0,08	134	147	127	7,93	6,27	4,29
3-Carene	300	133	97,3	109	85,8	64,4	233	300	244	274	2120	468	1500	232	157	171
alpha-pinene	297	170	122	157	162	119	300	300	300	300	1130	1520	2710	284	211	217
beta-Pinene (b)	30	15,2	11,8	15,3	16,9	9,33	33,1	55,9	52,9	47,8	157	145	187	34,9	23,7	28,4
Naphtalene	0,08	0,08	0,08	0,08	0,08	0,08	0,08	1,13	1,06	1,81	0,08	1,15	1,04	0,08	0,08	0,08
Limonene	64,7	21	16,1	17,5	15,8	10,7	23	59,7	51,9	46,3	178	118	289	30,2	21,9	25,1
Hexanal	48,9	23,8	19	21,3	16,4	9,88	20,7	79	57,8	65,9	199	218	244	57,1	42	66,9
Benzaldehyde	7,27	0,01	3,87	0,01	3,37	1,67	5,35	9,87	10,4	16,8	39,6	39,8	51,8	11,7	10,1	9,18
Acetic acid	10,4	17,6	26,9	26,9	138	8,29	22,6	0,01	0,08	0,08	65,5	41,3	141	34,9	23,2	83,4

After the construction of the building was completed, the first measurement was taken before the heating was started. At this stage the inside doors had not been installed yet. The measurement was taken in the living room. Most of the measured values stayed well below 50 μg/m^3, except for the values of limonene (64.7 μg/m^3), hexanal (48.9 μg/m^3), alpha-pinene (297 μg/m^3) and 3-carene (300 μg/m3), which differ substantially from the other values.
After the first measurementt the air-heating was turned on, this might be the reason of the decreasing values. In the living room, there were human activities just before the 3. measurement, which may have caused the increased concentrations despite of the drop in temperature. Before the 4th measurement the floor-heating was turned on, the indoor temperature lifted to 21°C. This must have caused the increased concentrations. This assumption of ours seems to be confirmed by study ofYoung [32].
During June, the indoor temperature was raised above 24°C which indicated the significant change in the concentrations. In this period were the rooms furnished, which could have affected the increasing values as well. Probably the frequent natural ventilation indicated the lowering of high VOCs concentrations. By summing the measured concentrations of VOCs, we get the total VOC values (TVOC). The TVOC value of the first measurements was 2150 μg/m^3, the last was 1190 μg/m^3. The maximum value (9480 μg/m^3) was measured at sampling 5. The graph (Fig.1) clearly shows that

TVOC concentrations were influenced by indoor temperature, indoor relative humidity, and air exchange rate. Human activities and the furniture had the greatest impacts on the concentrations (Figure.1).

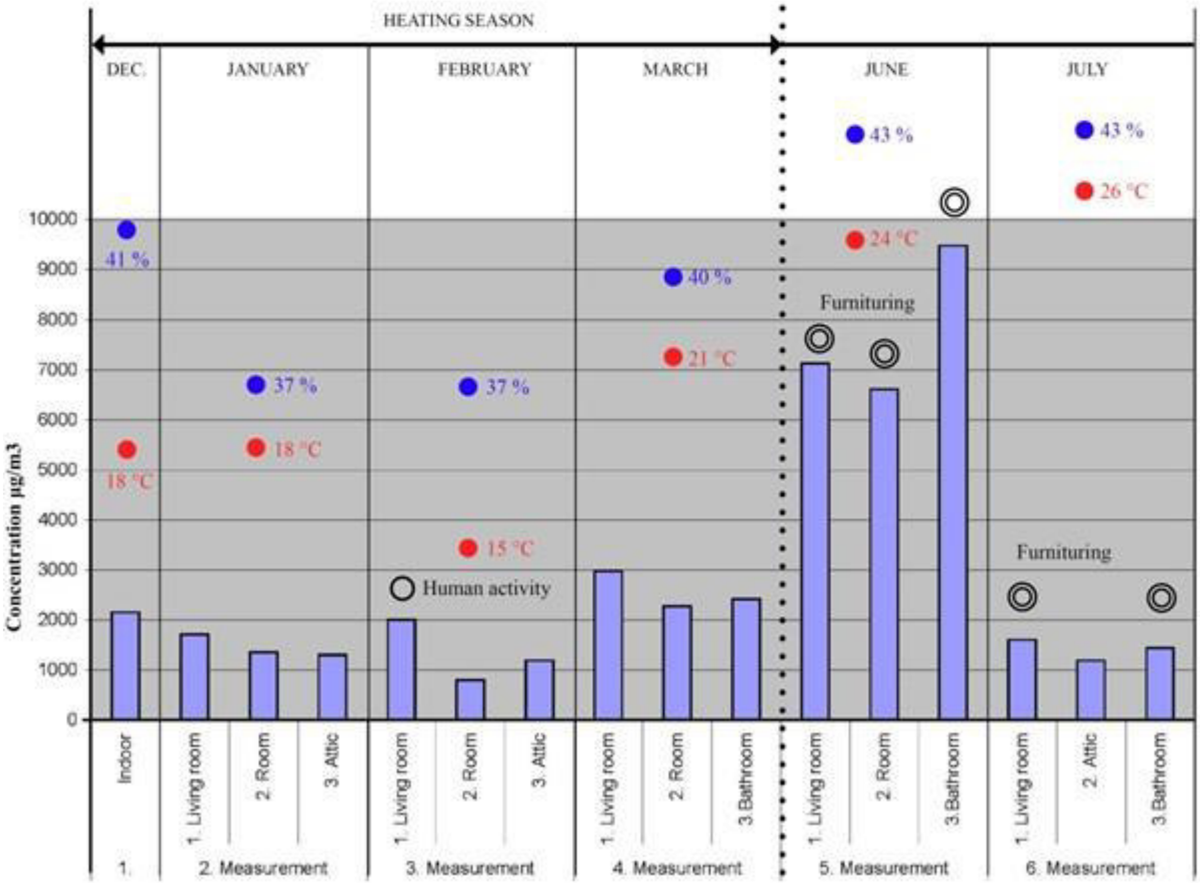

Figure 1. TVOC values of the measurements
The red dots show the indoor temperature, the blue dots show the indoor relative humidity, the circle shows human activity and the double circles show additional furniture

Some of the measured maximal concentrations were compared with the current Hungarian and international regulations (WHO) of air pollutants (Table 3)

Table 3. Comparison of the measured maximal values with the current Hungarian and international regulations (WHO) of air

Measurements (µg/m3)	1.	2.	3.	4.	5.	6.	Hungarian Regulations (MSZ) (µg/m3)	WHO (µg/m^3)
Benzene	3,11	2,79	0	1,66	2,35	1,65	3000	0,17 - 17
Toluene	11,6	5,09	6,13	19,07	38,4	4,86	190000	26
Styrene	3,06	1,32	0	4,98	147	7,93	50000	26
Formaldehyde	34	11	130	49	51	40	600	100
Naphtalene	0	0	0	1,81	1,15	0	5000	10

The maximum concentration of benzene was 3.11 µg/m^3, in the other measurements this value was decreased. The maximum value was not deviant from the values of the current Hungarian and

international regulations of air pollutants. The WHO did not recommend any safe level for benzene, it determines only the concentrations of airborne benzene associated with an excess lifetime risk of 1/10 000, 1/100 000 and 1/1000 000 are 17, 1.7 and 0.17 µg/m3.
The concentration of toluene was between 5.09 – 38.4 µg/m3. The increase was affected probably by indoor temperature, indoor relative humidity, human activity and the presence of furniture in the room. The highest concentration (38,4 µg/m3) exceeded the maximal value given by WHO (26 µg/m3). From the measured concentrations of styrene, it can be stated that the difference was significant only in the 5th measurement. The drastic increase is not related to the change in indoor air temperature and relative humidity (since these parameters also changed between measurements 3 and 4), but to the furnishing of the rooms. The concentration of formaldehyde with the value of 130 µg/m3 did overpass the values of the current international regulations by the WHO (100 µg/m3) during the third measurement, but it was just temporary. The main sources were the wooden materials cut into pieces in the living room. By the following measurements the concentration of formaldehyde was slightly increased because of the rise of the indoor temperature. The rate of the wooden clothing in each room presumably had an influence on the concentrations of alpha-pinene and 3-carene. Alpha-pinene and 3-carene are two natural substances that are not considered toxic. Their source is dried wood from which they are emitted in demonstrably high concentrations. Also, in soft trees (e.g. spruce), the concentration of natural evaporation of alpha-pinene and 3-caren is also observed to be high, which also depends on the age of the tree and the time of felling [46]. Based on these, it can be concludedthat there is a correlation between the proportion of spruce wood coverings in the rooms and the concentration of materials. Table 4 shows the wood cladding ratio of each room.

Table 4. The load of wooden building materials in the rooms

Ratio of wood in the rooms	(%)
Room	28
Living room	51
Bath	70
Attic	100

Figure (2) shows the influence of indoor temperature, indoor relative humidity, and the presence of furniture in the rooms on the concentrations of alpha-pinene and 3-carene.

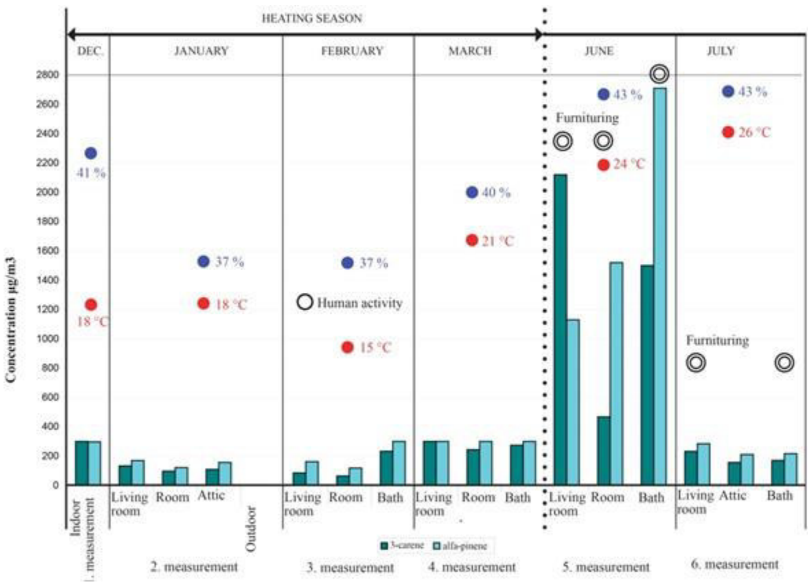

Figure 2. 3-carene and alpha-pinene values of the measurements. The red dots show the indoor temperatures, the blue dots show the indoor relative humidity, the circle shows human activity and the double circles show additional furniture.

Finally, we determined the health risk of all measured substances according to the German standard using the Lowest Concentration of Interest (LCI) analysis. German law stipulates that VOC emissions from building materials must be reduced in the long term so that they do not endanger the health of those in the building.
The working group of the German Building Materials Health Assessment Committee (Ausschuss zur gesundheitlichen Bewertung von Bauprodukten - AgBB) has established a list of VOC substances that determine indoor air quality and has also set a concentration limit for VOC substances that affect air quality[6]. The degree of health risk is expressed as a ratio, the value of the measured concentration divided by the limit value according to AgBB. If this ratio is less than one, the test substance does not pose a health risk. If the ratio is greater than one, the value of the health risk posed by the substance is proportional to the value of the ratio (AgBB, 2012).
We performed this test on all measurement results. The LCI table of the measurements contains the VOC substances we measured, their list number (CAS), the given LCI limit of the concentration, the measured concentration and their quotient. Table 5 contains the LCI values for those substances which measured values were the highest. We found that the quotient of the most component (measured value/LCI value) is not greater than 1, so they do not pose a health risk.
The quotient of 3-carene, alpha-pinene (measured value/LCI value) was greater than 1 in only the 5th measurement, so they represent a health risk in this measurement. However, as these high values were significantly reduced at the next measurement, it can be concluded that they do not pose a health risk in the long run.

Table 5. The LCI table of the measurements

Name of component	CAS	LCI [μg/m^3]	Measured highest concentration [μg/m3]	Measured highest concentration / LCI
Benzene (VOC)	71-43-2	5	3,11	0,62
Toluene (VOC) 1	108-88-3	1900	38,40	0,02
Etilbenzene	100-41-4	4400	66,50	0,02
1.3-Xylene and 1.4-Xylene (VOC) 1	106-42-3; 108-38-3	2200	96,80	0,04
Styrene	100-42-5	860	147,00	0,17
3-Carene	498-15-7	1500	2120,00	1,41
alpha-pinene	80-56-8	1500	2710,00	1,81
beta-Pinene (b)	127-91-3	1500	187,00	0,12
Naphtalene	91-20-3	10	1,15	0,12
Limonene	5898-27-5	1500	289,00	0,19
Hexanal	66-25-1	890	244,00	0,27
Benzaldehyde	100-52-7	90	51,8	0,58
Acetic acid	64-19-7	500	141,00	0,28

CONCLUSIONS AND RECOMMENDATIONS

The conclusion is that the wooden materials applied in the house are low-emitting materials and do not pose a health risk for people. The observations showed that the main influencing factors of indoor air quality were the changes in indoor temperature, relative humidity, air exchange rate, and human activities. This conclusion is correlating with other case studies [39-43]. The measurements of indoor air quality are providing the designers and the building occupants with essential information about the state of the building and the health impacts. They can be used in many type of the architectural procedures, e.g. in building diagnostics for renovations, in measuring the health impacts of a newly built house, and in finding the main sources of adverse chemicals of buildings with "sick building syndrome". For a detailed analysis of other building materials a further research work is needed.

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