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Ing. Imrich Sánka

Dissertation Thesis Abstract

Indoor air quality in nearly zero energy buildings

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Submitter: Ing. Imrich Sánka
Slovak University of Technology in Bratislava
Faculty of Civil Engineering
Department of Building Services
Radlinkského 11, 810 05 Bratislava

Supervisor: prof. Ing. Dušan Petráš PhD.
Slovak University of Technology in Bratislava
Faculty of Civil Engineering
Department of Building Services
Radlinkského 11, 810 05 Bratislava

Readers: doc. Ing. Elena Piecková PhD. MPH
Slovak Medical University in Bratislava
Department of Microbiology
Limbová 12, 833 03 Bratislava 37

prof. Ing. Karel Kabele CSc.
Czech Technical University in Prague
Faculty of Civil Engineering
Department of Building Services
Thakurova 7, 166 29 Prague 6

doc. Ing. Michal Krajčík, PhD.
Slovak University of Technology in Bratislava
Faculty of Civil Engineering
Department of Building Services
Radlinkského 11, 810 05 Bratislava

Dissertation Thesis Abstract was sent...

Dissertation Thesis Defence will be held on .... at …........................ h

at the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava, Radlinského 11, 810 05 Bratislava.

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Prof. Ing. Stanislav Unčík, PhD.
Dean, Faculty of Civil Engineering,
Slovak University of Technology in Bratislava

1. Introduction

The European Commission in 2010 accepted Energy Performance of Buildings Directive (EPBD) and the 2012 Energy Efficiency Directive (EED) are the main energy conservation legislative instruments for to reduce the energy consumption of new built and renovated buildings in Europe. The national regulation based on EPBD states that after the year 2016 only so called ultra-low energy buildings can be built. The next tightening in energy saving came in 2021 (for commercial buildings after 2019), when only nearly zero energy buildings (NZEB) were allowed to build. It means that these buildings must fulfil A0 category requirements by energy labelling. But what about the indoor environmental quality in objects like this? This thesis shows results of indoor environmental quality measurement in NZEB buildings. Indoor air temperature, relative humidity, carbon dioxide concentration and air exchange rate had been measured. Except the indoor environmental quality evaluation one special optimized renovation model was developed for the single family houses built in the second half of the 20th century.

2. Aim of the thesis

The thesis can be divided to two main parts. The first part is evaluation a standardized single family house from building energy and renovation point of view.

The second part is deal with indoor environment quality evaluation is two nearly zero energy buildings – single family house with radiant heating and cooling system (Unterrabnitz, Austria), and single family house with warm air heating and cooling system (Bad-Tatzmansdorf, Austria).

For the first part (energy evaluation of renovation) aim was to analyze the energy consumption of a single family house after technical service life. This building can be standardized, because in the second part of the 20th century almost all the family houses had been built with the same design – floor plan, building material characteristics, height.

The thesis presents 4 energy variants for the renovation with several energy saving measures (called design variants) as from the thermal insulation, as the building services point of view: Standard, Comfort, De-luxe and the actual state of the renovation. These design variants are different in applied thicknesses and thermal insulation material, and of course the installed HVAC systems.

For the second part (indoor environmental evaluation) the aim was to evaluate the influence of state of the art environmental technology – heat pumps, mechanical ventilation system etc., installed to nearly zero energy buildings - to indoor environmental quality, which directly affects human well being and health.

3. Energy evaluation of a single-family house

The aim of this part of the dissertation was to compare and evaluate the energy and economic aspects of the reconstruction of a standard family house after technical life in three variants. Each variant is based on certain conditions, and different technology requirements have been considered in each variant. Finally, the efficiencies of individual variants were evaluated depending on the specified requirements.

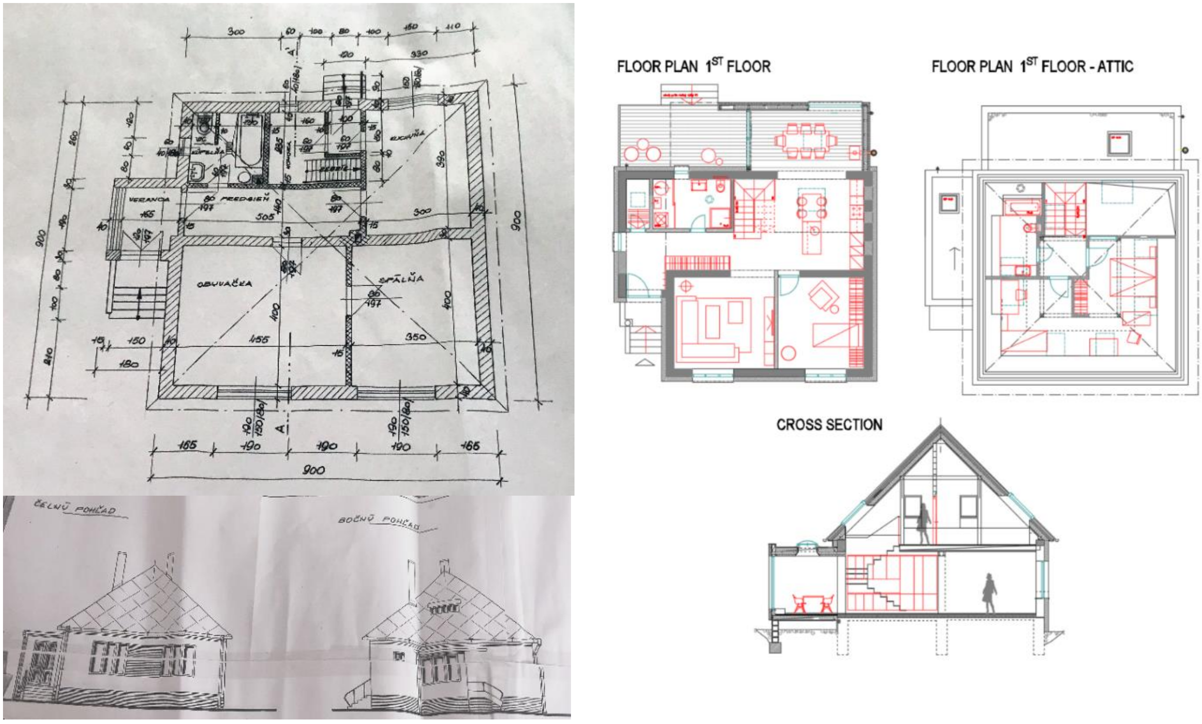


Fig. 1: Project documentation of the building for the former state (left) and for the renovation (right)

The family house is located in Šaľa. It is a family house, which was built between 1966 and 1970. Based on the agreed boundary conditions, an architectural competition was declared. After the elaboration of the project documentation (Arch. Doršic Drošicová), Three design variants of the energy saving measures had been created.

Standard variant

- Dimensioning of heat transfer coefficients based on STN 73 0540 - Z2 - to recommended values
- Heat source: gas fired condensing boiler, radiator heating, regulation based on internal temperature
- Domestic hot water preparation with 120L storage tank.
- Natural ventilation

Comfort variant

- Dimensioning of heat transfer coefficients based on STN 73 0540 - Z2 - to recommended values
- Heat source: gas fired condensing boiler, underfloor heating, equithermal regulation
- Domestic hot water preparation with 300L storage tank with combination of thermal solar system
- Natural ventilation

De-luxe variant

- Dimensioning of heat transfer coefficients based on STN 73 0540 - Z2 - to target recommended values
- Heat source air source heat pump, underfloor heating, equithermal regulation,
- Domestic hot water preparation with 300L storage tank with combination of thermal solar system
- Mechanical ventilation system with heat recovery

Variant current state of reconstruction

As with most buildings, there will be minimal changes during construction, but they cannot be neglected in the energy assessment. Therefore, a fourth category was created, which reflects the exact system, material and technical solution used compared to the planned solutions.

- Dimensioning of heat transfer coefficients based on STN 73 0540 - Z2 - to recommended and target recommended values
- Heat source: gas fired condensing boiler, radiator heating, regulation based on internal temperature
- Domestic hot water preparation with 120L storage tank.
- Natural ventilation in combination with the Velux intelligent ventilation system based

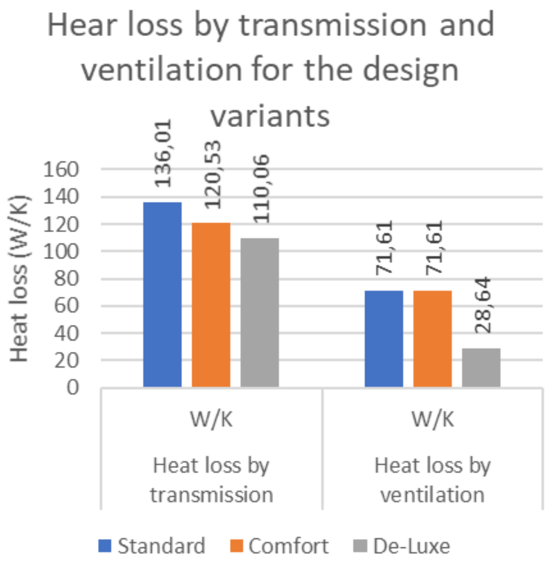
on the carbon dioxide concentration

The following results were found when evaluating the heat transfer coefficients "U":

Tab. 1: Heat transfer coefficient assessment for the single-family house: design variants

Variant	Building Structure	Heat transfer coefficient - calculated value Uc (W/m^2.K)	Heat transfer coefficient – standardized value Un (W/m^2.K)		Assesment
Standard	Exterior wall	0,213	0,22	Recommended values (valid after 2016)	**Complies**
	Exterior wall - extension	0,151	0,22		**Complies**
	Pitched roof	0,118	0,15		**Complies**
	Flat roof	0,116	0,15		**Complies**
	Transp. structures - windows	0,806	1,00		**Complies**
	Transp. structures - doors	0,863	1,00		**Complies**
Comfort	Exterior wall	0,213	0,22	Recommended values (valid after 2016)	**Complies**
	Exterior wall - extension	0,151	0,22		**Complies**
	Pitched roof	0,118	0,15		**Complies**
	Flat roof	0,116	0,15		**Complies**
	Transp. structures - windows	0,806	1,00		**Complies**
	Transp. structures - doors	0,863	1,00		**Complies**
De-luxe	Exterior wall	0,142	0,22	Target recommended values (valid after 2021)	**Complies**
	Exterior wall - extension	0,148	0,22		**Complies**
	Pitched roof	0,094	0,15		**Complies**
	Flat roof	0,093	0,15		**Complies**
	Transp. structures - windows	0,806	0,85		**Complies**
	Transp. structures - doors	0,863	0,85		**Poor**
Actual state of renovation	Exterior wall	0,114	0,22	Recommended values (valid after 2016)	**Complies**
	Pitched roof	0,100	0,15		**Complies**
	Flat roof	0,100	0,15		**Complies**
	Transp. structures - windows	0,800	1,00		**Complies**
	Transp. structures - doors	0,863	1,00		**Complies**

The following figures are presenting the heat losses by transmission and ventilation (left) and the heat gains in the heating season (right) based on the heat demand calculation. The table shows a comparison of energy demand for heating, energy demand for hot water preparation, total energy demand, total primary energy and CO_2 emissions in individual variants.



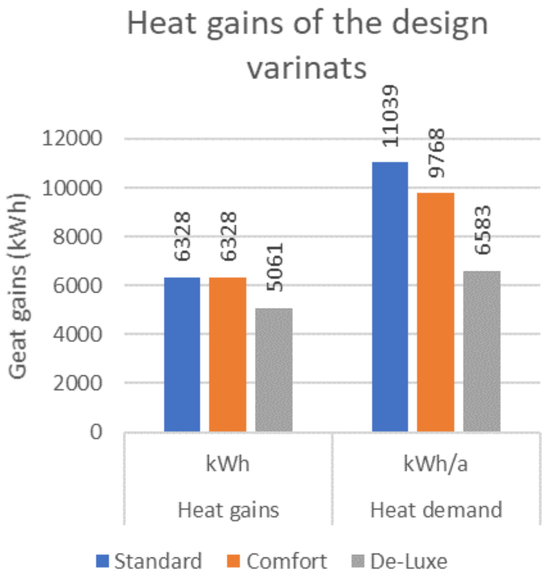


Fig. 2: Heat loss of the design variants (left), heat gains of the design variants (right) according to heat standardised demand calculation

Tab. 2: Design calculated values and classification to energy class for the variants

	Energy demand on heating	Energy demand on hot water preparation	Energy demand on mechanical ventilation and cooling	Total energy demand	Primary energy demand	CO_2 emissions
Units	kWh/(m².a)	kWh/(m².a)	kWh/(m².a)	kWh/(m².a)	kWh/(m².a)	kg/(m².a)
Original sate	353,0	34,0	0	387,0	425,7	117,92
	G (>258)	C (25-36)	Not evaluated	G (>258)	D (325-432)	-
Standard	63,9	28,1	0	92,0	101,2	28,03
	B (43-86)	C (25-36)	Not evaluated	B (55-110)	A1 (55-108)	-
Comfort	53,7	15,4	0	69,1	76,01	21,05
	B (43-86)	B (13-24)	Not evaluated	B (55-110)	A1 (55-108)	-
De-luxe	40,8	12,2	0,05	53	33,17	6,37
	A (<42)	A (<13)	Not evaluated	A (<54)	A0 (<54)	-
Actual state of renovation	43,1	22,6	0	65,7	75,93	14,28
	B (<42)	B (<12)	Not evaluated	B (<54)	A1 (<54)	-

In addition to energy performance parameters, the financing of the application of energy saving measures was also evaluated. Input data for energy savings and required investments are presented in the table below. The evaluation takes into accont combined financing - partly own resources, partly bank loan / mortgage. The results will be presented in 2 levels:

- Evaluation of the payback period based on a standardized calculation (taking into account the external design temperature: 11°C - the city of Šaľa)
- Evaluation of the payback period based on the average temperature in the heating season for the city of Šala: + 3.8°C

Tab. 3: Financial parameters of design variants

Variants	Investment costs	Required mortgage amount	Monthly mortgage payment (30 r.)	Payback period	
				Standardised evaluation according to external design temperature	Evaluation according to average temperature in the heating season
	(€)	(€)	(€)	years	years
Standard	50000	35000	120	6	15
Comfort	75000	60000	200	6	17
De-luxe	120000	105000	350	8 (6)	24 (18)
Actual state of the renovation	80000	65000	215	6	17

The De-luxe variant is a solution using renewable energy sources, which had been designed on the basis of the strictest energy regulations so that it meets energy category A0 based on primary energy consumption and is classified the building as nearly zero energy demand (NZEB).

The HVAC systems such as heat source and mechanical ventilation systems have a huge impact on investment costs, which directly affect the payback period.

Given that the payback period based on the average temperature in the heating season is longer than the service life of the installed equipment, it is necessary for the state to support the installation of such equipment in no way.

After all conditions have been met, is possible to contact the competent authorities and apply to support renewable sources and NZEB buildings. By using the system of the Slovak Innovation and Energy Agency and the Ministry of Transport of Construction of the Slovak Republic, it is possible to reduce the return on measures by 25%.

In conclusion, energy efficiency is the use of less energy to provide the same service. Increasing energy efficiency not only enables individuals and organizations to reduce investment and operating costs, but can also reduce energy consumption, thereby reducing greenhouse gas emissions and helping to prevent climate change. Most countries still do not have any energy regulations in place. This work showed the possibility of obtaining a building with ultra-low energy consumption (Standard and Comfort variants) or a building with almost zero energy consumption (De-luxe variant) from a 50-year-old building, thanks to the use of modern thermal protection and modern environmental technology [68].

4. Indoor environment quality evaluation

This part of the thesis reflects on the energy requirements of nearly zero energy buildings, which affects the quality of the indoor environment.

Two NZEB buildings had been analyzed from indoor air quality and thermal comfort point of view. The first building with radiant heating and cooling system, the second one with war air heating and cooling.

4.1 Indoor environmental quality evaluation in a nearly zero energy building Unterrabnitz, Austria

The evaluated building was built in Unterrabnitz, Austria in 2015. It uses a ground source heat pump in combination with photovoltaic panels as a heat source. The air exchange is ensured by a forced ventilation system with heat recovery.

Three basic parameters of indoor environment and indoor air quality were measured in winter and summer season in several rooms:

- Indoor air temperature (°C)
- Relative humidity in the interior (%)
- Carbon dioxide concentration (ppm)

The measured quantities were evaluated on the basis of STN EN 16798-1: 2019 (EN 15 251) in 4 time zones. The full time measurements were divided into another 3 time zones (work time, free time, night time).

The measuring equipment was installed into four rooms:

- Vestibule (winter season) / children's room (summer season),
- Workroom,

- Hall,
- Bedroom.

Selected results of the evaluation of the indoor environment for the Unterrabnitz family house are presented below.

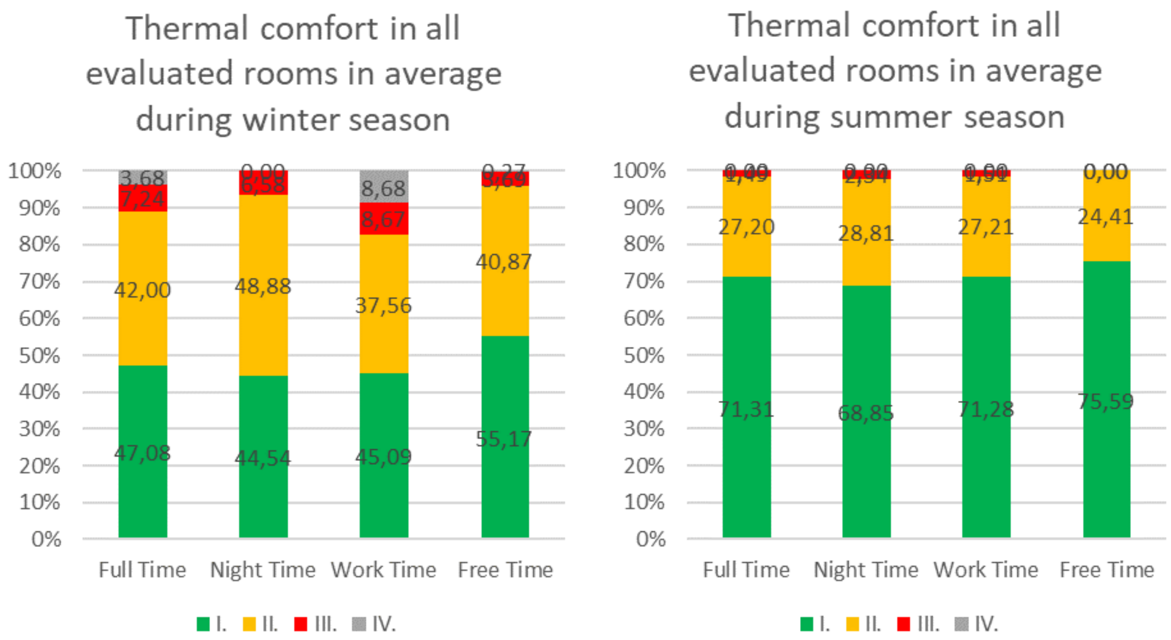


Fig. 3: Categorized data from thermal comfort measurements for winter (left) and summer (right) seasons for the whole single-family house

Tab. 4: Tabled results for thermal comfort evaluation for the whole single-family house in average – percentage of the spent time in the category

Single-family house Unterrabnitz	THERMAL COMFORT - WINTER SEASON (%)				THERMAL COMFORT - SUMMER SEASON (%)			
	I.	II.	III.	IV.	I.	II.	III.	IV.
Full Time	47,08	42,00	7,24	3,68	71,31	27,20	1,49	0,00
Night Time	44,54	48,88	6,58	0,00	68,85	28,81	2,34	0,00
Work Time	45,09	37,56	8,67	8,68	71,28	27,21	1,51	0,00
Free Time	55,17	40,87	3,69	0,27	75,59	24,41	0,00	0,00

Thermal comfort in the evaluated rooms in full time measurements ranged mainly between categories I. and II. Higher values during the day were measured in the living room, which are shown in the figure below. High temperature was measured almost every afternoon due to a lit fireplace. This fluctuation also had an impact on the categorization. 20,27 + 7,48% of the time was spent by residents in categories IV. and III. during worktime.

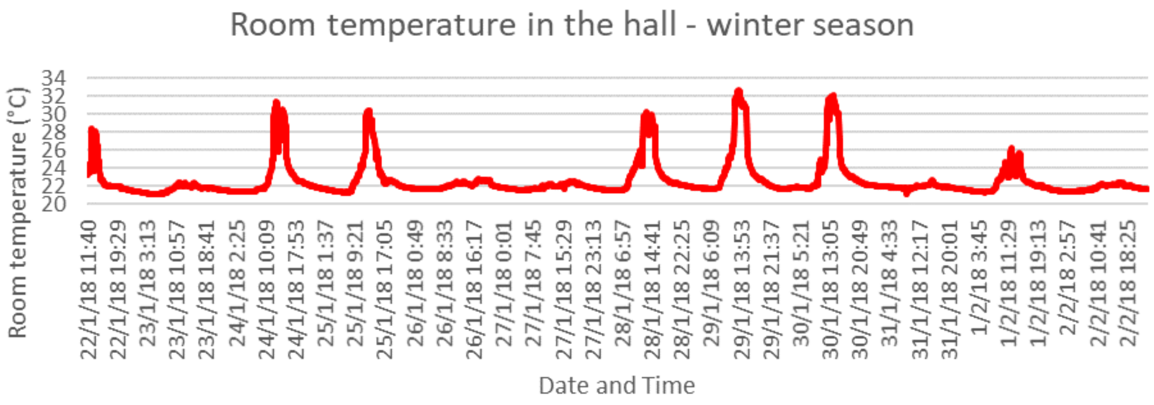


Fig. 4: Room temperature in the hall for winter season

Average distribution of categories for thermal comfort (for the full time measurements): 47,08% in category I., 42,0% in category II., 7,24% in category III. and 3,68% in category VI. The average temperature was 21,5°C.

Tab. 5: Summarization of statistical data from thermal comfort measurements

Single-family house Unterrabnitz	Winter measurements		Summer measurements	
	Temperature (°C)	Relative humidity (%)	Temperature (°C)	Relative humidity (%)
AVERAGE	21,5	41,4	21,6	68,1
MIN	19,3	27,5	19,8	54,1
MAX	32,6	50,9	23,7	75,2

The average temperature in winter was 21,5 ° C and the average relative humidity during the measurements was 41,4%. The lowest measured value was 19,3°C and 27,5%, while the highest recorded data were 32,6°C (fireplace) and 50,9% relative humidity.

In summer, the average relative humidity was 68.1%, while the average room temperature was 21,6°C. The highest measured value of the indoor air temperature was 23,7°C, while the lowest was 19,8°C. The highest value of relative humidity was 75,2% and the lowest recorded value was 54,1%.

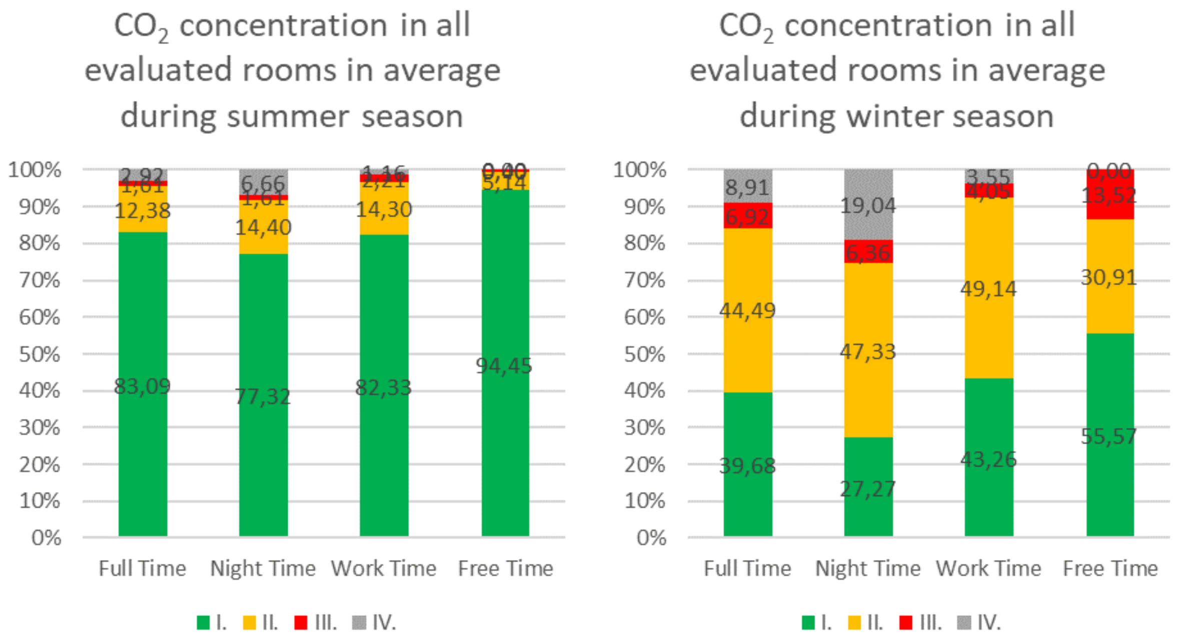


Fig. 5: Categorized data from CO2 concentration measurements for winter (left) and summer (right) seasons for the whole single-family house

The indoor air quality in the winter and summer seasons was very acceptable. The average values were included mainly in category I. (39,68% in winter; 83,09% in summer) and in category II. (44,49% in winter; 12,38% in summer). The measured rooms were only 8,91% (for the winter season) and 2,92% (for the summer season) of time classified as class IV., which represents unacceptable values.

The residents spent only 8,91% in the winter season and 2,92% in the summer season, places where CO_2 concentrations exceeded the limit of 1000 ppm. This happened mainly at night time in the bedrooms, while the mechanical ventilation system was in operation.

Tab. 6: Tabled results for indoor air quality evaluation for the whole single-family house in average – percentage of the spent time in the category

Single-family house Unterrabnitz	INDOOR AIR QUALITY - WINTER SEASON (%)				INDOOR AIR QUALITY - SUMMER SEASON (%)			
	I.	II.	III.	IV.	I.	II.	III.	IV.
Full Time	39,68	44,49	6,92	8,91	83,09	12,38	1,61	2,92
Night Time	27,27	47,33	6,36	19,04	77,32	14,40	1,61	6,66
Work Time	43,26	49,14	4,05	3,55	82,33	14,30	2,21	1,16
Free Time	55,57	30,91	13,52	0,00	94,45	5,14	0,40	0,00

One of the reasons for the high concentration of CO_2 in the bedroom could be the undersizing of the ventilation system in the room (according to the project documentation, only a 40 m^3/h supply is installed in the bedroom, which corresponds to 5,5 l/s for one person in the room), or the problem could be caused by poor regulation of the supply air by the ventilation system.

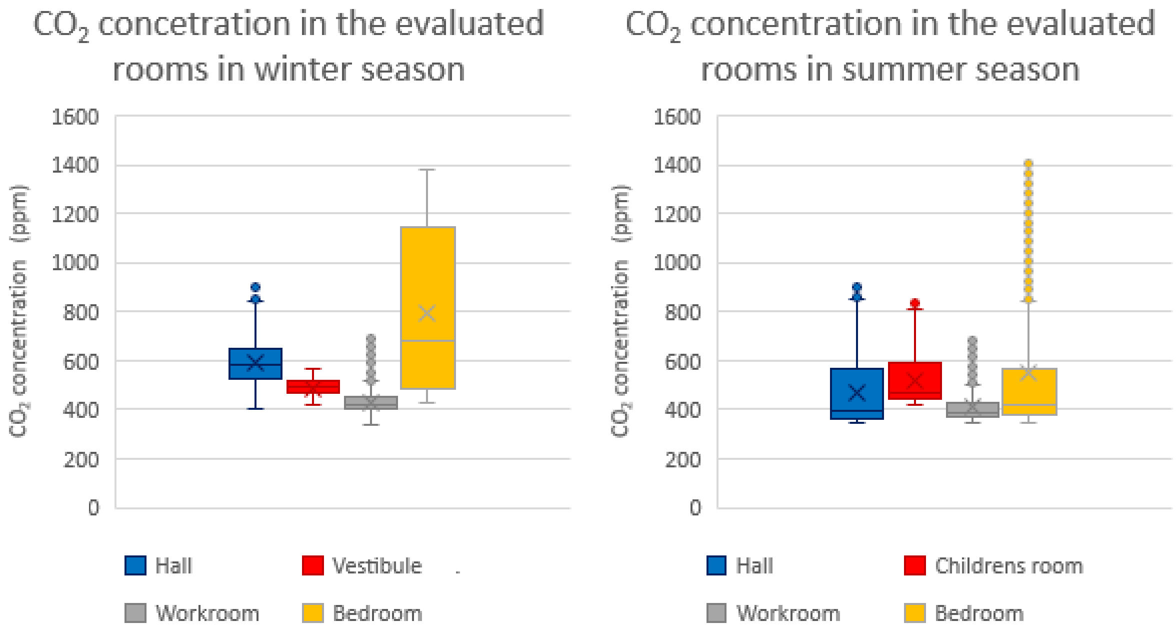


Fig. 6: CO_2 concentration illustrated on boxplot diagrams for the evaluated rooms for winter (right) and summer (left) season

The average CO_2 concentration in the 4 evaluated rooms in the winter season was 575,1 ppm and in the summer season 484,4 ppm. The average indoor air quality indicator, both in summer and in winter, did not exceed values higher than 1500 ppm.

The air exchange rate was calculated using the method of decreasing tracer gas concentration calculation. The results are very similar for evaluation in winter and summer. The CO_2 concentration in the supply / external air was chosen to be 400 ppm.

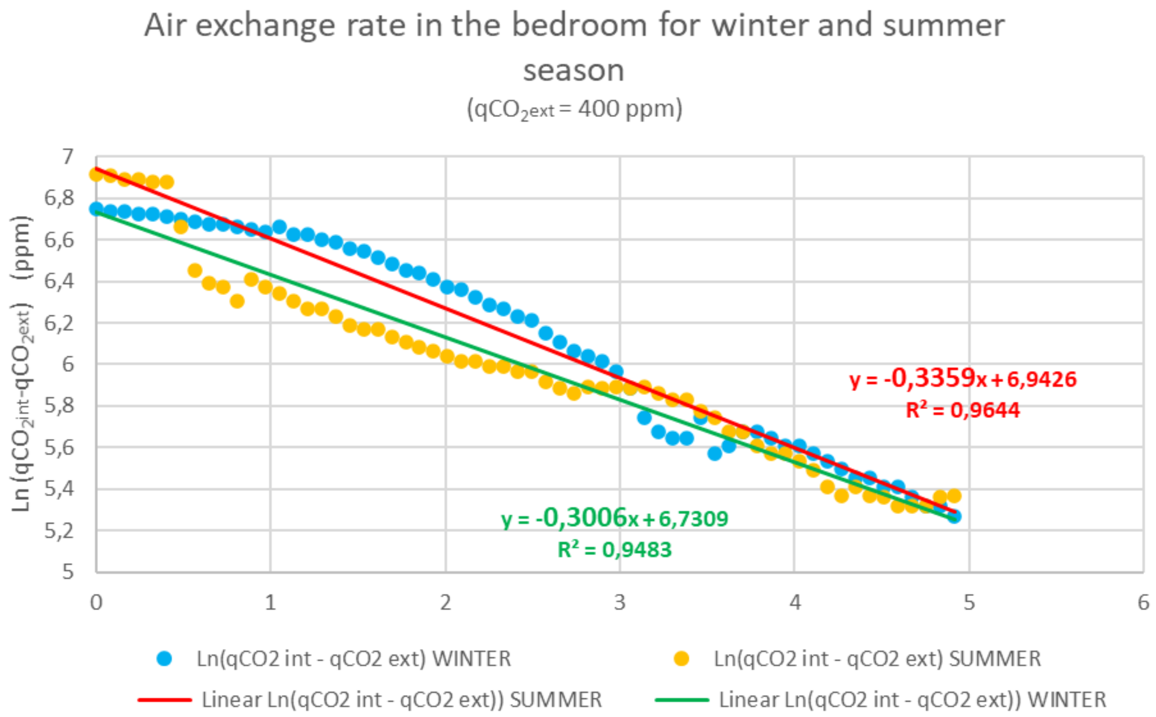


Fig. 7: Air exchange rate in the bedroom for winter and summer season

The figure above shows the results of the calculation. The intensity of air exchange for the winter and summer seasons was 0,3-0,33 n/h, which is very low.

Intake air - 40 m^3/h - and exhaust air - 15 m^3/h - should emit a higher air exchange rate (around 0,5 n/h). I would recommend increasing the supply air to 52-55 m^3/h to ensure a minimum of 7 l/s for one room occupant.

4.2 Indoor environmental quality evaluation in a nearly zero energy building Bad-Tatsmansdorf, Austria

The study below is very similar to the study presented in the previous section, evaluating the effects of energy efficiency measures on the quality of the indoor environment in the NZEB single-family house.

Unlike the building examined in the previous chapter, this family house does not have a radiant heating and cooling system installed - it has warm air system. The need for heat and cold is covered by an air source heat pump.

The building was built in 2013 as a prefabricated building, with a floor area of 141,6 square meters.

The measured quantities and the evaluation method are identical, the standard STN 16798-1: 2019 is used in the evaluated rooms:

- Living room
- Kid's room
- Bedroom

Selected results of measuring the quality of the indoor environment for a family house Bad-Tatzmansdorf are presented below.

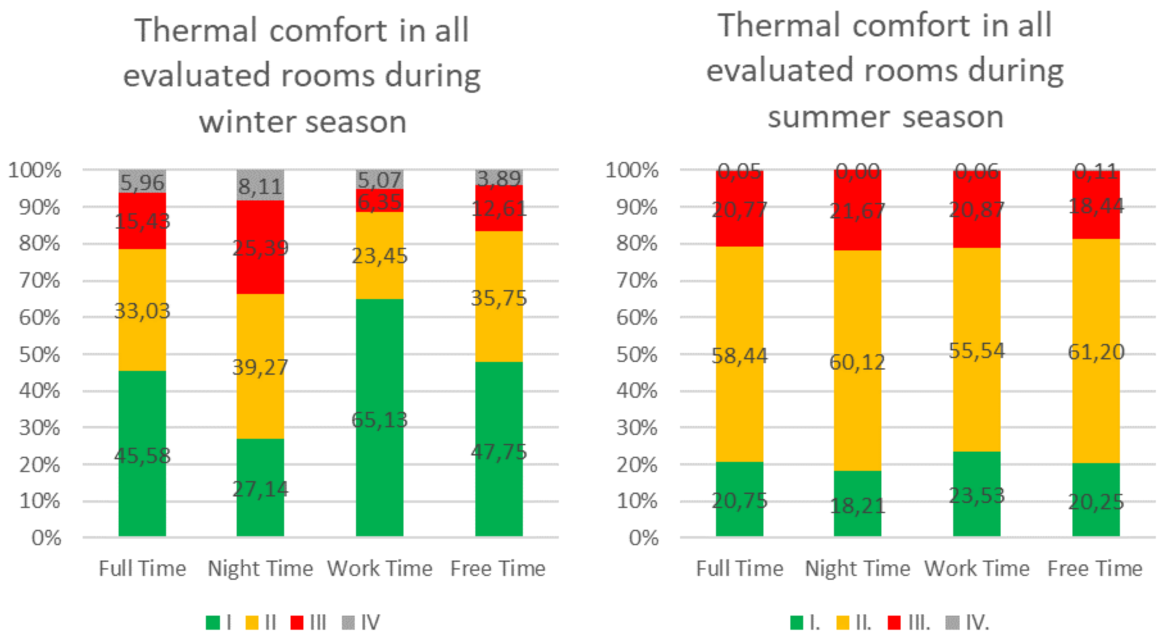


Fig. 8: Categorized data from thermal comfort measurements for winter (left) and summer (right) seasons for the whole single-family house

Tab. 7: Tabled results for thermal comfort evaluation for the whole single-family house in average – percentage of the spent time in the category

Single-family house Bad Tatzmannsdorf	THERMAL COMFORT - WINTER SEASON (%)				THERMAL COMFORT - SUMMER SEASON (%)			
	I.	II.	III.	IV.	I.	II.	III.	IV.
Full Time	45,58	33,03	15,43	5,96	20,75	58,44	20,77	0,05
Night Time	27,14	39,27	25,39	8,11	18,21	60,12	21,67	0,00
Work Time	65,13	23,45	6,35	5,07	23,53	55,54	20,87	0,06
Free Time	47,75	35,75	12,61	3,89	20,25	61,20	18,44	0,11

Indoor air temperature and relative humidity in a family home (and many other factors such as air velocity, clothing, etc.) affect the thermal well-being of the occupants. In this case, the thermal comfort was classified mainly into categories I. and II. In the winter season, during full time measurements, the inhabitants spent time in category I. 45,58% and in category II. 33,03%. In the summer season in category I. 20,75% and category II. 58,44%.

Tab. 8: Summarization of statistical data from thermal comfort measurements

Single-family house Bad Tatzmannsdorf	Winter season		Summer season	
	T (°C)	RH (%)	T (°C)	RH (%)
AVERAGE	23,2	30,9	23,5	53,5
MIN	20,8	20,4	21,8	39,6
MAX	26,7	34,5	25,9	65,4

The average temperature in winter was 23,2°C and the average relative humidity was 30,9%. In summer months, the average temperature was 23,5°C and the average relative humidity was 53,5%. From the monitoring of the relative humidity parameters, it is clear that the winter measurements show extremely low values. I recommend increasing the humidity in the winter with a mechanical humidifier to avoid the health risks associated with this type of thermal discomfort.

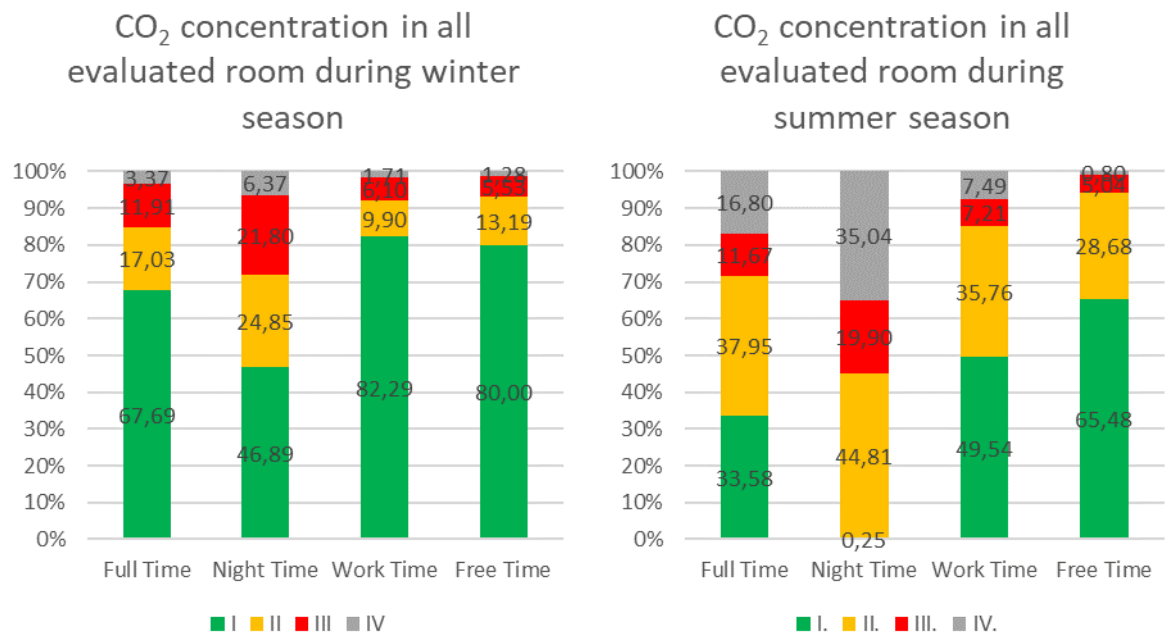


Fig. 9: Categorized data from CO2 concentration measurements for winter (left) and summer (right) season for the whole single-family house

The indoor air quality during the measurements, both in winter and summer season, was very acceptable. The main division of categories according to full time measurements is as follows.

Tab. 9: Tabled results for indoor air quality evaluation for the whole single-family house in average – percentage of the spent time in the category

Single-family house Bad Tatzmannsdorf	INDOOR AIR QUALITY - WINTER SEASON (%)				INDOOR AIR QUALITY - SUMMER SEASON (%)			
	I.	II.	III.	IV.	I.	II.	III.	IV.
Full Time	67,69	17,03	11,91	3,37	33,58	37,95	11,67	16,80
Night Time	46,89	24,85	21,80	6,37	13,42	54,69	16,40	7,47
Work Time	82,29	9,90	6,10	1,71	42,61	22,65	10,21	24,53
Free Time	80,00	13,19	5,53	1,28	54,63	37,51	5,44	2,41

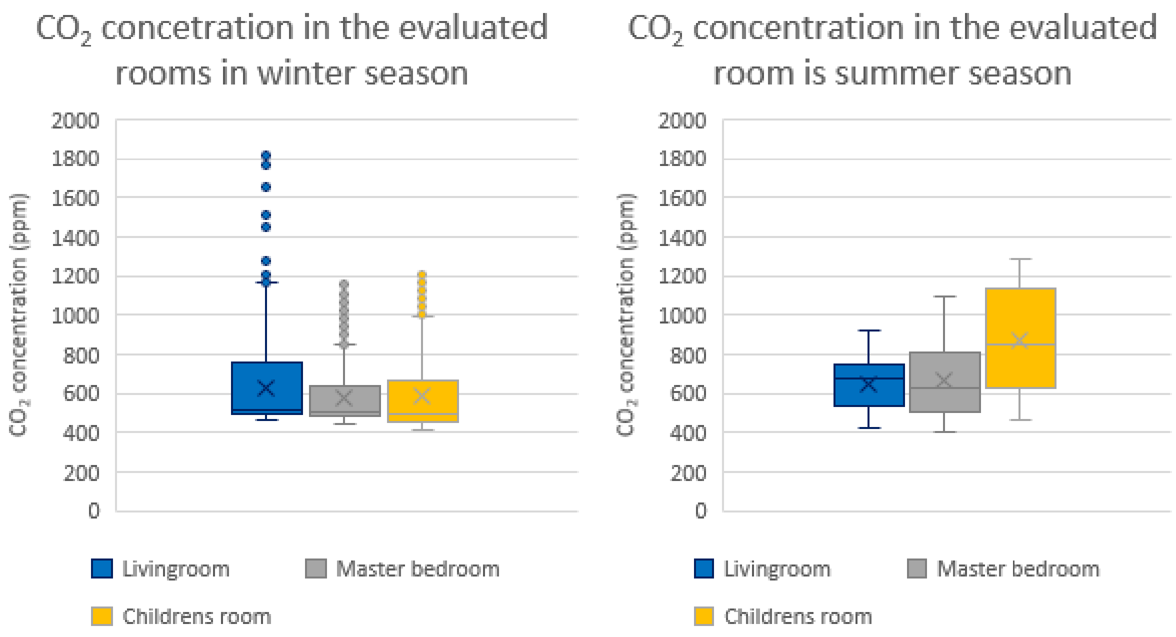


Fig. 10: CO2 concentration illustrated on boxplot diagrams for the evaluated rooms for winter (right) and summer(left) season

The average concentration for the evaluated rooms in the winter period was 595 ppm and in the summer season 730 ppm. The maximum measured value was in the living room during night time in winter season - 1817 ppm. The captured minimum value was in the master bedroom during the summer season - 407 ppm.

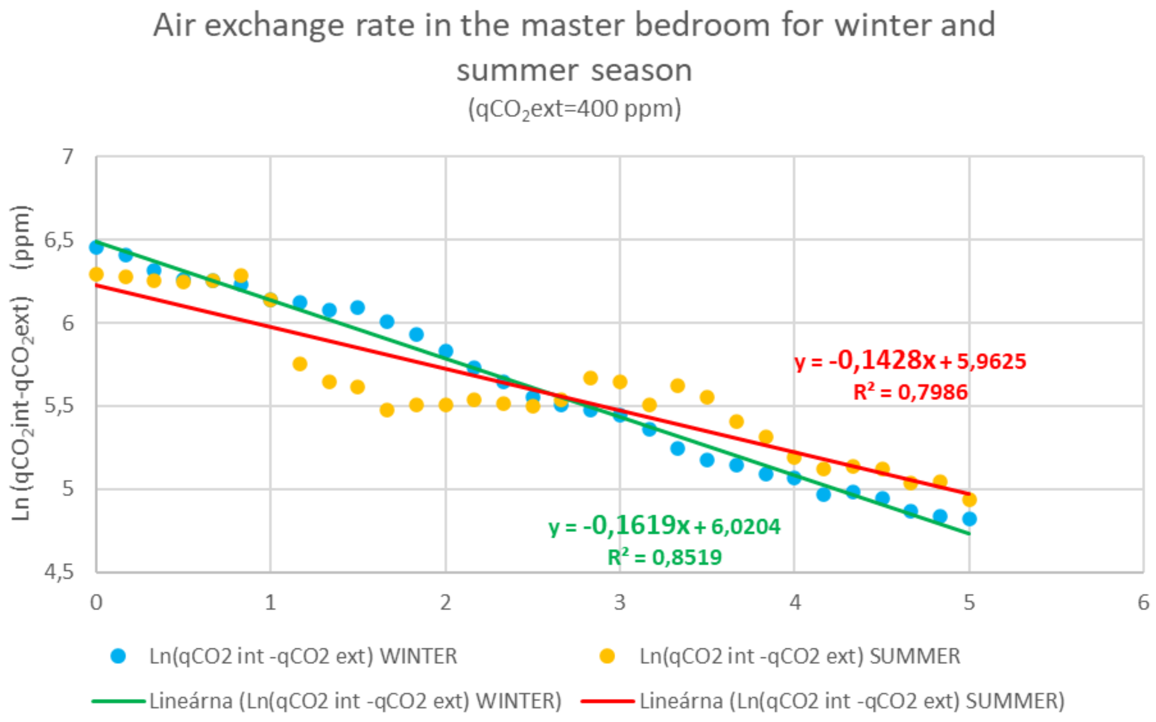


Fig. 11: Air exchange rate in the master bedroom for summer season

The figure shows that in the master bedroom, the air exchange rate was calculated to be only 0,15-0,2 n/h.

The reason for the low air exchange can be defined from the project documentation - this room was marked as an office space "büro", therefore the air supply was planned only around 25 - 30 m^3/h.

5. Conclusion

This work presented energy calculations for several variants of renovation of more than 50 years old building and its financing options. According to many other studies, we know that people spend most of their time indoors. For this reason, it is not enough to take care of the energy efficiency of these buildings, but also to pay attention to the quality of the indoor environment.

The following two main parts of the work were focused on the quality of the indoor environment of buildings with almost zero energy consumption in the summer and winter seasons. The work evaluates the quality of indoor air by measuring the concentration of CO_2 in two nearly zero energy bulildings - one with a radiant heating and cooling system, the other with a warm air heating and cooling system.

Indoor air quality and thermal comfort in rooms predominantly contribute to the overall feeling and productivity of people in households.

Studies have shown that buildings equipped with high-quality and modern environmental technologies provided residents with fresh air and perfect thermal comfort parameters.

The key findings of this study can be concluded as following:

- Energy renovation presented in three different variants (Standard, Comfort, De-luxe) had shown the possibilities for energy savings between 50-80% based on the chosen energy strategies (Standard: 101,2 kWh/(m^2.a), Comfort 76,01 kWh/(m^2.a), De-luxe 37,11 kWh/(m^2.a)).
- Investments for renovation presented in three different variants (Standard, Comfort, De-luxe) had shown large scale of costs needed for applying the energy saving measures in building envelope and HVAC systems (Standard: 50000€, Comfort 75000€, De-luxe 120000€).
- Indoor air quality assessment of two single family houses with two different heating / cooling systems with air forced ventilation confirmed acceptable parameters of hygienic air change rate with possibility to achieve the CO_2 concentration to meet standard requirements.
- Thermal environment evaluation based on indoor air temperature and relative humidity measurements presented results of thermal comfort in winter and summer season, which showed negative influence of moisture to providing acceptable thermal state for occupants in some rooms.
- The key findings of this study on “Indoor air quality in nearly zero energy buildings” can be concluded as the scientific and practical contribution, that it is possible to design and operate nearly zero energy buildings with acceptable indoor environment.

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Abstrakt

Európska komisia v roku 2010 prijala smernicu o energetickej hospodárnosti budov (EPBD) a smernicu o energetickej efektívnosti z roku 2012 (EED) ako hlavné legislatívne nástroje na úsporu energie zamerané na zníženie spotreby energie novopostavených a renovovaných budov v Európe. Národná legislatíva založené na EPBD uvádza, že po roku 2016 je možné stavať iba takzvané ultranízkoenergetické budovy. Ďalšie sprísnenie energetických úspor prišlo v roku 2021 (pre komerčné budovy po roku 2019), keď bolo povolené stavať iba budovy s takmer nulovou spotrebou energie (NZEB). To znamená, že tieto budovy musia spĺňať požiadavky kategórie A0 primárnej spotreby energie. Čo však s kvalitou vnútorného prostredia v objektoch, v takýchto budovách? Táto práca sa zaoberá meraním kvality vnútorného prostredia v NZEB budovách. Merala sa teplota vnútorného vzduchu, relatívna vlhkosť, koncentrácia oxidu uhličitého a rýchlosť výmeny vzduchu. Okrem hodnotenia kvality vnútorného prostredia bol pre rodinné domy postavené v druhej polovici 20. storočia vyvinutý špeciálny optimalizovaný model obnovy.

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1	SÁNKA, I. -- RAKŠÁNYI, P. Historický vývoj mesta a jeho komunikačnej siete. Bachelor thesis. Bratislava : SvF STU, 2014.	final thesis	2014
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