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Indoor Air Quality in Multi-Apartment Buildings before and after Renovation

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Abstract **– The article summarizes the IAQ parameters of multi-apartment buildings before and after renovation in Latvia. In a building with natural ventilation system air exchange is significantly dependent on the position of the apartment within the building. If CO_2 as an indicator of indoor air quality is analyzed, the results show that inhabitants' behavior has a considerable impact on IAQ. The planning of adequate investment in buildings to improve energy efficiency and choosing the modern, adequate and effective engineering solutions, it is possible to raise the comfort level of living space and to reduce heat and thermal energy consumption.**

Keywords **– CO_2 concentration, indoor air quality, renovation, ventilation.**

I. Introduction

Indoor air quality (IAQ) has a significant influence on human life and work quality, health, and productivity. Directive 2010/31/EU of the European Parliament and of the European Council of 19 May, 2010 on the energy performance of buildings continues to develop the energy efficiency requirements of the buildings, at the same time preventing the increase of energy efficiency at the expense of the quality of the indoor climate. Local national legislations are defining the minimum requirements of IAQ and energy efficiency parameters for the newly erected and renovated buildings. Latvian experience shows that the observance of building energy performance requirements is relatively easy to control, and these requirements are understandable by most inhabitants. On the other hand, IAQ requirements can be interpreted in a broad range of operating conditions. The IAQ fluctuations or IAQ indicators being outside of the acceptable range during the use of the living space and long-term influence on the human health is relatively difficult to assess and to understand for a typical inhabitant.

The research presented in this paper was carried out in the frameworks of Baltic Sea Transnational Cooperation Programme 2007-2013, within the project "Energy Efficient and Integrated Urban Planning (UrbEnergy)", which involved development of an internet portal for on-line monitoring of indoor climate and consumption parameters of renovated and not renovated buildings in Latvia (project identification No. SIA RPB 2009/6, līguma No. 5-5.3/2010-13).

The project objective was to identify the microclimate problems in residential buildings before and after renovation, develop recommendations for residential indoor climate and energy efficiency, to test the practical effect of upgrades aimed at indoor air quality improvement, to draw public attention to residential indoor climate problems, to promote civil education and the progress of high-quality renovation of residential buildings.

II. Methods and Materials

A. Project Buildings and Apartments

For the project, 5 MABs in Riga were selected, in two types of standard residential buildings. Three of the buildings were of the so-called project type 464 (5 floors, 3 staircases, 45 apartments in each building), and two were of the so-called project type 602 (9 floors, 2 staircases, 72 apartments in each building). Because the ownership of MAB apartments in Latvia is typically individual (each apartment has a separate owner), measurements in all the selected apartments had to be agreed with the apartment owners. Because such agreement was not reached in some cases, the planned microclimate monitoring was not realised in three apartments in one of the non-renovated 464-series building, but identical apartments were used in two nearby buildings. In addition, the total number of planned measurements (98 measurement points in 12 apartments) was not achieved because of various technical problems (for example, sealed exhaust ducts) and human factors. As a result, not all monitoring data were fully secured from all measurement points, and in some cases the missing data had been imputed by using indicators from the corresponding measurement point in another, equivalent building within the project. In such cases, the methodology of calculations is explained in the notes to the corresponding results table.

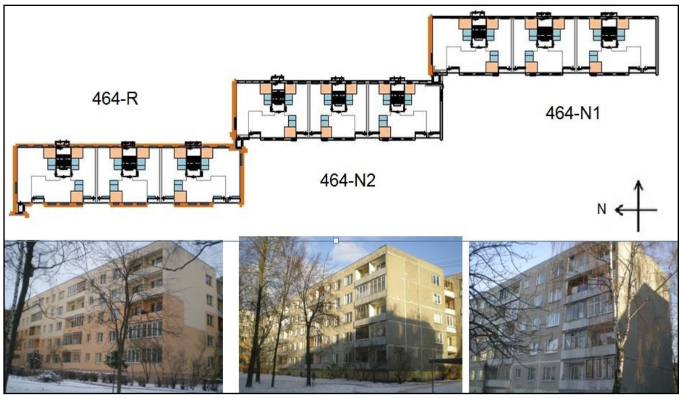

Fig. 1. 464. series MAB photo and schematic location (renovated: 464-R; not renovated: 464-N1 and 464-N2).

Standard 464-series MAB description [5]: construction year starting from 1961, five (5) floors, sectional type (with a staircase in the middle of each section), with basements and technical space on the attic level, with loggias or balconies; outer wall: 300 mm thick lightweight concrete panels, on outer corners of the balcony and stair area up to 420 mm thick lightweight concrete panels; windows and balcony doors: double glazing in wooden frames.

Renovation upgrades of the 464-series building in year 2008 included [3]: attic insulation with ecowool (200 mm); facade insulation with rock wool (100 mm); basement insulation with extruded foam (100 mm), common areas window and door replacement to double-glazed windows in PVC frames, installation of thermostats and heat meters (allocators) on each radiator.

The two unrenovated MABs 464-N1 and 464-N2 had the North oriented end-walls insulated, correspondingly in years 2007 and 2005. The schematic layout and photo (S end-wall, W facade with loggias) of the renovated 464-series building (464-R) and the two non-renovated buildings (464-N1 and 464-N2) are depicted in Fig. 1.

Standard 602-series MAB description [5]: construction year starting from 1967, 6 to 9 floors, sectional type (with a staircase in the middle of each section), with basements and technical space on the attic level, with loggias; external walls: 200 mm (facade walls) and 330 mm (end-wall) lightweight concrete panels; windows and loggia doors with double glazing in wooden frames.

Fig. 2. 602.series MAB photo and schematic location (renovated: 602-R; not renovated: 602-N).

Renovation upgrades of the 602-series MAB in year 2001 included [7]: window replacement to double-glazed windows in PVC frames, insulation of walls with 80 mm mineral wool, basement ceiling with 60 mm mineral wool, covering the top floor with a 140 mm mineral wool boards, changing the heating system from a one pipe to a two-pipe heating system, providing individual heat consumption control (thermostats) and accounting (allocators) facilities in each room, upgrading of heating sub-station, insulation of the heating distribution pipes, staircase repairs.

The schematic layout and photo of the renovated 602-series (602-R) and non-renovated (602-N) MAB (NW front with the entrance in staircase, SE facade with loggias) are depicted in Fig. 2.

Apartments for IAQ parameter measurements were chosen, taking into account their location within the building. Individual upgrades in the apartments are as follows:

- 464-R/middle (3) floor – extractor fan in the kitchen and in the combined sanitary facility;
- 464-R/top (5) floor – extractor hood in the kitchen, glassed loggia, combined sanitary facility;
- 464-N2/first (1) floor – recirculating hood in the kitchen;
- 464-N2/middle (4) floor – double-glazed windows in PVC frames, glassed loggia;
- 464-N1/top (5) floor – S end-wall insulated from inside (2004), new radiators (2009), extractor fan in the kitchen and in the combined sanitary facility;
- 602-R/top (9) floor and 602-N/top (9) floor – no data.

The IAQ parameters were measured in 3 apartments (on the first, middle and top floor) of two non-renovated type-464 buildings (464-N1 and 464-N2) and in 3 apartments (on the first, middle and top floor) of one renovated type-464 building (464-R), and in 2 apartments (on the top floor) of one renovated (602-R) and one non-renovated (602-N) type-602 buildings.

B. Measuring Equipment and Measurements

For indoor air parameter measurements, a complex measuring equipment was used, which was set up in coordination with the apartment's owner, in the owner's bedroom (about 1 m above the floor – the working area) or in the kitchen area (about 1 m to 1.8 m above the floor). Equipment measurement accuracy (at 25 °C) is the following: for temperature ± 0.5 °C, for relative humidity ± 3 % of reading value; for CO_2 concentration to ± 40 ppm + 3 % of reading value.

For indoor corner temperature measurements, a sensor with an accuracy of ± 0.3 K (at 25 °C) was used. For measurements of exhaust ventilation ducts of the kitchen and lavatory, measuring equipment with an accuracy of air flow rate < 0.5 m/s ± 7 % of reading value (at 25 °C); temperature < 0.5 °C (at 25 °C, > 0.5 m/s) was used.

Outdoor air temperature and relative humidity were measured approximately 1 m above the ground with an accuracy (at 25 °C) of ± 0.3 K, relative humidity ± 3 % of reading value (at 30 % ... 70 % r.m.), ± 5 % of reading value (at 10 % ... 30 % r.m. and 70 % ... 90 % r.m.), ± 10 % of reading value (at 5 % ... 10 % r.m. and 90 % ... 95 % r.m.).

The planned reading period was 1 minute. If a reading was not made due to the technical reasons, the point value in the chart did not appear for the respective period. If the reading was performed, but the measuring equipment „has not provided an answer", the value was recorded outside of the measuring range, allowing it to be ignored during the data processing (details on data collection – see Section 2.3). At the present time, the total number of simultaneously measured parameters is 55. In each of 8 project apartments air temperature, relative humidity and CO_2 concentration level in bedroom or kitchen (Table I) are measured; in 7 project apartments air temperature and air flow velocity in two exhaust ventilation ducts are measured; in 1 project apartment air temperature at the exterior corner is measured; outdoor air temperature, and relative humidity are measured.

C. Data Extraction and Processing

The following equipment has been used in the course of data collection [1]:

- controller – provides instantaneous measurements of temperature, relative humidity, carbon dioxide concentration and air flow rate of the object and object points;
- server (hardware and software) for data acquisition and processing – set up as a real physical IBM PC-type device which operates based on the Linux type environment, the server regularly communicates with the existing controllers, surveying the current (instantaneous) data values (data collected at 1 min intervals);

There are regular communication sessions taking place between the server and the controllers, during which data are obtained from the controllers and transferred to the data processing module. Physical or transport-level disturbances are recorded in files.

Program modules ensure the data analysis by performing the following functions:

- separate the controller data from possible interference, which does not include physical or transport-level disturbance categories;
- make the data format adjustment and rounding of data values: temperature – accuracy of 0.1 °C, relative humidity – accuracy of 1 %, CO_2 concentration – 0.001 %, air flow rate – 0.1 m/s.

D. Calculation of Air Exchange

In accordance with the law [4], the normative exchange of air L_{norm} in an apartment is calculated as:

- minimally secured air vent from the apartment, the sum of all the facilities required airflows: at least 50 m^3/h from a combined sanitary facility, at least 25 m^3/h from toilet facilities, at least 25 m^3/h from a bathroom, at least 60 m^3/h to 90 m^3/h from a kitchen (from a kitchen with an electric oven or with a 2-ring gas stove – minimum of 60 m^3/h, from a kitchen with 3-ring gas stove – minimum of 75 m^3/h, from a kitchen with 4-ring gas cooker – at least 90 m^3/h);
- minimum air supply to be provided in the apartment, the sum of all the facilities required airflows: at least 3 m^3/m^2 per hour flow to the living areas and bedrooms.

In this study, the IAQ measurements and calculations have been made in apartments with more than one living room or bedroom, so the exhaust airflow is assumed to be at least 90 m^3/h from the cooking area; the actual data about the type of cooking stove was not collected. Bedroom and living room areas have been assumed to be average, according to the standard project plans; in all building types the apartment ceiling height is assumed to be 2.5 m, whereas the actual measurement or comparison with data from the inventory file has not been done. In the calculations, the air exchange in the apartment is assumed to be the largest amount obtained by comparing the required exhaust and supply air quantity for an apartment.

Air exchange L_{mes}, in accordance with the measurements of airflow speed in the exhaust ventilation channels from kitchen and toilet facilities, has been calculated in the following way (3):

$$L_s = s \cdot 0.9 \cdot v \cdot 3600 \quad (3)$$

where L_s – airflow through the exhaust ventilation channel, m^3/h;
s – area of the exhaust ventilation channel, in all calculations assumed equal to $0.10 \cdot 0.15 = 0.015$ m^2;
0.9 – applied correction coefficient for the distribution of airflow speed within the cross-section of the ventilation channel;
v – measurement of the airflow speed, m/s;
3600 – coefficient for transition from seconds to hours.

III. Results and Analysis

Table I presents the location of complex measurement equipment in the apartments and minimum, maximum and average measured values of IAQ parameters in January, 2011.

The average outdoor air parameters in Riga, January, 2011 were: temperature −1.38 °C, relative humidity 84.45 %.

TABLE I

LOCATION OF THE COMPLEX MEASURING EQUIPMENT AND MEASURED IAQ VALUES (JANUARY, 2011)

MAB - apartment / floor	S_H, m^2	Location of complex measuring equipment	Average airflow speed in ventilation channel, m/s		Room temperature, °C (corner of the room)			Room relative humidity, %			Room CO_2 concentration, %		
			bathroom	kitchen	Min.	Max.	**Av.**	Min.	Max.	**Av.**	Min.	Max.	**Av.**
464-N2 /first	65.65	bedroom, S end-wall and W facade with loggia	0.821	0.682	22.71 (10.88)	25.60 (20.06)	**24.07 (18.29)**	14.16	29.89	**22.63**	0.036	0.133	**0.075**
464-R /first	65.01	kitchen, E facade	0.547	0.500	20.71	28.68	**22.46**	20.49	54.58	**27.32**	0.039	0.199	**0.062**
464-N2 /middle	48.13	bedroom, W facade with glassed loggia	0.399	0.763	16.24	23.05	**20.70**	19.39	55.36	**28.41**	0.039	0.199	**0.083**
464-R /middle	38.44	kitchen, W facade	0.297	0.635	18.41	25.92	**20.57**	20.22	81.56	**44.82**	0.034	0.199	**0.107**

464-N1 /top	64.59	bedroom, S end-wall and W facade with loggia	0.322	0.376	21.22	27.37	**23.42**	22.81	6847	**43.87**	0.031	0.199	**0.122**
464-R /top	67.90	bedroom, N end-wall and W facade with glassed loggia	0.368	0.083	16.59	21.72	**18.21**	39.68	78.95	**59.16**	0.031	0.199	**0.121**
602-N /top	~60.90	no data	0.945	0.721	16.65	25.04	**20.36**	18.45	75.60	**43.94**	0.034	0.199	**0.124**
602-R /top	60.90	no data	no data	no data	21.56	24.57	**23.10**	23.71	66.42	**49.30**	0.031	0.199	**0.110**

To reach the normative level of air exchange L_{norm} in apartments with the defined exhaust ventilation channel parameters (see Section 2.5) and to provide airflow exchange of L_{norm} = 140 m^3/h in apartments (with 2 exhaust ventilation channels) of type 464 MAB, the necessary airflow speed is 1.44 m/s. In apartments (with 3 exhaust ventilation channels) of type 602 MAB for L_{norm} = 165 m^3/h, the necessary airflow speed is 1.13 m/s. Typical results of measures show that air velocity in exhaust ventilation channels does not exceed 1 m/s, and the ventilation problems increase in the upper floors and in the renovated MAB without organized supply ventilation.

Temperature measures in different apartments demonstrate the necessity to change the heat consumption in accordance with individual financial capabilities and comfort demands. Temperature difference between the corner and the middle of the room in a typical unrenovated MAB exceeds on average 5 °C.

The relative humidity level increases in the upper floors and in the renovated MAB without organized supply ventilation. Under specific outdoor climate conditions, excessively dry indoor air is a problem with good ventilation without humidifying.

CO_2 concentration level increases in the upper floors and in the renovated MAB without organized supply ventilation. Problems are most often created by blocked exhaust ventilation channels. CO_2 concentration level in apartments is mostly dependent on habits of the inhabitants. Figs. 3–10 present IAQ fluctuation changes based on the results of CO_2 concentration measures in apartments in January, 2011. The period of measures (data) is displayed on the *x*-axis, and the concentration of CO_2 (%) is displayed on the *y*-axis. The graphs were obtained by processing the data in R.

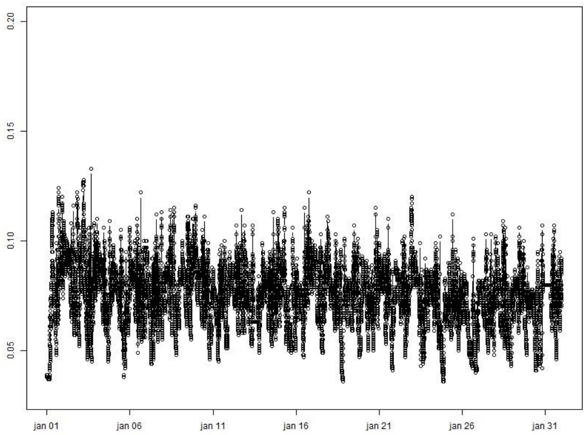

Fig. 3. Indoor air CO_2 concentration, 464-N2/first, January, 2011.

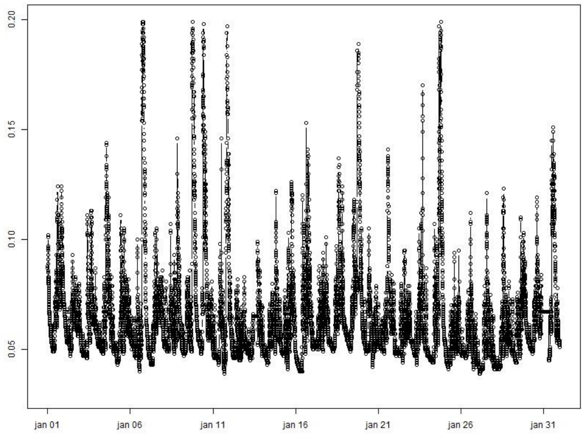

Fig. 4. Indoor air CO_2 concentration, 464-R/first, January, 2011.

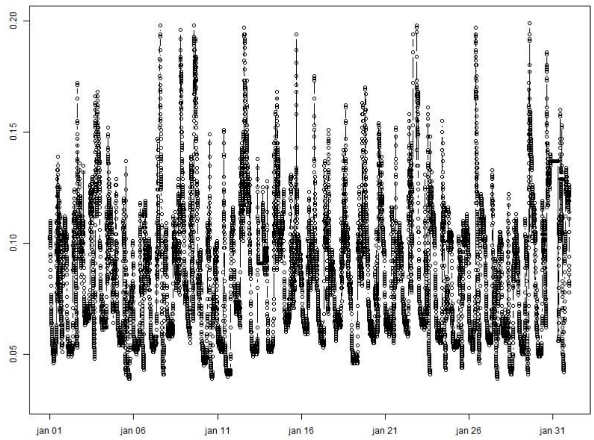

Fig. 5. Indoor air CO_2 concentration, 464-N2/middle, January, 2011.

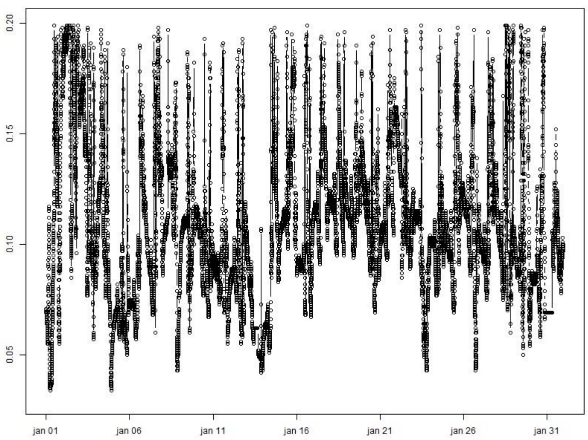

Fig. 6. Indoor air CO_2 concentration, 464-R/middle, January, 2011.

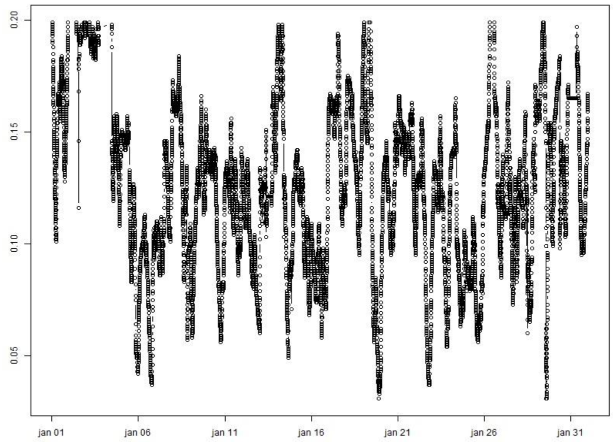

Fig. 7. Indoor air CO_2 concentration, 464-N1/top, January, 2011.

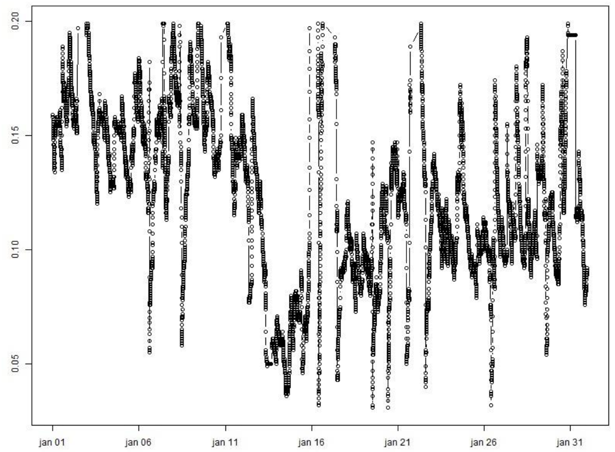

Fig. 8. Indoor air CO_2 concentration, 464-R/top, January, 2011.

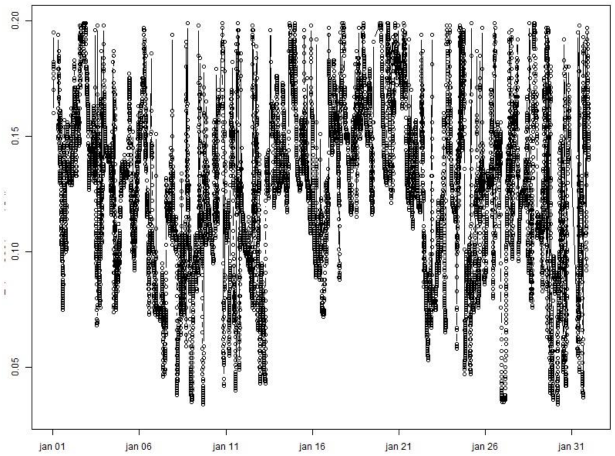

Fig. 9. Indoor air CO_2 concentration, 602-N/top, January, 2011.

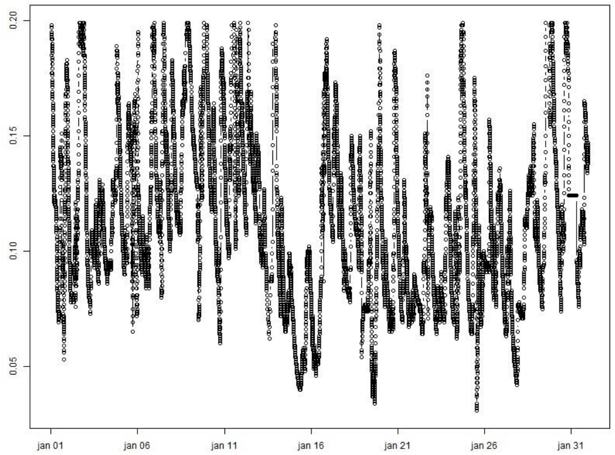

Fig. 10. Indoor air CO_2 concentration, 602-R/top, January, 2011.

IV. Discussion

Taking into account the regulatory requirements for ventilation in apartments in MABs and actually completed unrenovated building energy audit inspection data, which suggest an increased omitted air infiltration through gaps [11], it can be predicted that CO_2 concentration level in the existing building indoor air should be according to the recommended standards – up to 1000 ppm [12], [13]. However, inspection and measurement data show that increased air infiltration in local building construction defect places (along the window frames, panel seams) does not enhance the effective natural ventilation of apartments [14]. As a result of increased heat losses in buildings, indoor climate does not provide healthy and comfortable conditions for humans as determined by the standards.

Other studies of renovated multi-apartment buildings with natural ventilation and ventilation calculations and measures to confirm microclimate maintenance problems identify similar problems and attest concentration of CO_2 as an effective air quality control tool [15], [16].

Similar problems are presented in studies of IAQ in kindergartens in buildings with natural ventilation before and after partial renovation without improvements of the existing ventilation system [17], [18].

Not complex renovation projects and some improvement in apartments, for example, household exhaust fan installation in apartments and adding it to the natural exhaust ventilation ducts, as well as the replacement of double glazing windows in wooden frames with the uncontrolled quality double-glazed windows in PVC frames may cause inadequate ventilation in apartments and indoor climate deterioration both in the housing and the building as a whole.

The main influence on the operational capability of the existing functional ventilation systems of renovated and unrenovated MABs and, correspondingly, on the IAQ, is the behavior of the inhabitants.

V. Conclusion

Results of IAQ measurements confirmed the presence of ventilation problems and a reduced level of healthy indoor climate.

Typical solution for MAB ventilation - natural exhaust channels from the toilet facilities and kitchen premises, and not organized outdoor air infiltration through the leakages in the building envelope, etc., does not provide the maintenance of weather independent, suitable for human comfort microclimate in MAB before and after renovation.

To improve the microclimate in the MABs, ventilation system must be updated in all apartments in the renovated and unrenovated buildings.

Planning of adequate investment in buildings to improve energy efficiency and choosing modern, adequate and effective engineering solutions, it is possible to raise the comfort level of the living space and to reduce heat and thermal energy consumption.

It is important to note that engineering solutions without a proper training of residents on the engineering systems use may not provide the desired performance due to human behavior.

VI. Author note

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The described study was presented at the:

- International scientific conference „Civil Engineering'11" (Jelgava, Latvia, May 12 – 13, 2011) with the corresponding paper published in the conference proceedings [19];
- 12th International Conference on Air Distribution in Rooms „Roomvent 2011" (Trondheim, Norway, June 19 – 22, 2011) with the corresponding paper published in the conference proceedings [20];
- 52th International Scientific Conference of Riga Technical University (Riga, Latvia, October 13 – 15, 2011);
- 3th World Congress of Latvian Scientists and 4th Lettonica Congress "Science, Society and National Identity" (Riga, Latvia, October 25, 2011).

The described data were published in the project report No. 5 (December 2011) and results were presented in the international project "Energy Efficient and Integrated Urban Planning (UrbEnergy)" closing conference "Energy Efficiency and Urban Future" (Riga, Latvia, December 2, 2011).

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