Using HAIEQ methodology for holistic analysis of IEQ in modern family houses

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Abstract. The indoor environment of buildings consists of a set of physical, chemical, and social reactions between users and the building, including phenomena that affect the technical, natural, and medical sciences. To describe and quantify the parameters of the indoor environment of buildings, we commonly use a simplified model, describing and evaluating the individual components of the environment separately - thermal comfort, air quality, acoustics, lighting, electromagnetic and other fields that co-create the final state of the environment. Presented methodology is based on a holistic approach to the integration of information about the building-technical design and interior, heating, cooling, ventilation, lighting, acoustics and electromagnetic, ionic, -static fields, and ionizing radiation, information about the real operation of the evaluated building, based on data from measurements, mathematical model, and questionnaire survey. The output is a set of information expressing whether the object under assessment, in terms of each criterion, is solved at the level of the current state of knowledge or has the potential to improve the quality of the indoor environment, or whether there are significant deficiencies in terms of the quality of the indoor environment. The methodology is applied here to the assessment of two similar modern family houses. The output shows not only the evaluation of IEQ in both houses, but also the potential to improve IEQ in these houses with identification of causes of the potential problems and ways of possible solutions. The case study points out, among other things, interesting differences in the perception of the indoor environment by individual occupants and shows user behaviour in connection with ensuring the indoor environment of their homes.

Keywords. Indoor Environmental Quality (IEQ), Holistic IEQ Assessment, IEQ Assessment Method, etc.
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1. Introduction

Current design, implementation, and operation of buildings based on energy savings have an impact on the quality of the indoor environment. The primary emphasis on energy savings leads to such a building design where energy savings in most cases minimize the natural interaction of the indoor and outdoor environment. Many building functions that previously took place without human intervention are eliminated in modern low-energy buildings and replaced by technical systems with high energy efficiency but negative impact on the quality of the indoor environment. (1). Examples are systems to ensure thermal comfort. The mass and shape proportions of the building, optimized by millennia of development, are being replaced in today's modern fully glazed buildings by the installation of cooling and heating equipment. Natural air exchange by window infiltration is replaced by controlled ventilation in buildings with a perfectly sealed envelope. Daylight is replaced by artificial lighting in extended rooms.

There are sophisticated and well-established tools and methods for the determination and assessment of energy performance (energy performance certification, building certification, etc.). Quantification of IEQ is more difficult, and tools and methods are being developed only.

2. HAIEQ (Holistic Assessment of Indoor Environment Quality) assessment methodology

The aim of this methodology is to create a complex holistic view of the assessed object in terms of all factors of the indoor environment.

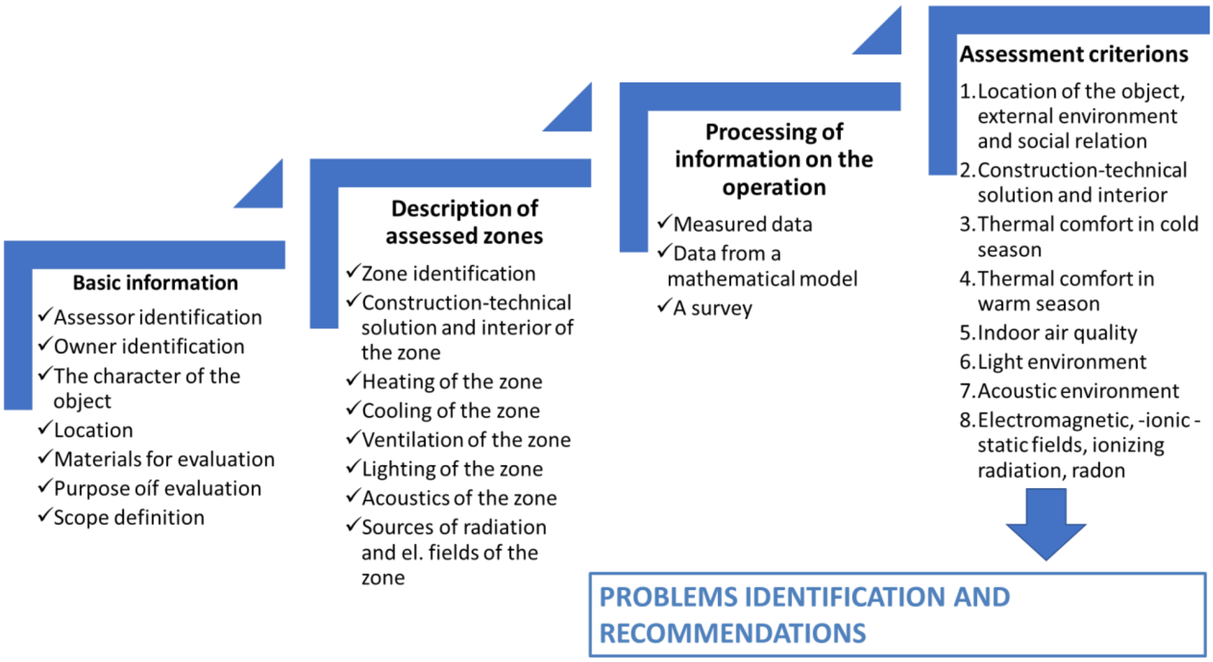

Fig. 1 HAIEQ assessment methodologv.

The HAIEQ methodology is based on a holistic approach to the integration of information about the building-technical design and interior, heating, cooling, ventilation, lighting, acoustics and electromagnetic, -ionic, -static fields and ionizing radiation, information about the real operation of the assessed building, based on data from measurements, mathematical model, and questionnaire survey [2]. The output is a set of information expressing whether the object under assessment, in terms of each criterion, is solved at the level of the current state of knowledge or has the potential to improve the quality of the indoor environment, or whether there are significant deficiencies in terms of the quality of the indoor environment. The advantage of the methodology is the assessed method, which is intended not only to classify IEQ in buildings, but primarily to indicate bottlenecks. In addition, a holistic approach helps to identify the causes of the problems and to better find ways to possible remedies. The information obtained can also be used to evaluate the SRI (Smart Readiness Indicator [3]).

The HAIEQ methodology [2] contains four basic parts, which are described in **Fig. 1.** The fourth final part contains an assessment of the state described above of the building solution in terms of the eight criteria, **Tab. 1**. Each of the eight criteria contains 3-10 subcriteria, each of which is scored with grade 1 to 3 or N (not evaluated). The grades are awarded based on the subjective assessment of the assessor, who has information about the object, measured data, and, if possible, the result of a questionnaire survey. The evaluation expresses the state of the assessed criterion. If there are not enough data for the assessment of the given criterion or if its assessment is not relevant for the given object, it is evaluated as '0'. If there are sufficient data to assess the criterion and the analysis of the criterion, considering user feedback, does not provide any recommendations to improve the current situation, it is evaluated as '1'. If the assessor suggests a measure that leads to an improvement in the indoor environment, he evaluates the criterion '2' or '3'. A rating of '3' indicates a serious problem in a given criterion that must be addressed immediately (eg, violation of binding regulations, emergency state, malfunction, or malfunctioning equipment). A rating of '2' indicates a condition that is acceptable but can be improved, and it is desirable to do so. The proposed measure must be feasible for the given object and substantiated by justification (e.g., technical-economic analysis, expression of the benefit of the given measure, etc.).

Tab. 1 Criteria for assessment

LS	Locality and place of the object in terms of the external environment and social relations
STI	Building structures and technical solution and interior of the evaluated zone (STI)
TCW	Thermal comfort in the cold season
TCS	Thermal comfort in the warm season
IAQ	Indoor air quality
LC	Light comfort
AC	Acoustical comfort
EC	Electro-magnetic, -ionic, - static fields, ionizing radiation

3. Case study

IEQ assessment using the HAIEQ methodology is based on the assessment of data describing architectural and construction design, the design of technical systems and the operation. The evaluated buildings are two similar family houses built in 2019-2020. These are single-storey brick houses with hipped roofs with five living rooms, inhabited by two adults and two children. All windows have outdoor blinds. One of these houses (FM1) is equipped with a controlled ventilation system with heat recovery and climatization, windows are not used for ventilation. The main heating system is electric underfloor heating foils controlled by room controllers with a thermostat, located on the walls of the rooms, and with the possibility of communication with the central AHU unit. Thermostats are not used by the user; the required temperature of 22.5 ° C is set in all rooms for heating. The sources used for artificial interior lighting are LEDs with the possibility of adjusting the light intensity at the discretion of the users. The other house (FM2) has a natural ventilation system combined with negative pressure ventilation of the kitchen and the sanitary facilities, and main heating system is underfloor hot water heating with the possibility of control by room thermostats located on the walls of the rooms. The heat source is an electric boiler with equithermal regulation. The sources used for artificial interior lighting are LEDs with the possibility of adjusting the intensity and colour of light at the discretion of users.

The assessment of both buildings was based on project documentation, detailed local investigation, measurements of the state health institute immediately after the construction of the houses, own measurements and questionnaire survey. The case study of selected zones of two family houses shows the use of the methodology not only for the evaluation of IEQ, but also for the diagnostic and identification of problems related to indoor environment quality in buildings with low energy consumption, [4].

3.1 Measurement

An important source of information is the measurement of selected IEQ parameters. The monitoring process started with one-off indicative measurements of selected parameters (VOC, CO2, formaldehyde, negative ions, measurements of illuminance, electromagnetic fields) to get an overall picture of the state of the environment. The installation of long-term online monitoring of air temperature, relative humidity, CO_2 concentration, sound, and barometric pressure levels followed. Several sensors have been placed in characteristic locations of selected zones of the building (mainly habitable rooms and bathrooms). Data were evaluated using the VISIEQ method developed within the 'CTU Methodology' [2], **Fig. 2**. This allows an integrated view of measured data and allows time identification of problem situations.

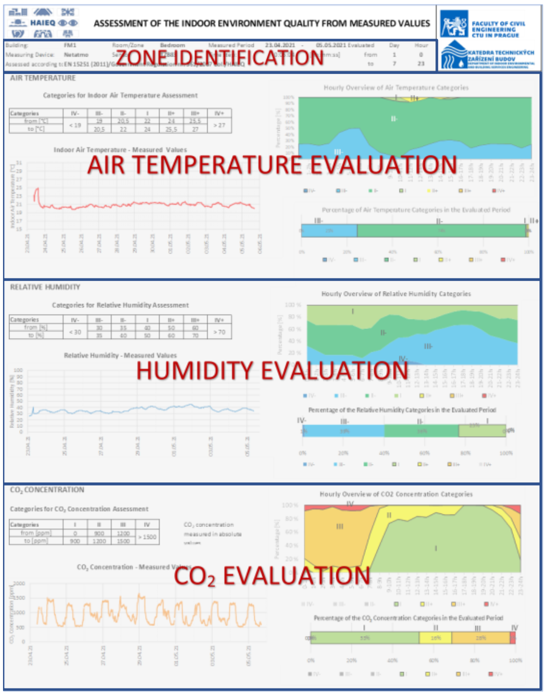

Fig. 2 Evaluation concept of measured values in the VISIEQ format.

3.2 Questionnaire

To determine how users subjectively perceive the environment, a questionnaire focused on individual components of the indoor environment and their perception by users was elaborated.

All the data obtained formed a picture of the object, which was assessed and evaluated in the next step.

3.3 Assessment

Based on all data (local survey, available documentation, monitoring of selected parameters of the indoor environment, questionnaire), an IEQ assessment of both family houses was prepared according to the HAIEQ methodology in eight criteria. The evaluation result is quantified by the grades according to **Tab. 2**.

Tab. 2 Table of grades for criteria evaluation.

Grade	Meaning
N	Not evaluated - e.g. lack of data, not relevant for the zone, other reasons (the reason must be stated)
1	No comments – without a draft measure, optimal condition, suitable solution
2	Proposed measure - Comments, shortcomings
3	Serious deficiency - failure to comply with legislation, emergency state, equipment malfunction, and, in the case of comments and serious deficiencies, their specification for comment.

The principle of the HAIEQ methodology, based on a rating of N / 1 / 2 / 3 of a total of 48 subcriteria grouped into eight areas, provides a holistic view of indoor environmental quality. The following tables (**Tab. 3** to **Tab. 10**) summarise the results of the evaluation of each criterion and comment on the criteria rated 2 or 3 for both houses; first house is marked 'FM1', the second 'FM2'.

Evaluation of the first criterion Locality and place of the object in terms of the external environment and social relations ´LS´ is in the **Tab. 3**, where LS2 for FM2 is rated as '2' based on an open windy landscape.

The second criterion Building structures and technical solution and interior of the evaluated zone 'STI' is in the **Tab. 4**. STI4 for FM1 is rated as '2' based on low daylight when the blinds are lowered (not closed). STI5 for FM1 is rated grade '2' due to automatic control of all blinds at once. STI3 for FM2 - is rated as '2'; it is a new building with new materials and furniture and measurements revealed traces of formaldehyde which, although not exceeding the permissible limits, can be removed. STI4 for FM2 is rated as '2'; there are poor light conditions during a day due to lowered blinds, curtains, and smaller windows. STI5 for FM2 is rated grade ´2"; there is an application available for electrically powered blinds installed in the building that are not used.

Tab. 3 Evaluation of the locality and the location of an object in terms of the external environment and social relations (LS).

Criterion		FM1	FM2
LS1	Air quality (pollution)	1	1
LS2	Wind region	1	2
LS3	Noise from the surroundings	1	1
LS4	Orientation to cardinal points	1	1
LS5	Influence of heat island	1	1
LS6	Psychic perception of surroundings, interpersonal relationships	1	1
LS7	Risk of energy poverty	1	1
LS	**Average of non-zero values LS1 to LS7**	**1,000**	**1,143**

Tab. 4 Evaluation of building structures and technical solution and interior of the evaluated zone (STI).

Criterion		FM1	FM2
STI1	Use of hazardous materials in building structures (asbestos, etc.)	1	1
STI2	Risk of water vapor condensation on structures (thermal bridges)	1	1
STI3	Use of hazardous materials for equipment (formaldehyde, etc.)	1	2
STI4	Use of daylight	2	2
STI5	Active shielding and its control	2	2
STI6	Greenery in the interior	1	1
STI7	Visible defects and disorders (mold, leakage, cracks, poor surfaces, etc.)	1	1
STI8	Color space solution	1	1
STI9	Layout solution, occupancy of the zone	1	1
STI10	Maintenance	1	1
ST	**Average of non-zero values STI1 to STI10**	**1,200**	**1,300**

Tab. 5 Evaluation of thermal comfort (TC) in the cold season (TCW).

Criterion		FM1	FM2
TCW1	Choice and operation of the heating system	2	1
TCW2	The ability of the heating system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment – e.g. individual temperature control, user feedback – subjective environmental quality assessment	2	2
TCW3	The ability of the heating system to report energy usage to the user	2	2
TCW4	The ability of the heating system to report the quality of the indoor environment in terms of thermal comfort in cold to the user	1	2
TCW5	Summary of TC assessment results for the cold season from the measurement/simulation (e.g. risk of overheating of the zone in cold due to heat gains, underheating, etc.)	2	N
TCW6	Summary of TC assessment results for the cold season from the questionnaire survey (if performed)	1	1
TCW	**Average of non-zero values TCW1 to TCW6**	**1,667**	**1,600**

The third criterion Evaluation of thermal comfort in the cold season ´TCW" is in **Tab. 5**. TCW1 for FM1 is rated grade ´2´– Choice and operation of the heating system are comfortable, but it has a high energy consumption, which can have a secondary impact on the quality of the environment. TCW2 for FM1 is rated grade ´2´ - the heating system allows the function, but the user does not take full advantage of the control options; temperature is set to a fixed value of 22.5 ° C. TCW3 for FM1 is rated grade ´2´ – the secondary electricity meter is not installed. TCW5 for FM1 is rated grade ´2´ - there is low relative humidity in the building. TCW2 for FM2 is rated grade ´2´ – Heat source - The electric hot water boiler is a common source for heating and hot water and its output is incorrectly controlled based on heating demand only. To ensure sufficient hot water, the heating system must be set so that the boiler is not switched off when the required room temperature is reached. The user has solved this by setting the room thermostats in each room to 26°C, thus de facto taking them out of operation in winter. The installed underfloor heating never reaches this temperature when operating with equithermal control, so the heat source is not switched off. TCW3 for FM2 is rated grade ´2´ – the secondary electricity meter is not installed. TCW4 for FM2 is rated grade ´2´ – only the air temperature report is available. TCW5 for FM2 is not rated (´N´) due to the lack of data for the evaluation of TC in the cold season.

The fourth criterion Evaluation of thermal comfort in the warm season ´TCS´ is in **Tab. 6**. TCS3 for FM1 is rated grade ´2´ – the control system is sophisticated, but the information is not used by users. TCS2 for FM2 is rated grade ´2´- adapting ability is not available. TCS3 for FM2 is not rated (´N´) only shielding elements are used in the building; there is no cooling system. TCS4 for FM2 is rated grade ´2´ – only the air temperature report is available. TCS5 for FM2 is not rated (´N´) due to the lack of data to evaluate TC in the warm season.

Tab. 6 Evalation of thermal comfort (TC) in the warm season (TCS).

Criterion		FM1	FM2
TCS1	Choice of the cooling system	1	1
TCS2	The ability of the cooling system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment – e.g. individual temperature control, user feedback – subjective environmental quality assessment	1	2
TCS3	The ability of the cooling system to report energy usage to the user	2	N
TCS4	The ability of the cooling system to report the quality of the indoor environment in terms of thermal comfort in warm season to the user	1	2
TCS5	Summary of TC assessment results for the warm season from measurement/simulation (e.g. risk of overheating of the zone in cold due to heat gains, under-heating, etc.) (if performed)	N	N
TCS6	Summary of TC assessment results for the warm season from the questionnaire survey (if performed)	1	1
TCS	**Average of non-zero values TCS1 to TCS6**	**1,278**	**1,500**

Tab. 7 Evaluation of indoor air quality (IAQ).

Criterion		FM1	FM2
IAQ1	Choice of the ventilation system	2	3
IAQ2	The ability of the ventilation system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment – e.g. user feedback – subjective environmental quality assessment	2	1
IAQ3	The ability of the ventilation system to report energy use to the user	2	2
IAQ4	The ability of the ventilation system to report the quality of the indoor environment in terms of indoor air quality	1	2
IAQ5	Summary of IAQ assessment results from measurement/simulation (if performed)	2	2
IAQ6	Summary of IAQ results from the questionnaire survey (if performed)	1	1
IAQ	**Average of non-zero values IAQ1 to IAQ6**	**1,667**	**1,833**

The fifth criterion Evaluation of indoor air quality ´IAQ´ is in Tab. 7. IAQ1 for FM1 is rated grade ´2" – the entire building is ventilated as one zone regardless of the stay of the persons. IAQ2 for FM1 is rated grade ´2´ – the system is able to adapt, but requires the intervention of the user, who uses this option only to reduce air flow in the building at night, which is an unsuitable solution for sleeping rooms. IAQ3 for FM1 is rated grade ´2´ – the system cannot do this. IAQ5 for FM1 is rated grade ´2´ – high concentrations of CO2 in the bedroom were measured at night.

IAQ1 for FM2 is rated grade ´3´ – natural ventilation is conditioned by high user cooperation and without IAQ indication it cannot ensure air quality. IAQ3 for FM2 is rated grade ´2´ – there is no information on heat consumption for heating the ventilation air. IAQ4 for FM2 is rated grade ´2´ - information not available. IAQ5 for FM2 is rated grade ´2´ – high concentrations of CO2 were measured in the bedroom at night and higher but below the limit values of the formaldehyde concentration were measured during the control measurement.

The sixth criterion Evaluation of light comfort ´LC´ is in Tab. 8. LC3 and LC4 for FM1 is rated grade ´2´ – the system cannot do this. LC5 for FM1 is rated grade ´2´ – low daylight when the blinds are lowered (not closed). LC3 and LC4 for FM2 is rated grade ´2´ – the system cannot do this. LC5 for FM2 is rated grade ´2´ – bad light conditions during a day due to lowered blinds, curtains and smaller windows.

Tab. 8 Evaluation of light comfort (LC)

Criterion		**FM1**	**FM2**
LC1	Choice of the lighting system	1	1
LC2	The ability of the lighting system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment – e.g. regulation of intensity and spectrum of light sources in the workplace, user feedback – subjective environmental quality assessment	1	1
LC3	The ability of the lighting system to report energy usage to the user	2	2
LC4	The ability of the lighting system to report the quality of the indoor environment in terms of light comfort	2	2
LC5	Summary of light comfort assessment results from measurement/simulation (if performed)	2	2
LC6	Summary of light comfort assessment results from the questionnaire survey (if performed)	1	1
LC	Average of non-zero values LC1 to LC6	**1,500**	**1,500**

Tab. 9 Evaluation of acoustic comfort (AC).

Criterion		**FM1**	**FM2**
AC1	Sources of noise and measures to eliminate them	2	1
AC2	The ability of the system to report the quality of the indoor environment in terms of acoustic comfort	2	2
AC3	Summary of acoustic comfort assessment results from measurement/simulation (if performed)	2	1
AC4	Summary of acoustic comfort assessment results from the questionnaire survey (if performed)	2	1
AC	**Average of non-zero values AC1 to AC4**	**2,000**	**1,250**

Tab. 10 Evaluation of electro-magnetic, -ionic,- static fields, ionizing radiation (EC).

Criterion		**FM1**	**FM2**
EC1	Sources of Electro-magnetic, -ionic,- static fields, ionizing radiation and measures to eliminate their negative effects	1	1
EC2	Summary of assessment results from measurement/simulation (if performed)	2	1
EC3	Summary of assessment results from the questionnaire survey (if performed)	1	1
EC	**Average of non-zero values EC1 to EC3**	**1,333**	**1,000**

Zone:			FM1		FM2	
Evaluation criteria			Evaluation	Potential for improvement	Evaluation	Potential for improvement
	LS	Locality and place of the object in terms of the external environment and social	1,000	0%	1,143	7%
	STI	Building - construction and technical solution and interior of the evaluated	1,200	10%	1,300	15%
	TCW	Thermal comfort for the cold period	1,667	33%	1,600	30%
	TCS	Thermal comfort for the warm period	1,278	14%	1,500	25%
	IAQ	Indoor air quality	1,667	33%	1,833 !	42%
	LC	Light comfort	1,500	25%	1,500	25%
	AC	Acoustic comfort	2,000	50%	1,250	13%
	EC	Electro-magnetic, -ionic,- static fields, ionizing radiation	1,333	17%	1,000	0%

Fig. 3 Summary evaluation and potential for improvement

The seventh criterion Evaluation of acoustic comfort ´AC´ is in Tab. 9. AC1 for FM1 is rated grade ´2´ – the source of noise is the air handling unit. There is a spread of noise through the open space of the house layout (unrealized door between the living area and the hallway) and the openings under the door. AC2 for FM1 is rated grade ´2´ – the system cannot do this. AC3 for FM1 is rated grade ´2´ – the measurement shows the probability that the air handling unit in the technical room affects the sound pressure level of the surrounding rooms. These values may be higher after increasing the ventilation intensity to ensure comfort at night. AC4 for FM1 is rated grade ´2´ – users are bothered by noise from the technical room. AC2 for FM2 is rated grade ´2´ – the system cannot do this.

The eighth criterion Evaluation of electro-magnetic, -ionic,- static fields, ionizing radiation ´EC´ is in Tab. 10. EC2 for FM1 is rated grade ´2´ – in the interior of the bedroom, the values of negative ions are lower than the recommended optimum and sometimes lower than the recommended minimum.

3.4 Results

An overview of partial evaluations of individual criteria is given in **Fig. 3** for both evaluated objects. The evaluation of the criterion can take values from 1, which expresses the state without comments, to a value of 3, which points out a serious problem of the entire evaluated criterion. The occurrence of the classification ´3´ (marked ´!´) in the criterion indicates that there is a serious problem in one or more parameters of the criterion.

Based on the evaluation, the potential for improving the indoor environmental quality is determined, expressed as a percentage from 0% to 100%.

Overall, family house FM1 does not show any serious problems and all criteria are classified as level 1 or 2. The greatest potential for improvement is in the field of acoustics (AC), where the air conditioning unit is a source of noise. This is noise that does not exceed hygienic limits, however, it is perceived by the user as annoying and indirectly affects the air quality (IAQ), because the performance of the air handling unit is reduced for the user at night. This will reduce the sound pressure level, but at the same time worsen the air quality, which will be reflected in higher (though not dangerous) CO_2 concentrations in the bedroom. A possible measure would be to zone the ventilation system and control according to the CO_2 concentration in the individual rooms. The air conditioning control system is sophisticated; however, its control requires the involvement of the user. The area of thermal comfort in the cold season (TCW) has the potential to improve, especially in the concept of heating solutions and its control. Electric underfloor heating in direct heating mode is one of the most energy intensive (from the point of view of primary energy from non-renewable sources). High energy intensity is reflected in the higher price, and in the case of unfavorable development of the user's economy, it can lead to energy poverty. It would be appropriate to supplement the heating system with a system that provides the user with feedback on the state of thermal comfort and at the same time on energy consumption with possible optimization of the operating mode with a self-learning function. The field of lighting (LC) has potential mainly in the absence of information on the amount of electricity used for artificial lighting and its regulation. The criterion of electromagnetic fields (EC), including the amount of negative ions, draws attention to the fact that during measurements in the bedroom interior, the values of the concentration of negative ions were lower than the recommended optimum and sometimes lower than the recommended minimum. This is not a critical condition; however, if users experience heavy air, this is a possible cause, and we recommend installing an air ionizer commonly available on the market, for example, in some air purifiers.

Overall, family house FM2 does not have any serious problems and all criteria are classified as level 1, 2 and in one case 3. These are the air quality criterion

(IAQ) and the choice of ventilation concept, which is based on natural ventilation. This system requires a high level of user cooperation and, without any indication of air quality indicators, cannot ensure the required air quality while maintaining operating economy. This fact was reflected in the CO_2 concentration course in the bedroom at night, which regularly exceeded 2000 ppm. At the same time, measurable formaldehyde concentrations were measured during a single measurement, which contributes to the assumption that sufficient air exchange is not ensured when the windows are closed. A possible low-cost measure is to equip the building with a CO_2 indication system, which alerts the user to the increasing concentration of harmful substances in the air, which can react by opening a window. There is a higher potential for improvement in the area of heating and its regulation, where the user is looking for the optimal setting of the system so that he has enough hot water and heat for heating at the same time. Currently, the heating operation does not use the possibility of individual regulation, the entire system is switched to equithermal mode. Likewise, information on heating energy consumption would help optimize plant operation. The thermal comfort in the summer is ensured by the building itself with a large construction, active shading and the size of the windows, and based on user feedback, the thermal comfort is subjectively ensured. Sensitive automation of blind settings and monitoring of internal temperatures would contribute to its increase. The absence of controlled ventilation can also be expected in the summer. The field of lighting (LC) has potential mainly in the absence of information on the amount of electricity used for artificial lighting.

4. Conclusion and summary

Many questions arise with the assessment of the quality of the indoor environment, but they do not and cannot have a clear-cut answer. The aim of this methodology is to obtain a detailed analysis of the state of the indoor environment of a building in context and the resulting proposals for measures to improve or eliminate risk factors, even though all the building's structures and technical systems have been designed according to valid standards and knowledge of current technology. This analysis is the basis for decision making on changes in maintenance, operation, or the need for refurbishment leading to increased building resilience.

HAIEQ methodology does not compete with evaluation tools such as BREEAM, WELL, LEADS etc., which are primarily intended for the comprehensive evaluation of buildings. These instruments assess IEQ only as part of the overall assessment and have different weightings [5].

The case study of two family houses shows the use of methodology not only for IEQ evaluation, but also for diagnostics and identification of problems related to indoor environment quality in buildings with low energy consumption. The aim of this study is also to show the potential for improving the indoor environment quality in the building.

5. Acknowledgement

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Data sets analysed during the current study are not available as they are sensitive to the privacy of the owners of the objects under study.