Ref. Ares(2025)2660103 - 02/04/2025

DELIVERABLE 1.2

Scientific report on the indoor environmental quality assessment with the use of smart sensors

DOCUMENT TRACKING DETAILS

Project acronym	SmartWins
Project title	Boosting Research for a Smart and Carbon Neutral Built Environment with Digital Twins
Starting date	01/10/2022
Duration	36 months
Call identifier	Twinning (HORIZON-WIDERA-2021-ACCESS-03)
Grant agreement number	101078997

Deliverable information	
Deliverable number	1.2
Work package number	1
Deliverable title	Scientific report on the indoor environmental quality assessment with the use of smart sensors
Lead beneficiary	POLIMI
Authors	Livio Mazzarella (PoliMi), Rossano Scoccia (PoliMi), Paris Fokaides (KTU), Paulius Spudys (KTU)
Due date	31/03/2025
Actual submission date	03/04/2025
Type of deliverable	R
Dissemination level	PU

Legal Disclaimer

VERSION MANAGEMENT

Revision table

Version	Name	Date	Description
1	Paulius Spudys	13/01/2025	TOC
2	Rossano Scoccia	07/02/2025	First draft
3	Rossano Scoccia	19/03/2025	Second draft
4	Paulius Spudys	24/03/2025	Third draft
5	Rossano Scoccia	03/04/2025	Final version

TABLE OF CONTENT

List of Tables

List of Figures

1. Introduction

Indoor Environmental Quality (IEQ) is at the intersection of occupant well-being, energy efficiency and sustainable building design. A growing number of research studies show that comfort indoor conditions, including thermal comfort, visual comfort, acoustics and indoor air quality, have a direct impact on occupant productivity, health and overall well-being. This increased focus on occupant-oriented outcomes has led building practitioners and researchers to explore advanced IEQ assessment and improvement strategies in a wide range of environments, from commercial offices and educational institutions to healthcare facilities and residential homes.

Conventional IEQ assessment methods are often based on punctuated sampling or manual measurements, providing only current data on conditions that can fluctuate significantly throughout the day. However, rapid advances in Internet of Things (IoT) technologies have started to change the landscape. Low cost and highly accurate sensor networks can now provide continuous monitoring of environmental parameters such as temperature, humidity, CO_2, volatile organic compounds (VOCs), light and sound levels. By capturing these variables in real time, building managers and researchers can better understand how operational schedules, occupant habits and external factors interact. This detailed insight allows them to develop targeted interventions - adjusting ventilation rates in response to increased CO_2 levels or optimising lighting schemes to align energy savings with occupant needs.

Task 1.2 of the SmartWins project addresses these linked challenges by providing an overview of the state-of-the-art methods for measuring and analysing IEQ. The project highlights the potential of smart sensors - both stand-alone and all-in-one devices - to capture a comprehensive set of parameters with minimal costs. At the same time, the researchers analyzed controlled environment set-ups, in particular environmental chambers, with a focus on refining and validating the measurement methods under similar conditions. These insights are then contrasted with field observations from real buildings, where the diversity of occupants and changing usage patterns are even more complex.

The main objective of D1.2 “Scientific report on the indoor environmental quality assessment with the use of smart sensors” is to provide an overview of the fundamentals of IEQ assessment practices, with an overview of common and advanced measurement strategies. Secondly, the role of "smart sensors" in real indoor environments is explored, with an emphasis on the prospect of continuous high-resolution data collection and processing. This document presents the research conducted and the main findings observed related to enhanced IEQ and energy related parameters monitoring and analysis by utilizing the most common digital practices and technologies such as IoT, BIM and digital twins.

Deliverable is structured as follows:

1. **Introduction** - sets the stage by clarifying the deliverable's aims, scope, and alignment with the task.
2. **Background** - defines IEQ and its constituent factors (thermal comfort, visual comfort, acoustic comfort, indoor air quality) and discusses their implications for the health, safety and comfort of the occupants. In addition, relevant measurement methods are examined, including established standard practices and state-of-the-art sensor-based methods.
3. **Methodology and Achievements** - presents how the research was conducted, both conceptually (review of scientific literature, existing best practices and relevant standards) and empirically (examination of environmental chambers, field tests and monitoring infrastructure). The main achievements reflect the identification of advanced measurement tools, architectures developed as well as the challenges identified and overcome.
4. **Gained Knowledge by KTU** – defines the knowledge and skills acquired by KTU SEBERG researchers during the implementation of the task activities. This includes both technical improvements as well as strengthened relationships with other project partners.
5. **Conclusions** - summarizes the key takeaways, emphasizing the value of occupant-focused IEQ measurements, the significance of smart sensors.
6. **Bibliography** - lists the technical standards, scientific papers, and other references that validate key findings.

2. Background

In this Chapter first of all an introduction to Indoor Environmental Quality (IEQ) is given, then the IEQ measurement methods and tools are described, afterwards the so called "smart sensors" are presented and finally a brief discussion of infection risk mitigation is discussed.

2.1. Introduction to Indoor Environmental Quality

To provide a definition, Indoor Environmental Quality (IEQ) refers to indoor conditions in a building related to both comfort and health, i.e., wellness, of those who occupy it. It includes thermal comfort, air quality, but also occupant control over lighting and pleasant acoustic conditions. Additionally, the evaluation may consider the quality of building materials and finishes, as well as their moisture content (Figure 1).

Figure 1: Indoor Environmental Quality.

All these factors are taken into account to prevent Sick Building Syndrome (SBS), which manifests as mucous membrane irritation of the eyes, nose, and throat; headaches; unusual tiredness or fatigue; and, less frequently, dry or itchy skin. The hallmark of these symptoms is their tight temporal association with building occupancy and their rapid resolution, within minutes to hours, once affected individuals leave implicated buildings.

Sick building syndrome's causes are not clearly defined due to its subjective nature, reversibility, and high prevalence within implicated buildings. It probably results from a combination of factors, such as (Figure 2):

- poor ventilation or poorly maintained air conditioning systems;
- dust, smoke, fumes or fabric fibres in the air;
- bright or flickering lights;
- Issues related to cleanliness and layout, such as overcrowded workspaces.

Figure 2: Sick Building Syndrome

Therefore, it is essential to extend the concept of comfort and well-being beyond the traditional IEQ parameters (ITC, IAQ, IAC, ILQ). The FOR HEALTH framework (Allen et al., 2017) set additional conditions to be fulfilled to obtain an "Healthy Building" (Figure 3), including:

- Moisture in building material: represent the key factor for mold growth, which promotes bacterial proliferation, attracts insects, and releases volatile organic compounds (VOCs) from wet building materials;
- Dust and pests: major contributors to building deterioration, allergies, diseases, insect bites, and psychological stress;
- Safety and security: decreases one's overall health and productivity in a given space, because the body engages in a small-scale "fight or flight" response, that cannot be remedied simply by time passing;
- Water Quality: Aging pipe systems can both release lead into the water supply and foster the growth of Legionella bacteria.

Figure 3: Healthy Buildings

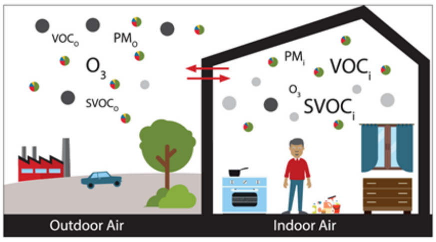
Regarding human well-being and comfort assessment, it is essential to consider the characteristics of the subject and the external stimulus, as well as the interaction of the phenomenon with the human perception. It can be divided into three main aspects:

- Physical stimulus: includes thermal and hygrometric characteristics of the environment as well as the objective characteristics of the observer;
- Physiological sensation: refers to the biophysical characteristics of the observer's senses;
- Psychological perception: involves the observer’s interpretation of the received stimulus.

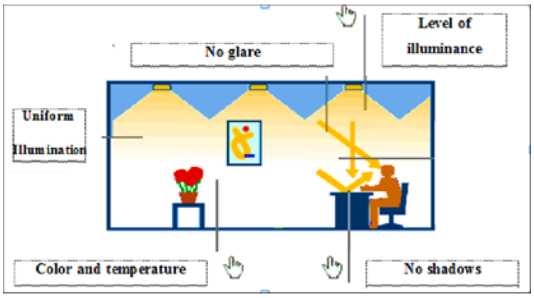
The assessment of the Standard Indoor Environmental Quality (IEQ) is conducted through different indicators (Figure 4):

- Indoor Thermal Comfort (ITC)

- Indoor Air Quality (IAQ)



- Indoor Lighting Quality (ILQ)



- Indoor Acoustic Comfort (IAC)

Figure 4: Indoor Environmental Quality indicators

To evaluate these parameters, is necessary to assess the environmental factors which affect human perception. These factors can be categorized as follows (Figure 5):

- Environmental parameters: air temperature and humidity, mean radian temperature, air velocity;
- Air pollutants' concentrations: PM10, PM2.5, CO, CO2, VOCs, Radon, etc.;
- Noise coming from outside or inside noise production: sound pressure level, noise reduction coefficient, etc.;

- Light quality: Illuminance, glare, etc..

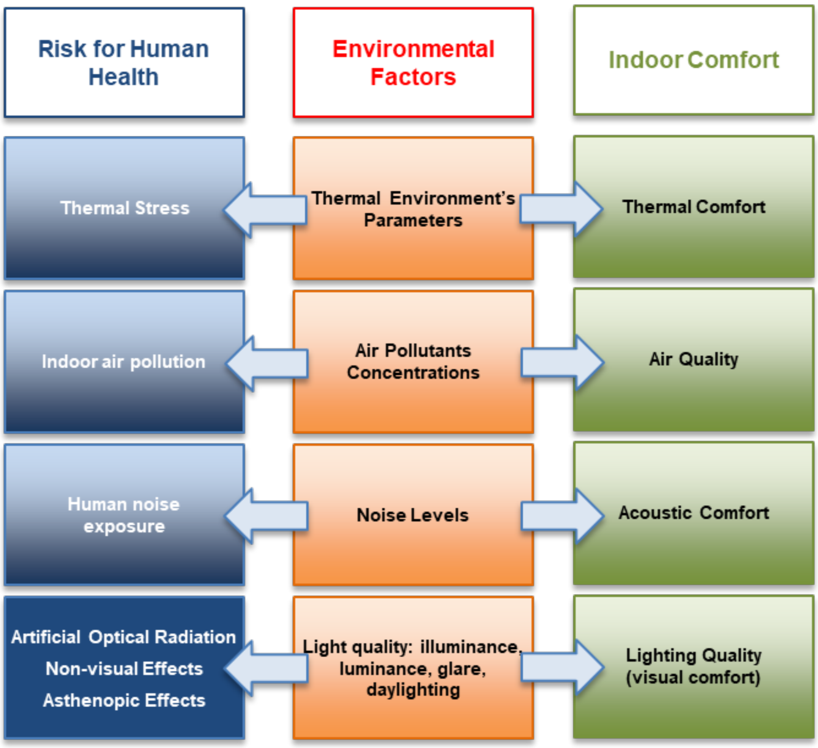


Figure 5: Environmental factors of human perception

The Indoor Environment Model implements four distinct set of indicators (I_{ITC}, I_{IAQ}, I_{IAC}, I_{ILQ},) which should be evaluated from two counterpoised point of view: the risk for human health and human comfort.

Several international technical standards are available in literature with the aim to provide guidelines for IEQ assessments.

Regarding IAQ, ISO 16814:2008 [2]specifies methods for expressing indoor air quality suitable for human occupancy, allowing for multiple acceptable target levels based on local requirements, constraints, and expectations. Another relevant standard is ISO 17772-1:2017 [3], which defines indoor environmental input parameters for the design and assessment of building energy performance, covering thermal environment, indoor air quality, lighting, and acoustics. According to ISO 7730:2005 [4], thermal comfort is assessed using the PMV and PPD indices, along with local thermal comfort criteria. There is currently a lack of a comprehensive framework for assessing light quality and acoustic comfort. Existing standards primarily provide measurement guidelines rather than defining comfort levels. For example, ISO 16032:2024 [5] focuses on sound pressure level measurements rather than evaluating acoustic comfort.

However, not all indicators have a clearly defined regulatory framework for accurately assessing their impact on human well-being. With the exception of thermal comfort, standardized quality thresholds are often lacking. Moreover, most of the indicators currently used to assess Indoor Environmental Quality do not explicitly consider health risks, except indirectly in some cases.

2.2. IEQ measurement methods and tools

In the literature there are several methods and tools to evaluate IEQ.

The most used methodologies are based on a multi-criteria analysis, allowing all indicators to be combined into a single IEQ index. This model is based on a linear weighting of the four distinct indicators, using the following equation:

$I_{IAQ} = \sum_{i=1}^{4} w_i \, I_{IXi}$ with $I_{IX1}=I_{ITC}$; $I_{IX2}=I_{IAQ}$; $I_{IX3}=I_{IAC}$; $I_{IX4}=I_{ILQ}$

Several types of analysis were conducted to determine the weighting values w_i. The main challenge of this model lies in the additivity assumption of human perception: the overall assessment of IEQ cannot be based solely on an average comfort score, as it must also account for discrepancies between different indicators.

To overcome this issue, the ALDERAN Project developed a new scheme called TAIL to rate IEQ [1]. The approach consists of evaluating the four standard indicators with a score from I to IV, determined by evaluating twelve parameters identified through an extensive literature review (Figure 6).

Figure 6: TAIL rating scheme

The evaluation of the four components is carried considering the following quality parameters for each indicator:

- Thermal environment: Air Temperature;
- Acoustic environment: Sound Pressure Level in dB(A);
- Indoor air quality: air relative humidity, ventilation rate, CO_2 concentration, formaldehyde concentration, benzene concentration, PM 2.5 concentration, radon concentration, visible mould area;
- Light – Luminous (visual) environment: illuminance & daylight factor.

Threshold values for each parameter are established to determine the quality level of each IEQ factor. The overall IEQ quality is defined by the lowest-rated component, ensuring that the most critical deficiencies are not masked by high scores in other areas.

2.3. Smart sensors for IEQ evaluation

Smart sensing and advanced technologies are driving the development and deployment of real-time monitoring solutions in spatially distributed indoor environments. A sensor network can provide both spatial and temporal data essential for implementing targeted and effective mitigation measures [2] This capability enables fine-grid mapping of energy demand and consumption patterns, as well as Indoor Air Quality conditions.

These sensors operate within a network connected through the Internet of Things (IoT) to the Building Management System (BMS), ensuring real-time data acquisition for optimized building management [3]. The architecture of an IoT-based smart building control system can be conceptualized as a multi-layered structure. At the foundational level, the perception layer is responsible for collecting data from sensors and user inputs, capturing key environmental and occupancy-related parameters. This information is then transferred to the network layer, where it is stored and processed to generate meaningful outputs. At this stage, user-related data can be leveraged to enhance comfort and optimize indoor conditions. Finally, the application layer translates this processed data into actionable insights, facilitating the interaction between occupants and building equipment while improving the effectiveness and performance of devices [4].

The choice of sensors depends on the specific application, whether the goal is energy savings, enhancing human comfort, ensuring optimal visual conditions, or improving IAQ [5]. Regardless of their function, regular sensor checks and maintenance are crucial to ensuring the efficiency of the system. A well-maintained sensor network supports an energy-efficient approach to building control, optimizing ventilation and heating strategies while maintaining high indoor environmental quality (Painter et al., 2012).

Smart sensors can be classified into several categories based on their function and application. These include:

- Air quality;
- Thermo-hygrometric conditions;
- Lights;
- Acoustic;
- Occupancy;
- All-in-one;
- Wearable.

It follows a brief description of the above categories.

2.3.1. Air quality sensors

air quality sensors are particularly important due to their direct impact on the health and comfort of a building's occupants. These sensors measure key air quality parameters to assess indoor conditions and ensure a healthy environment in order to evaluate ventilation performance and maintain proper air exchange rates.

Air pollution sensors can be broadly divided into two main types: those that measure the concentration of gas-phase species and those that assess mass concentrations or other properties of airborne particles. One of the most critical parameters in this context is carbon dioxide (CO_2) concentration, since its levels correlate with occupancy serve as a key indicator of indoor air quality and ventilation effectiveness. However, CO_2 monitoring alone is not sufficient to guarantee good indoor air quality, as other pollutants must also be considered: CO, CO2, SOx, NOx, CH_2O, O_3, benzene, formaldehyde, VOCs and particulate matter [7].

2.3.2. Thermo-hygrometric conditions

Thermo-hygrometric sensors are primarily associated with thermal comfort, as they measure key parameters such as indoor air dry bulb temperature and humidity. In addition, outdoor air conditions are also evaluated. One of the main challenges in this field is the accurate estimation of operative temperature, which depends on the type of instrumentation required for its assessment. For instance, in the TAIL scheme, air temperature is assumed as a proxy for operative temperature, based on the assumption that the two values are similar in well-insulated buildings [1]. However, it remains unclear whether this approximation is always acceptable.

These sensors have various applications across different contexts. In residential buildings, smart thermostats can respond to grid incentives, helping to reduce energy consumption and costs without compromising thermal comfort. In historical buildings, such as museums, temperature and heat flow sensors are used to monitor surface conditions, ensuring the preservation of indoor environmental stability. Additionally, in large-scale spaces, demand-based temperature control systems rely on these sensors to measure temperature at breathing level, enabling more efficient and adaptive thermal management [8].

2.3.3. Lights

Indoor Lighting Quality (ILQ) is assessed using illuminance, measured according to the EN 12464-1 standard, and the daylight factor, which is evaluated through simulations [1]

Photometric sensors measure light intensity levels in indoor environments and adjust the power output of artificial lighting accordingly. By dynamically increasing or decreasing light levels, these sensors help meet occupants' lighting needs, ensuring the required total illuminance while minimizing energy waste. Inadequate lighting can disrupt circadian rhythms, negatively impacting sleep quality and cognitive performance [7].

2.3.4. Acoustic

Regarding indoor acoustic comfort evaluation, standards such as EN ISO 10052 and EN ISO 16032 specify that assessment is based on sound pressure levels [1]. Acoustic comfort is typically measured using the equivalent sound level (LAeq), and sensors are employed to detect any events that exceed a predefined sound level threshold [9].

A range of measuring instruments is used to assess acoustic requirements [10], including sound level meters and prepolarized free-field microphones. In Kemar case study [11],[11] the assessment of acoustic comfort is evaluated through an ear simulator that houses a microphone to measure sound levels at the eardrum

2.3.5. Occupancy

Actual occupancy patterns often differ significantly from standardized schedules, leading to potential inefficiencies in system design and operation [12]. Integrating occupancy-based control strategies for lighting and HVAC systems can enhance energy efficiency by adapting to human presence and comfort levels, thereby minimizing unnecessary energy consumption [13]. Among the various indicators used for occupancy detection, CO_2 concentration and moisture levels are considered the most reliable parameters [14].

Several devices are used for detecting occupancy [15], including:

- CO_2-based systems: these sensors measure gas concentrations in parts per million (PPM), providing both occupancy estimates and insights into indoor air quality (IAQ).
- Passive infrared (PIR) systems: detect infrared radiation emitted by objects, including humans, to determine presence.
- Ultrasonic systems: emit and receive ultrasonic sound waves, analysing the time taken for the signal to travel to detect location and presence.
- Microwave systems: measure changes in the frequency of reflected signals to determine movement and occupancy.
- Sound-based systems: detect sound waves to infer occupancy, though their reliability is limited due to interference from non-human sources.
- Image-based systems: use video cameras for occupancy detection, though processing the signals remains complex.
- Energy measurement systems: analyse power consumption patterns to infer user location and presence, but accuracy can be a limitation.
- Chair sensors: detect human presence by integrating personal devices into seating arrangements.

These systems vary in accuracy, complexity, and applicability, with their selection depending on the specific requirements of the indoor environment. While some sensors, such as cameras, may raise privacy concerns, others, like door counter sensors, provide a more transparent and widely accepted solution for occupancy detection. Current research primarily focuses on energy efficiency rather than indoor environmental quality (IEQ). However, integrating HVAC systems with occupancy sensors can not only optimize energy consumption but also improve ventilation management, ultimately enhancing indoor air quality (IAQ).

2.3.6. All-in-One

Another emerging technology is the so-called "All-in-One" sensor, designed to combine the strengths of multiple sensing technologies while minimizing their limitations, ultimately surpassing the performance of individual sensors [9]. Several case studies in the literature highlight devices capable of simultaneously monitoring multiple indoor environmental parameters:

- Off-the-shelf wireless Netatmo room climate sensors: The base station of this system measures temperature, relative humidity, barometric pressure, acoustic levels, and CO_2 concentration, with a sampling time of five minutes. The collected data is transmitted directly to the Netatmo cloud [14]
- Smart desk lamp: This device integrates temperature and relative humidity sensors. The device is also connected to a CO_2 sensor and an available light measurement station. Parameters are recorded every 10 seconds and transmitted to other IoT components [16]
- SAMBA continuous IEQ monitoring system: Designed for comprehensive indoor environmental quality assessment, this system evaluates air quality, thermo-hygrometric conditions, illuminance, and sound pressure levels. It is installed on each occupant's desk, with measurements collected every five minutes [17]
- HOBO data logger: measure temperature, humidity illuminance and CO_2 concentration [18]

2.3.7. Wearable

Wearable sensors, or connected devices, offer continuous tracking of occupants' physiological conditions, such as skin temperature and heart rate, as well as behavioural actions. Additionally, they can be used to gather real-time survey feedback on an individual's thermal perception, enhancing the understanding of comfort levels [19].

The most common wearable devices include wristbands, watches and bracelets that simultaneously track skin temperature and mobile devices capable of assessing occupancy through radiofrequency-based methods [20]

2.4. Infection risk mitigation

Nowadays the research is focus on the understanding of airborne infection route. The objective is to develop guidelines focused on providing recommendation about specific components, buildings/space types, and suggesting mitigation measures. Several strategies can be implemented to reduce airborne infection risk in enclosed spaces such as buildings. First, ventilation rate should be increased to guarantee both comfort and energy issue. Regarding the indoor air quality, also the reduction of recirculated air can provide benefits in terms of health. From the occupants' perspective, key recommendations include avoiding direct exposure to airflow from other individuals, minimizing the number of people sharing the same indoor environment, and wearing protective face masks when in shared spaces.

To assess the spread of airborne infections and evaluate potential mitigation measures, Prof. Mazzarella propose a simplified tool to compare the effectiveness and applicability of different strategies in both existing and new building and HVAC systems [26]

The proposed tool is based on Wells-Riley model to assess the infection risk but is physically based (i.e. mass balance based) and can easily updated with different infection risk probability functions. It is based on a multi-room with possible air recirculation among rooms, through centralised HVAC system.

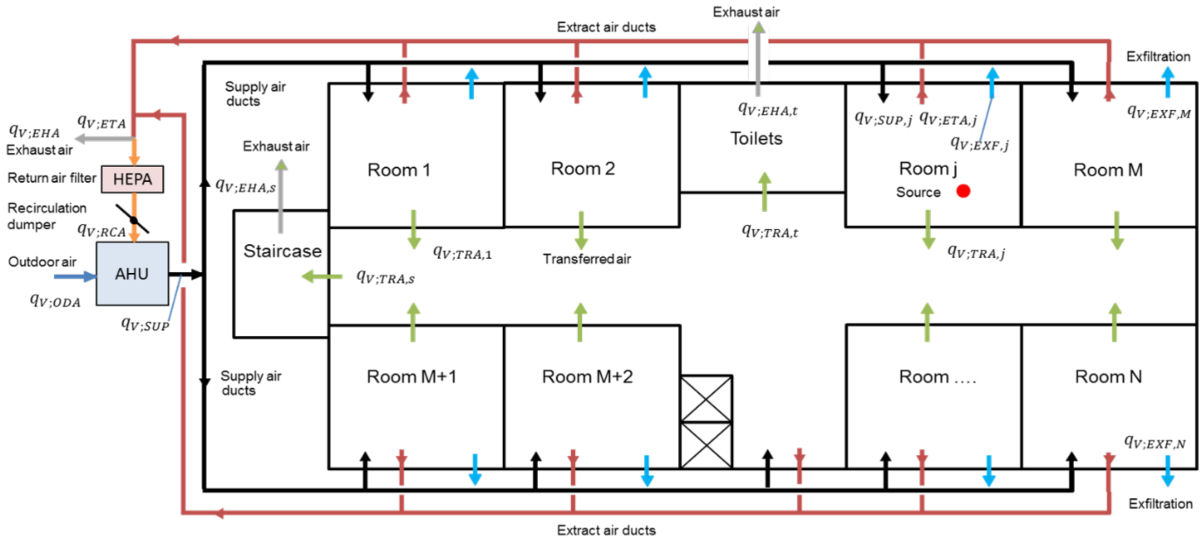


Figure 7: multi-room model with centralised HVAC system

The calculation outputs provide information about:

- average virus concentration in each space (Figure 8);
- virus air to surface deposition over the day (Figure 9).
- individual infection risk over the day in each space (Figure 10) ;
- average number of potentially infected people (Figure 11).

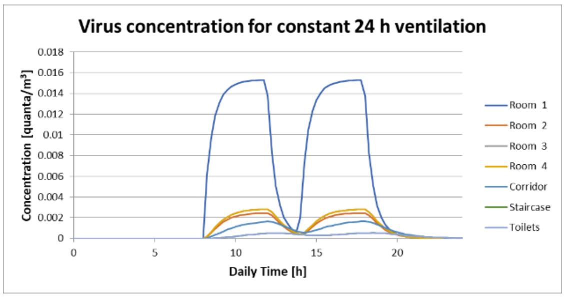


Figure 8: virus concentration.

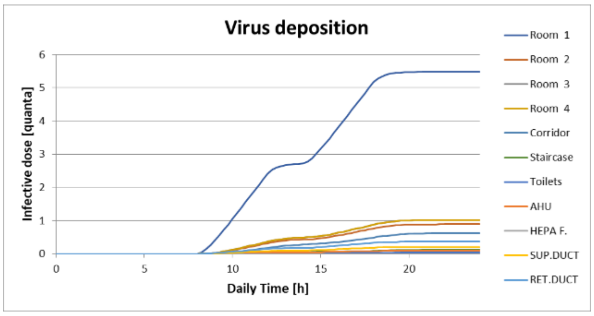


Figure 9: virus deposition

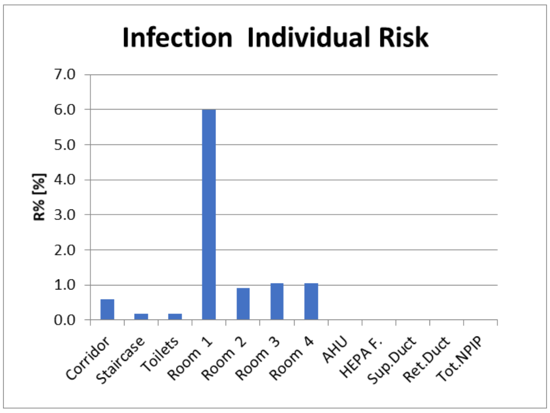


Figure 10: infection individual risk

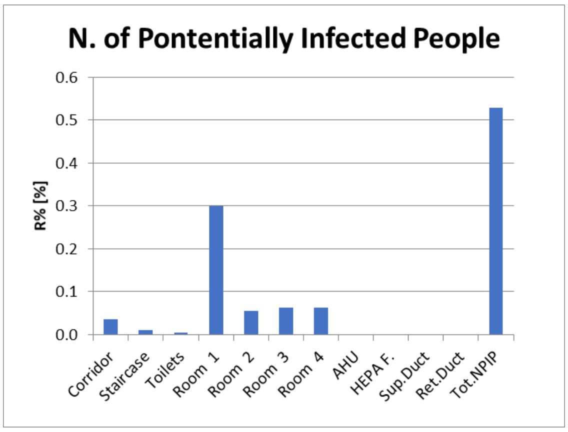


Figure 11: N. of potentially infected people

Further details on the calculation method can be found at the following link: REHVA Journal 05/2020.

3. Methodology and Achievements

As the aim of the task was to identify the sources, tools and measurement equipment that can be used for IEQ assessment, a detailed analysis was carried out to identify and review the best practices already applied. This section describes the methodologies used and presents the main findings of the research conducted.

3.1. Review of advanced tools and practices for IEQ assessment

The expansion of smart building in modern architecture has heightened the awareness of the increasing energy demand required to maintain healthy, comfortable, and safe indoor environments. In this context, a review of advanced tool and practices for IEQ assessment is conducted and will be published on a scientific journal. The purposes are to explore the relationship between IEQ and occupant well-being in smart residential buildings, assess its impact on occupants, and identify the essential sensors for effective indoor environmental management.

The review is structured as follows:

Understanding IEQ: Defines IEQ and its key components—indoor air quality, thermal comfort, visual comfort, and acoustic comfort—emphasize the benefits of high-quality indoor environments in terms of occupant health, well-being, comfort, and productivity. The main technical standards and evaluation frameworks for IEQ assessment across various contexts are examined to determine the most relevant parameters for monitoring. A key challenge addressed is the development of a unified methodology for IEQ evaluation based on its fundamental components.

Definition of Smart Buildings: Outlines the primary characteristics of smart buildings, which integrate various technologies and automation systems aimed at enhancing user experience while ensuring energy-efficient and sustainable operation. Additionally, a detailed analysis of the role of Building Management Systems (BMS) is provided, covering existing BMS solutions, their functions, and the significance of data collection and analysis in smart building management.

Sensors for Monitoring Indoor Environmental Conditions: this section lists the key sensors used in smart buildings. They can be grouped in the following categories:

- Air quality sensors
- Temperature and Humidity sensors;

- Light Sensors;
- Acoustic sensors;
- Occupancy Sensors;
- All-in-one or multi-sensors;
- Wearables.

The classification is based on the core components of IEQ (indoor air quality, thermal comfort, visual comfort, and acoustic comfort). Given the extensive range of parameters to be monitored, the aim is to identify the most critical ones necessary for a comprehensive and accurate assessment of IEQ.

Implementing a Management System for IEQ: Integrate data from different sensors, define which are the most important parameters in each case and allow users to provide specific feedback in real-time. The integration of AI and machine learning tools can be exploited for predictive analysis and model a tailored control system to adapt each single case to occupant's needs. The outputs can also be used to develop control strategies for HVAC systems including the feedbacks from the occupants.

Challenges and Future Directions: list of the most relevant difficulties encountered regarding efficacy of IEQ assessment schemes, divergencies between energy efficiency and IEQ improvements, technical limitations in monitoring environmental parameters, privacy concerns, integration between legacy systems and new technologies. The second part involve the possible future developments and improvements such as innovations in sensor technology and data analytics through AI and ML, the role of occupant feedback in system design/operation and how to incentivize the interaction between occupants and management system.

3.2. IEQ assessment in controlled environments

IEQ research can be carried out from a theoretical perspective, for example through detailed calculations or Computational Fluid Dynamics (CFD) simulations, also through practical field experiments and tests, as well as under controlled conditions. Ideally, both aspects should be combined to provide the most accurate results of IEQ analysis. As there are numerous tools and practices for CFD related simulations, less attention is drawn into field experiments in controlled conditions environments. Within this part of the task activities KTU FCEA and PoliMi members aimed to analyse existing environmental chambers across Europe and to observe the best practices applied.

3.2.1. Importance of research in environmental chambers

Environmental chambers are specialized infrastructures critical for controlled investigations into indoor environmental dynamics. Studies conducted in such chambers are essential as they provide a controlled environment to accurately assess various aspects of indoor air quality and environmental comfort, including VOC emissions from building materials, air flow dynamics and thermal performance of various building components. They facilitate detailed research on occupant thermal comfort, ventilation efficiency and the performance of innovative technologies such as phase change materials or passive cooling systems, etc. In addition, the chambers can simulate real indoor conditions, making the findings more reliable and easier to apply. It can also enable accurate validation of computational models, such as CFD and dynamic energy simulations

3.2.2. Review of environmental chambers and research practices

Within this task of the SmartWins project, a detailed review and systematic classification of environmental chambers employed in IEQ research across Europe was conducted. The main aim was to analyze and assess the methodological approaches and document notable research outcomes and innovations in this field. Conducted systematic state-of-the-art analysis revealed that there are numerous chambers across the Europe that differs in their technical parameters as well as the main research focus.

The methodological approach of the work was structured around three primary axes of classification: the scale of chambers, specific research focus and technological integration. Detailed categorization based on chamber scale included:

- **Small-scale chambers (area <10 m²):** these chambers are often used to conduct accurate studies on the emission of volatile organic compounds (VOCs) from building materials, to analyse airflow patterns in depth, to assess thermal performance and to evaluate the efficiency of specialised equipment. It should be noted that these chambers are rarely used for studies involving human subjects or thermal mannequins
- **Medium-scale chambers (area 10-25 m²):** commonly used for experiments investigating indoor environmental quality, including detailed assessment of thermal comfort, system optimisation and ventilation efficiency. Notably, a significant proportion of the studies (~70%) simulate occupancy in the

presence of humans or thermal mannequins, reflecting realistic scenarios for more practical insights.
- **Large-scale of full-scale chambers (>25 m²):** such chambers are typically used to test building envelope components, evaluate innovative materials and investigate their performance and impact on IEQ under near realistic conditions. Almost half of the studies analyzed involve human subjects or mannequins to simulate real usage of the premises.

The second axis of the classification was by specific research focus of environmental chambers, providing clarity on their application areas:

- **Indoor environmental quality** chambers mainly focus on the assessment of thermal comfort, ventilation efficiency and occupants' perception of environmental conditions. These chambers allow for a detailed investigation of comfort parameters such as temperature gradients, airflow distribution and people's reactions to different indoor conditions.
- **The energy efficiency and building envelope performance** chambers focus on the assessment of building materials, façade components and innovative insulation strategies to improve energy performance. This category includes the assessment of phase change materials, double façade and passive solar cooling and heating methods. However, even the main focus related to building components, impact to IEQ is also considered in most studies of such type.
- **The air quality and ventilation** chambers specialise specifically in ventilation efficiency, air pollutant dispersion and airflow dynamics. These chambers are essential for the investigation of innovative ventilation technologies, including displacement ventilation, merging flows and decentralised systems for optimising indoor air quality.
- **The extensive research focus** chambers are versatile rooms that can be used for a wide range of research applications, including the performance of HVAC systems, energy efficiency in buildings, and in-depth studies of indoor environmental quality. These adaptable rooms allow for large-scale studies and multidisciplinary research activities.

Considering the third aspect of classification, technological integration, detailed categorization based on chambers technological advancement indicated the most applied monitoring and control practices:

- **In-situ measurements and control**: The systems collect and store monitored parameters on-site using manual or semi-automated processes. Typically data is stored in data loggers, without remote connection. While this approach is simple, it can limit real-time analysis and remote access capabilities, which can affect operational efficiency.
- **Remote monitoring and control**: Advanced chambers with remote data access and control capabilities to facilitate real-time adjustments. Such features ensures flexibility and enable continuous real-time data access, which enhances operational flexibility, facilitates timely interventions, and supports international research collaboration
- **Not clear**: chambers with insufficient documentation to clearly identify technological integration, suggesting the need for improved methodological reporting in future research publications.

The systematic approach of this review and classification exercise provides a solid basis for strengthening collaboration and for the strategic development of a research infrastructure for environmental cameras in Europe. By understanding current capabilities, research directions and technological advances, future efforts can be strategically guided to address emerging IAQ issues, improve indoor comfort standards and achieve significant advances in building energy efficiency.

3.2.3. Outcomes of environmental chambers review

The systematic approach of this review and classification exercise provides a solid basis for strengthening collaboration and for the strategic development of a research infrastructure for environmental research chambers in Europe. By understanding current capabilities, research directions and technological advances, future efforts can be strategically guided to address emerging IAQ issues, improve indoor comfort standards and achieve significant advances in building energy efficiency. This structured overview can help to guide further research and increase the potential use of environmental chambers in EU-funded projects. However, this deliverable only reveals the main idea behind the analysis and the research carried out, as the detailed results, characteristics and conclusions is used in an open access scientific paper that is being finalised during the preparation of this deliverable.

3.3. Activities related to KTU's Energy and Microclimate Laboratory

Based on previous activities on the identification of the best practice and advanced IEQ assessment tools, as well as a detailed analysis of existing chambers and their monitoring, measurement and control equipment, the existing KTU Energy and Microclimate Laboratory has been analysed in detail, with a focus on the possibilities for improving its technological integration. The core objective of this assessment was to understand and document the current operational principles of the equipment installed, identifying how these systems can be upgraded or connected for enhanced digital and remote management.

Overall, the comprehensive assessment has led to a digitisation roadmap that demonstrates the significant potential for integrating advanced automation and remote-control technologies into existing laboratory infrastructures. Such improvements could considerably increase the operational efficiency, experimental precision and resource sustainability of the KTU Energy and Microclimate Laboratory.

The envisioned digitisation concept consists of two main phases. The first phase would focus on the integration of advanced monitoring instruments and software. A detailed list of requirements is provided in the following subsection.

3.3.1. 1st Phase – Monitoring devices and software

The main objective of this phase is to create a digital twin of the lab space with one-way data flow. In order to do this, the monitoring equipment should be selected according to the expected criteria of monitoring range, accuracy, response time, connectivity features

Table 1. At this stage, dedicated software should be developed that can process all the data streamed and collected by the monitoring equipment, and display it spatially, numerically and visually, using best practices for a digital twin.

Key features for the solution:

- Real-time data visualization.
- Spatial representation of monitoring points and its values in digital twin environment.
- Historical data access and visualization.
- Warnings of potential failure/faulty measurements.
- Intuitive user-friendly solution.

Scalability and interoperability:

- The system should be able to collect data from a wide range of measuring devices, as well as to receive data from physical HVAC equipment devices (existing and foreseen), such as sensors, actuators, controllers, etc.
- The system should be flexible and easy expandable by adding new HVAC equipment or measuring devices without disrupting the existing system. Adding new device should be as much user-friendly as possible.
- The system should adhere to industry-standard communication protocols, ensuring interoperability with a wide range of HVAC equipment or measuring, control devices.
  This includes compatibility with common standards such as BACnet, Modbus, MQTT, BLE, Zigbee or other relevant protocols commonly used in the IoT industry.
- Scalability tests and performance optimisation measures should be carried out to assess the ability of the system to efficiently add and manage the increasing number of sensors, devices, users and data.
- The system should be pre-designed for 2nd Phase implementation which includes control devices and bidirectional data flow.

Accessibility and security:

- The system should have remote connectivity for users, allowing them to access it via the internet from any location.
- The system should have password protection (with mechanism for password recovery and reset) and access control levels (administrator, user, service) to ensure authorized access to the system.

- It should be foreseen that in the 2nd Phase, control actions will only be allowed to the basic user after approval by the administrator. Only one user at the time should be able to make control actions.
- Historical data should be protected against unauthorised attempts to delete it and should only be allowed with administrator access and an additional password.
- The system should employ industry-standard encryption protocols to safeguard sensitive data. This includes incorporating robust encryption algorithms for data in transit (e.g., HTTPS for secure data transmission) and data encryption at rest to protect information stored within the system.

Usability and User Experience:

- The system and user interface should be available in English and Lithuanian languages.
- The system should have an intuitive interface with clear navigation, logical menu structure, and consistent design elements to enhance user understanding and interaction. The user interface elements, such as buttons, colour schemes, and typography should create a cohesive and visually pleasing experience.
- The user should have an option to modify the spatial placement of the sensor/monitoring device in digital twin environment without disrupting the assigned data flow. Sensor representation should have lock/unlock button that allows to move it in the software.
- Digital representation of the laboratory and connected measurements should have all 3D viewer features, such as, but not limited to – rotation, zoom, tilt, section view, etc. Supported format for 3D representation - .ifc file.
- The system should offer a personalized experience, providing features like customizable dashboards and preferences, such as the ability to select units of measurement.
- UI window should have a clear icon “Start the experiment”, “Stop the experiment”. After “Start the experiment” button is pressed, the user should be requested to select the parameters that he wants to monitor and add to report. After all the parameters are set, additional “Run” button should appear. Selected parameters during the period between “Run” and “Stop the experiment” should be reported in selected manner. More in Reporting section.
- The user should have an option to select between different types of real time and historical data visualization – graphs, numbers, bars, pies, etc.

- The user should be able to select the period of historical data and retrieve the data in the window (graphs could be default view). Selected period data should be able to be reported. More in Reporting section.
- The user interface should feature clear and concise supporting instructions to assist users in navigating and utilizing the application effectively.
- The system should have clear and immediate feedback mechanisms to communicate with users, providing information on the success of their actions, alerting them to errors, and reminding them about maintenance tasks.
- The system should have an automated recovery.
- The system should integrate comprehensive user documentation tailored for distinct access levels (user and administrator), encompassing detailed user manuals and guides. Additionally, the system may include a support feature, such as Frequently Asked Questions (FAQs).

Reporting:

- The system should support the export of data in various formats, including PDF, XLSX, XLS, CSV, ensuring compatibility with different analytical tools.
- Users should have the option to choose the type and structure of reports generated by the system, allowing for personalized and relevant information. Selection of relevant information to be reported could cover time period, parameters selection, granularity of data, type of visualization, etc.

Communication Protocols:

- The system should support communication protocols commonly utilized in HVAC systems and IoT devices, such as but not limited to: BACnet, Modbus, MQTT, BLE, Zigbee, Ethernet/IP, HTTP/HTTPS etc.
- The communication protocols chosen should be applicable to both legacy and modern HVAC and measurement equipment. The chosen solution should also be adaptable to the extension of new HVAC or monitoring equipment and devices.
- Protocols chosen should support real-time data exchange, allowing for timely responses and actions in the HVAC system or other type of actuators.
- Documentation detailing the implementation and usage of each supported communication protocol should be provided.

Backup, Recovery Strategies:

- The system should be designed to autonomously execute periodical data backup process. It should create copies of essential data and system configurations.
- The system should have a documented and tested recovery procedure outlining the steps to efficiently restore data from backups in the event of data loss due to hardware failures or other issues.

Redundancy, and Failover Strategies:

- The system should have redundancy by duplicating critical system components, such as servers or data storage, to mitigate the risk of a single point of failure.
- The system should have an automated failover mechanism to seamlessly switch to backup systems in case of primary system failure, ensuring uninterrupted HVAC control operations.

Feedback:

- The system should have feedback mechanism which allows user to communicate the problems or suggestions for software. Feedback mechanism should have the main features: select the category of the of the feedback, write a comment and attach the screenshot of the problem if needed.

Data privacy:

- Compliance with relevant data privacy regulations, such as GDPR, or other applicable standards for measured, monitored, streamed and stored data should be implemented.
- Measures to protect sensitive information and personally identifiable data should be implemented.
- The purpose of the data collection should be clearly stated and explicit consent obtained before the user starts to use the system and equipment.

Data retention policy:

- There should be an option to configure retention periods based on administrator user specific requirements for both real-time and historical data.
- Automatic purging mechanisms should be implemented to delete data beyond the defined retention period.
- Data retention policies should be clearly communicated to users before using the system.

Data collection:

All the parameters should be collected based on the defined intervals in the

- Table 1 with the ability to edit data granularity. This applies to newly installed sensors, monitoring devices. Existing infrastructure data can be stored at the shortest possible periods, if it exceeds secondly granularity.
- The user should be able to select data collection intervals before starting the experiment.

Table 1. Monitoring equipment and requirements

Parameter	Unit	Measurement points	Measuring range	Accuracy	Response time	pcs
Air temperature	°C	Sitting: 1.1m, 0.6m, 0.1m; Standing: 1.7m, 1.1m, 0.1m	10 °C to 40 °C	Required: +-0.5°C; Desirable: +-0.2°C	The shortest possible	16
Relative humidity	%		25% to 95%	+- 5%		
Mean radiant temperature	°C	Depends on the aim of the research	-40 °C to +150 °C	Required: +-2 °C; Desirable: +-0.2 °C	The shortest possible	1
Air velocity	v_a, m/s	Depends on the aim of the research	0.05 m/s to 1 m/s	Required +- (0.05+0.05 v_a) m/s; Desirable +- (0.02+0.07 v_a) m/s	Required: 0.5s; Desirable: 0.2s	6
Surface temperature	t_s, °C	Cooled wall, wall, floor	0 °C to 50 °C	Required +- 1 °C; Desirable +- 0.5 °C	The shortest possible	10
CO2 concentration (ISO 16000 P.26, ASHRAE62.1-2022)	ppm	Shall not be installed in zones with indoor sources of CO2 other than occupants, or with CO2 removal mechanisms. Height of 1.5m, min1-2m from the walls	1 ppm to 5000 ppm	±10 to ±75 ppm		4
VOC concentration (ISO 16000 P.5, 9, 10, 25, 29)	µg/m³		0 to 2.5x107 µg/m³	within ±20% of indication value	300s or less	4
Illumination (BS 667:2005)	Lux	Depends on the aim of the research	0 lux to 100000 lux	±1% of reading (maximum acceptable error over effective range)		4
Air flow (ISO 17089-2:2012 P.2)	l/s	Supply/extract ducts, air terminals ducts		within ±1.5% to 5%		6
Supply/extract air temperature	°C	Supply/extract ducts before chamber				2
Windows/doors	O/I	Door/window frame	-	-	-	2

3.3.2. 2nd Phase – Controlling device and software improvement

The main objective of this phase would be to enable bi-directional data flow to enable control actions for the HVAC system and its supplementary components. To achieve this, additional actuators or equipment may need to be purchased and integrated into the existing infrastructure. Additional monitoring and control should be selected according to the expected criteria of accuracy, response time, connectivity features. At this stage, previously developed software should be upgraded to enable control actions by the user and to provide additional information on system components, actuators position, etc.

Key features for the upgrade:

- Control actions using virtual representation of the laboratory;
- Real-time data visualization of system components, actuators status;
- Warnings of potential failure/faulty control actions;
- Intuitive user-friendly solution.

Priority should be given to the use of existing infrastructure and the sensors of already installed HVAC systems, rather than acquiring new measuring equipment that measures the same parameters.

All the specific requirements for the 1st Phase have to be met also during the 2nd Phase.

Control actions:

- The following control actions have to be enabled during the 2nd Phase implementation:
    1. Set supply/extract air flow (main unit);
    2. Modify supply/extract air flow to classroom;
    3. Modify supply/extract air flow to Laboratory;
    4. Modify supply/extract air flow in each diffuser;
    5. Set supply air temperature (with cooling, heating enabled);
    6. Set supply air humidity;
    7. Release fog to supply air;
    8. Set room temperature with radiator (heating);
    9. Set room temperature with underfloor heating (heating);
    10. Set external wall temperature (cooling).
- The system should be designed and implemented in such a way that all control actions can be performed remotely. The system should also provide the status of devices and actuators (open, closed, 50%, etc.).
- Basic users must be restricted in their control actions. There should be an option for the administrator to allow the basic user to perform control actions, and only within a specified time period.

- When implementing control actions, it should be requested to specify the period for which the set parameters must be maintained. After this period, the system should send a warning message asking whether the existing conditions should be maintained or whether it can be switched to standby mode. If no response is received within 30 minutes, the system should switch to standby mode.
- Scheduling option has to be enabled where users can set the parameters and the system to automatically adjust the operation of the HVAC equipment at specific times.
- The system shall indicate to the user if the set parameters do not meet the boundary conditions and cannot be maintained. It shall also indicate whether the set conditions correspond to 80 % of the capacity of the HVAC equipment.

3.3.3. Outcomes of activities related to KTU's Energy and Microclimate Laboratory

Since the main aim of this task was identification of the best practices and procedures for an advanced IEQ assessment, digitisation of the existing Laboratory was not one of the task's objectives but KTU SEBERG and PoliMi researchers have made additional efforts to increase their potential for comprehensive and accurate future research in the field of IEQ assessment. In this context, based on the best practices obtained and identified, detailed specifications covering the afore mentioned aspects have been developed and the possibilities for such improvements have been discussed with the technology providers. However, no actual implementation actions are foreseen during project duration.

3.4. IEQ assessment in operational conditions

Another focus within this task was IEQ related assessment within the operational conditions of building, which provides an opportunity to analyze building systems and indoor environment parameters under varying conditions and scenarios. It provides additional value, as some of the scenarios cannot be fully implemented or taken into account during the tests in controlled environments, such as chambers.

3.4.1. Methodology of the field practices for integrated assessment of buildings

The work related to field measurements and integrated assessment approach, that also covers monitoring and assessment of IEQ parameters, as an integral part of energy audits, is presented in the research article "Digitizing buildings sustainability assessment: integrating energy audits, operational energy assessments, and life cycle assessments for enhanced building assessment", published by P. Spudys, A. Jurelionis and P. Fokaides, https://doi.org/10.1016/j.energy.2025.134429.

The presented approach addresses the practical challenges of accurate IEQ and related parameters evaluation by capturing the authentic interactions between building occupants, operational practices and building systems under real-life conditions. In addition, the study focuses on reducing building energy demand, which is directly related to ensuring sufficient IEQ for occupants.

A key part of the innovative approach in this study was the integration of advanced digital methodologies into the practice of field experiments. Digitalisation allowed to transform conventional energy audit, operational and life cycle assessment methods from manual data collection and processing, which is usually labour-intensive, error-prone and time-consuming, to continuous, accurate and automated monitoring and calculation. Using smart meters, IoT sensors and Building Information Modelling (BIM) technologies, the developed framework significantly improved the accuracy and efficiency of IEQ data collection, capturing key parameters such as temperature, humidity, air quality and user behaviour directly in the operational environment.

Figure 12 presents an integrated monitoring infrastructure workflow that was developed to enable the continuous monitoring and processing of IEQ and energy-related parameters, such as natural gas consumption, electricity use, heating efficiency, temperature and humidity. This infrastructure (Figure 13) uses advanced IoT sensors and smart meters that communicate over multiple data transfer protocols including HTTP, Wi-Fi, Modbus, Zigbee and WM-Bus to facilitate reliable data collection and flexibility. Collected data is centrally managed through gateways (Wi-Fi/LAN, M-Bus, Zigbee) and cloud platforms, allowing seamless integration of data from different sources and brands. This allows scalability and inclusion of other related parameters for the continuous monitoring. Data is stored and processed using Home Assistant and InfluxDB, ensuring organised data management, analysis and visualisation. This set-up significantly enhances real-time monitoring and historical analysis capabilities, allowing for detailed IEQ assessments based on authentic operational scenarios. Overall, the framework presented is a practical, scalable methodology developed in the context of the study to efficiently integrate different data streams. The developed approach provides the tools needed to accurately and continuously assess IEQ and energy-related indicators, gathering information on building management, indoor environment and sustainability practices in a real environment at selected levels of detail.

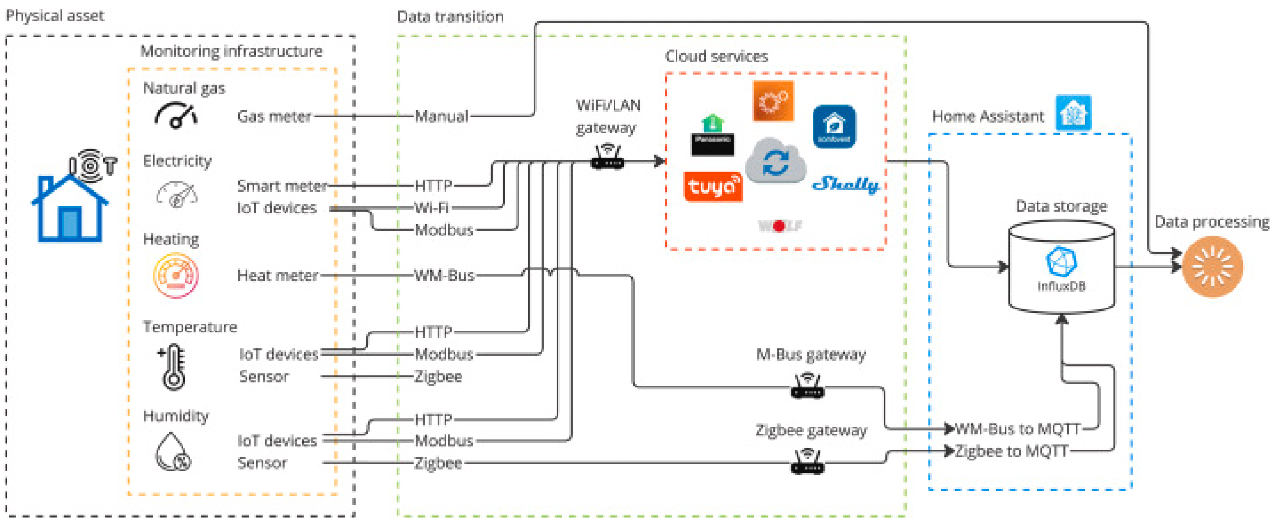


Figure 12. Data collection and processing architecture

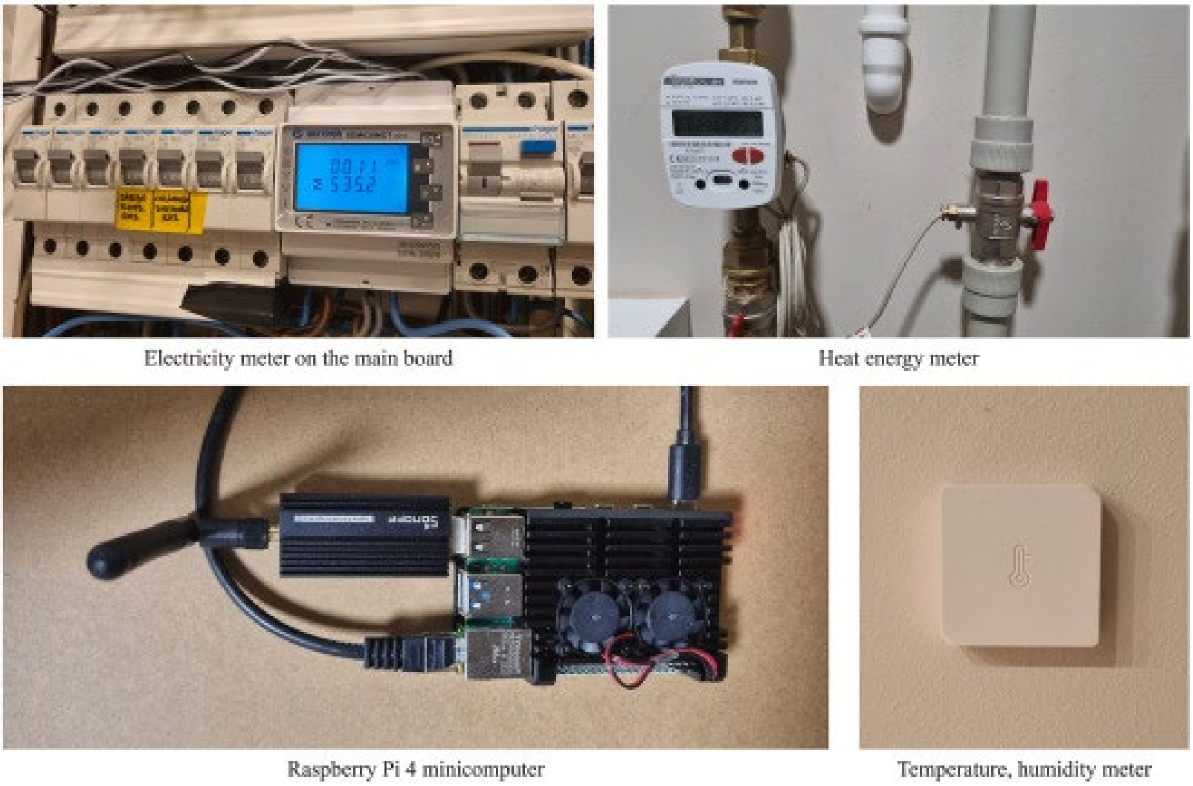


Figure 13. Monitoring infrastructure

A case study was carried out to demonstrate the practical application of the proposed workflow in integrating digital technologies for continuous assessment of building. The case study phase included data collection and processing of the following:

- Development of comprehensive as-built BIM model, that that provides structured information about the building elements, materials at the required level of detail.
- Live and historical one year period monitored data of energy and IEQ related parameters.
- Information on occupants behaviour, such as occupancy, occupancy patterns, lighting control and other indoor environmental conditions preferences.
- Comprehensive records of maintenance and operational activities that may have influenced the efficiency of building systems.

3.4.2. Outcomes of integrated assessment of buildings

The assessment framework developed includes digitally enhanced energy audits, continuous operational energy assessment and a life cycle assessment focusing on energy savings, at the same time while ensuring sufficient IEQ. An extensive IoT network continuously provided high-resolution data on key IEQ and energy-related parameters and occupant presence, enabling detailed insights into the building's behaviour under different operating conditions throughout different seasons. A significant contribution of this digitised approach is the improved ability to assess trade-offs between energy efficiency, environmental sustainability while maintaining optimal indoor environmental quality. The study also proposes a new indicator allowing to assess the relationship between embodied carbon emissions and IEQ-related energy savings, helping stakeholders to make decisions that optimise both occupant comfort and environmental performance.

3.4.3. IEQ monitoring in operational conditions – key challenges identified

Additional research was carried out to identify current challenges of IEQ and related parameters monitoring in building under operational conditions. Research conducted provides insights into the challenges and solutions related to the digitalisation of indoor environmental quality monitoring, based on the real experience of KTU SEBERG research group. The study, carried out in the frame of SmartWins project, focuses on the employment of digital technologies such as IoT, BIM, digital twins for IEQ monitoring in an existing academic building, providing a practical example of how it can be scaled up and sustainably implemented in the built environment.

The study highlights some of the main challenges that occurs during the implementation of advanced IEQ monitoring under operational conditions. A key aspect is the same as in previous study, **interoperability** - managing data formats and communication protocols between different sensor manufacturers and BMS suppliers. The lack of standardisation in the equipment protocols requires custom middleware solutions and pre-processing to unify the time series data structures. Another major challenge concerns the geometrical representation, when photogrammetry, LIDAR scanning and semantic BIM models provide different granularity and file formats that need to be combined for accurate geolocation, alignment, and meaningful spatial data mapping.

Data classification is also considered to be a crucial component that could be challenging. In large datasets, especially in systems where multiple parameters are monitored, data classification is a crucial step in organising and ensuring that the right data are accurately analysed. In order to link a specific device or monitored parameter with a BIM attribute or a specific building element for analytical or visualisation purposes, the value of the parameter should also include an explicit identification component. For this purpose, tags are typically used to provide relevant contextual information.

Effective **visualisation** of monitored parameters is essential to interpret complex IEQ data both for research and system managing purposes by different stakeholders. However, integrating large amounts of heterogeneous data, such as environmental measurements, occupancy levels and spatial representation, into clear and intuitive visual interfaces is a non-trivial task. The variety of formats and sampling intervals often requires adaptation of the visualisation workflow.

In addition, **cyber-security** issues arise due to the distributed and internet-connected nature of IEQ monitoring systems. With multiple IoT devices, cloud APIs and third-party services, the system is exposed to external threats, including data breaches, unauthorised access and service disruption. The secure operation of such a network requires robust, but often costly and technically complex security strategies. In addition, the lack of standardised security protocols across devices and platforms hinders implementation, especially in multi-vendor environments.

Even there are many challenges identified, KTU SEBERG have successfully developed digital twin that incorporates a complex infrastructure consisting of IoT devices, building management systems, and data gateways to monitor over 2000 parameters in real-time. These parameters include air temperature, humidity, CO_2 levels, volatile organic compounds (VOCs), noise, light, motion, occupancy, and energy consumption. Integration of these diverse data sources is achieved through open-source platforms such as Zabbix and Grafana, allowing seamless data aggregation, processing, and visualization.

The challenges identified and the actions taken to address these challenges are documented and will be presented as a CLIMA2025[1] conference paper by P. Spudys, R. Scoccia, D. Pupeikis, A. Jurelionis, P. Fokaides, L. Mazzarella, entitled Challenges in Digitizing Indoor Environmental Monitoring: Insights from the IEQ Monitoring Systems at Kaunas University of Technology.

The paper shows how through developed digital twin solution (Figure 14) holistic and field-based IEQ assessment can be facilitated, overcoming barriers related to data integration, system compatibility and visualisation (Figure 15), as well as cyber security. The methodology presented can be further improved and applied to future EU initiatives aimed at standardising and extending digital IEQ assessment practices.

[1] https://climaworldcongress.org/0

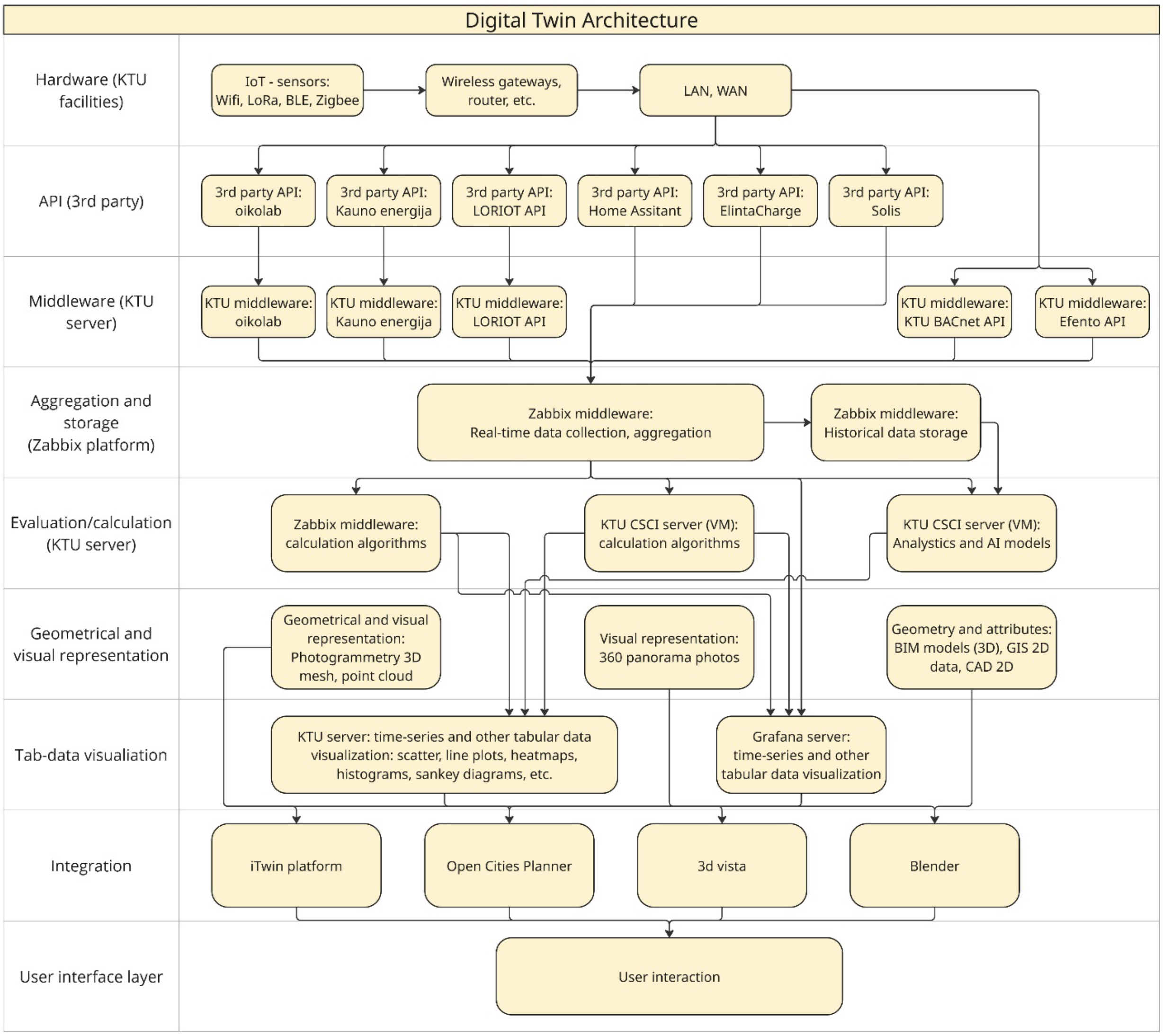


Figure 14. KTU's digital twin architecture

Figure 15. 360º tour integration with monitored IEQ parameters

4. Gained Knowledge by KTU

Throughout the activities of Task 1.2 “Indoor environmental quality assessment with smart sensors”, Sustainable Energy in the Built Environment Research Group has significantly enhanced its expertise and practical knowledge in the field of IEQ assessment using smart sensors and advanced digital tools. This newly acquired or enhanced knowledge has been gained through (i) a comprehensive review of existing IEQ measurement methodologies and best practices, (ii) a direct analysis of environmental chambers and their application in research, and (iii) an on-site assessment of actual buildings and their operating conditions. In addition, KTU's collaboration with other consortium partners, in particular in the research on cutting-edge monitoring technologies, digital twins and occupant-oriented control methodologies, has strengthened the SEBERG capacity to lead robust IEQ research initiatives and to contribute to the development of strategies for IEQ improvement in the wider research community. The following is a comprehensive overview of the competences and insights gained during the implementation of this task.

4.1. Expanded understanding of IEQ principles and standards

One of the initial outcomes of the KTU SEBERG was the establishment of a comprehensive approach to understand and assess IEQ. By combining insights from literature reviews, technical standards and real-life case studies, the researchers gained a better understanding of the topics in the following sub-sections.

4.1.1. IEQ dimensions and indicators

KTU SEBERG researchers have strengthened their knowledge of the four main aspects of IEQ - thermal comfort, indoor air quality, acoustic comfort and visual comfort - while taking into account related factors such as humidity control, material off-gassing and occupant control over their environment. This multi-parametric approach highlights that a building with a high score in one parameter (e.g. thermal comfort) may still not provide overall occupants comfort if other aspects (e.g. acoustic conditions) are insufficient.

4.1.2. Existing regulatory frameworks

Familiarity with technical standards, including ISO 16814 for IAQ, ISO 7730 for thermal comfort, and ISO 16032 for acoustics has allowed KTU to link its measurements to recognised international guidelines. Furthermore, familiarity with the TAIL (thermal, acoustic, indoor air and light) scheme has expanded KTU's capacity to carry out more comprehensive IEQ assessments in line with the latest research directives. Such practices help KTU to conduct research on more balanced improvements in buildings, promoting occupant-centric comfort across all domains rather than a singular focus on aspects such as energy efficiency or sustainability.

4.1.3. Health oriented approach

KTU SEBERG members has gained a better understanding of the links between IEQ and occupant well-being, including the amount of moisture in buildings (mould risk), building materials as sources of pollutants, and the vulnerability of occupants to airborne infections. This understanding is particularly important in the context of the increasing focus on occupant health in the post-pandemic era, which has led to widespread interest in infection risk modelling, better ventilation and monitoring of occupant behaviour.

4.1.4. Infection risk mitigation

By looking at simplified mass balance or Wells-Riley models of viral transmission, KTU researchers have learned to incorporate health risk factors into IEQ analysis. Real-world consequences, such as the effect of air recirculation in central HVAC systems or the distribution of people indoors, are now more prominent in KTU's research proposals and building design guidelines.

Overall, this broadened IEQ perspective not only influences KTU’s research direction but also enriches teaching perspective, enabling future engineers and architects to design healthier and more environmentally responsible buildings.

4.2. Improved understanding of IoT devices and architectures for IEQ assessment

Task 1.2 provided a unique opportunity for SEBERG members to delve into advanced sensor technologies and the communication infrastructures that enable real-time IEQ parameters monitoring and processing.

4.2.1. Comprehensive analysis of sensors

SEBERG researchers significantly expanded their knowledge of available commercial and research-grade solutions for an advanced IEQ assessment. They examined gas-phase pollutants (CO_2, CO, NOx, VOCs), particulate maters sensors (PM2.5, PM10), thermo-hygrometric sensors for temperature and humidity, illuminance and daylight sensors, acoustic sensors for sound pressure level, and occupancy sensors employing infrared, ultrasonic, or image-based detection. By assessing sensor accuracy, calibration needs, and connectivity options, SEBERG is now able to better define the equipment needs and requirements for various use cases.

4.2.2. IoT-enabled data flows

KTU strengthened its competence in multi-layer data collection architectures. That were presented in this report. This also involves:

- **Perception Layer**: Collecting raw measurements from distributed sensors.
- **Network Layer**: Transferring and storing data using various protocols such as Modbus, MQTT, Zigbee, Wi-Fi, etc.
- **Application Layer**: postprocessing of collected IEQ related measurements using advanced tools for data analysis, visualizing the results in various forms and environments.

Being able to develop and maintain such IoT ecosystems is a crucial skill, as built environment is transforming to digital world, especially as buildings grow more interconnected through occupant feedback loops, occupant preferences, and advanced building monitoring and automation systems.

4.2.3. Data validation and quality assurance

KTU also increased knowledge of the importance of systematic calibration and data maintenance procedures. Over time, sensor drift can compromise research or building management strategies, complicate occupant safety measures or undermine occupant confidence in the system. Learning how to schedule sensor inspections, back up datasets and detect anomalies in real time lays the foundation for reliable long-term IEQ monitoring.

4.2.4. Occupancy sensing and behavioural data

Another area where SEBERG researchers deepened its knowledge is occupant-oriented data collection. Researchers have explored the potential of motion sensors, CO_2 signatures and wearable devices (e.g. smart bracelets) adoption to map occupant patterns and behaviours. Such data is essential for the research topic related to user-centric building systems and equipment, which can reduce energy use based on real occupancy rather than static timetables.

By absorbing these insights, KTU has expanded its capacity to undertake large-scale sensor deployments, ensuring that future projects meet both the academic and industry needs for real-time, data-driven energy efficiency and sustainability oriented solutions.

4.3. Enhanced perspectives on environmental chambers and related research

In parallel to previously explored topics, SEBERG members comprehensively reviewed existing environmental chambers and best practices that provided valuable lessons on how experiments in controlled environments can inform and complement field-based studies.

4.3.1. Typological analysis of IEQ chambers across Europe

Comprehensive literature analysis revealed that environmental chambers vary considerably in size (small chambers up to 10 m², medium chambers up to 25 m², and large chambers or full-scale chambers larger than 25 m²), and in the specific purpose of the research (studies on ambient air quality, building envelope performance, occupant behaviour and energy efficiency). By comparing methodologies applied in different types of chambers, KTU researchers now have a background of various methodologies depending on the research scope and layout of the chambers, that can be adopted to their research topic. Additionally, the analysis also allows researchers to understand which research directions are most critical and to identify new research gaps.

4.3.2. Implications for KTU's Energy and Microclimate Laboratory

KTU performed a comprehensive assessment of its own laboratory's setup, identifying areas where investments in remote sensors, occupant simulation (via mannequins or volunteer participants), improved data logging, and real-time parameter control would provide more robust results and expand research topic. This process led to a two-phase digitization plan:

- **Phase 1**: Emphasizing real-time monitoring, sensor integration, and the creation of a digital twin for one-way data flow and thorough data visualization and processing platform.
- **Phase 2**: Expanding the capabilities of the Phase 1 by including two-way data streams - enabling direct control of HVAC setpoints, monitoring and other

research related equipment parameters as well as system scheduling within the same platform.

4.3.3. Potential for collaboration

By mapping European environmental research chambers, KTU has also identified potential partners for future collaborative experiments or comparative studies. This allows the exchange of knowledge on both hardware (sensor arrays, occupancy dummies, etc.) and software (data analysis tools, occupant feedback loops, etc.) and promotes closer cooperation within the EU network of IEQ research utilizing controlled environments.

4.3.4. Experimental protocols

Given that a key advantage of environmental chambers is the capacity to isolate variables (e.g., occupant load, air changes per hour, or specific pollutant sources), KTU researchers have improved their understanding of how to design robust experimental protocols. These protocols ensure repeatability, facilitate multi-parameter correlation studies, and reduce uncertainty factors that might otherwise be unavoidable in field experiments.

4.4. Field-based IEQ assessment and integrated building assessment

In parallel to exploring controlled-environment research, KTU placed substantial focus on assessing IEQ under real operational conditions within existing buildings that included:

4.4.1. Integrated assessment methodologies

A highlight is the combination of conventional energy audits, operational performance assessment, and sustainability studies into a single framework while at the same time digitizing the procedures using extensive IoT network, as well as BIM and digital twin technologies. While energy audits typically target energy-saving opportunities, an important constituent part is focused on indoor environment conditions. As reduction of ventilation rates might save energy but reduce indoor air quality and increase the risk of hidden mould or moisture, or both combined, it is important to take into account all the factors during comprehensive building assessment. By integrating all the procedures into unified framework, KTU researchers can now examine more holistic strategies to improve IEQ while at the same time improving energy efficiency and considering environmental performance of buildings.

4.4.2. Continuous monitoring

By using various middleware and IoT devices solutions in real-life case studies, KTU has adopted and improved their expertise in continuous, high-resolution IEQ and energy-related data collection. Opposite to periodic measuring, continuous monitoring provides opportunity to capture occupant behaviours, short-term spikes, or equipment malfunctions in near real-time. This approach and collected data also lay a foundation for future advanced data analysis, such as predictive models, which can be used to detect anomalies, occupancy patterns and other changes in the systems in order to sustain optimal performance of building services.

4.4.3. Data interoperability challenges

In field deployments, KTU researchers encountered heterogeneity among different sensor and IoT devices vendors, BMS suppliers, communication protocols, and data file formats. During the duration of the project, members improved their practical knowledge and ability to design “middleware” solutions that helps to unify data streams and data postprocessing procedures. Researchers now anticipate the importance of standardized data models (e.g., using consistent naming conventions, timestamps, or building geometry references), as well as data classification tags such i.e. embed location, device ID, and parameter type.

4.4.4. Occupant engagement

By analyzing occupant patterns and occupant surveys, SEBERG members had opportunity to deepen their understanding on how occupant behaviour and building systems interact. Such insight enables a better planning process of future experiments where occupancy will be considered in IEQ chambers or field studies experiments, so that building users become active participants, rather than passive subjects.

4.5. Strengthened collaborative and research capabilities

Beyond technical growth, KTU SEBERG researcher also benefited from collaborative networks and community-building:

4.5.1. Enhanced interdisciplinary approach

Activities performed under Task 1.2 required a synergy between different fields such as building physics, IAQ, data science, programming, design, etc. During the activities KTU researchers improved their skills in collaboration among different disciplines with the aim to ensure that conducted research and findings are truly integrative. This holistic approach is especially beneficial for large-scale EU projects that require broad-based solutions for occupant well-being, as well as these skills are beneficial in many other research areas.

4.5.2. European networking and co-authoring

By directly engaging with other SmartWins partners, in the context of this task especially PoliMi, SmartWins researchers already published one research paper, as well as finalizing other two during the preparation of this deliverable, and planning to present their finding in scientific conference together with conference full-paper prepared. Furthermore, KTU and other partners strengthened their relationships and collaboration potential that pave the way for future joint publications, research proposals, and other activities. With an improved understanding of the capabilities and areas of expertise of each partner and their laboratory, KTU SEBERG can now more easily propose further activities and efficiently suggest roles and responsibilities in international projects.

4.5.3. Educational evolution

KTU is integrating its newly acquired knowledge into study programs related to building services design and control. Acquired knowledge is integrated into bachelor's and master's degrees studies through expanded definitions of overall IEQ concept and case studies that reveals how occupant comfort ties into energy system design, occupant behaviour, sensor calibration, data security, and advanced occupant monitoring. Additionally, PoliMi is continuously and strongly supporting KTU in its educational activities with its expertise and presence in joint lectures already two years in a row. With this support KTU is able to provide the students possibility to become the professionals, able to combine the well-being of occupants with the technical details of modern buildings.

4.6. Conclusion on the acquired knowledge

To conclude, KTU SEBERG researchers in Task 1.2 acquired knowledge that is broad and deep. On the one hand, researchers now have a comprehensive theoretical framework for IEQ assessment covering relevant standards, occupant health, virus risk mitigation, sensing technologies, building physics, etc. On the other hand, they have accumulated a significant amount of practical experience, from designing and implementing IEQ and energy related parameters monitoring networks to creating a roadmap for the digitisation of the KTU's Energy and Microclimate Laboratory.

By combining continuous IEQ monitoring, occupant-oriented data analysis, infection risk modelling and robust remote monitoring practices, KTU is well equipped to meet the challenges of tomorrow's built environment. This integrated vision goes beyond short-term applications; it contributes to the SEBERG research trajectory, fosters interdisciplinary collaboration and raises the benchmark for occupant health and comfort in buildings. The competences developed in Task 1.2 is expected to be continuously developed, not only through academic research, but also through practical, tangible improvements for actual buildings and the occupants within these buildings.

Significantly important outcome of Task 1.2 activities is the possibility to establish and expand collaborative networks. By collaborating closely with project partners, including advanced European research institutions with specialised environmental chambers, KTU has gained new perspectives on common challenges and best practices in the implementation of IEQ assessment. This cooperation is set to continue with new joint initiatives to accelerate the deployment of technologies that meet the needs of building occupants, both in academia and in studies.

5. Conclusions

The work carried out in Task 1.2 emphasises the fact that indoor environmental quality encompasses four main interrelated components - thermal comfort, air quality, acoustics, visual comfort - all of which need to be considered together in order to ensure that indoor environments are safe and suitable for occupants. Furthermore, each component includes number of related aspects that in overall affects IEQ level, i.e. air quality is dependent on air pollutants' concentrations, air velocity, ventilation rates, effectives, etc. A thorough review of standards, existing research practices, environmental chamber studies and field research has revealed some key insights that can be beneficial for research communities, as well as for KTU SEBERG members, considering their enhanced understanding and experience in the field of IEQ assessment using advanced methods.

First, a literature review of advanced tools and practices for IEQ assessment have been done. Focusing on the following research questions: understanding IEQ; definition of smart buildings; sensors for monitoring IEQ; implementing a management system for IEQ; challenges and future directions.

Exercise related to comprehensive analysis of existing environmental chamber across the Europe allowed to understand the typology, measuring and monitoring equipment, types of the research performed and best practices of the usage of such infrastructure. Furthermore, insights observed allowed SEBERG members to critically analyze existing KTU's Energy and Microclimate Laboratory within the aim to assess the possibility to adopt the best practices and upgrade existing equipment through the lens of digitisation. As a result, a detail roadmap of digitization and improvement was prepared, but the implementation actions are outside the scope of the project and are not foreseen to be implemented during the project duration. However, it provides a solid basis for future improvements after the end of project.

Another research activities implemented concludes that adoption of smart sensors and IoT, BIM and digital twin technologies can significantly increase the completeness, reliability and availability of IEQ assessment both in fully controlled environments, such as IEQ chambers, and in field experiments in operational buildings. By adopting a variety of interlinked sensors (temperature, humidity, ventilation rate, air pollutants, light and sound level), researchers are able to collect and analyze large amounts of IEQ and energy related data with much greater accuracy and increased time and cost efficiency.

Another key development is the methodology for integrated building assessment that covers energy audits, operational performance and sustainability assessment through the lens of digitization. Several documented research activities show the importance of holistic assessment and focus on energy and IEQ related parameters when considering energy efficiency improvements in buildings. When energy performance data are compared with measured IAQ, thermal comfort and acoustic performance, it becomes clear that building performance measures need to be aligned with the needs of the occupants, especially in terms of ventilation intensity, temperature control and lighting adequacy. Such integrated approach prevents the risk that energy efficient buildings may unintentionally compromise comfort or health over the energy efficiency.

Finally, research conducted and insights observed under Task 1.2 activities further confirms that occupant-oriented, data and health-based building systems are key to achieving the safe and resilient indoor environments. As buildings become more and more digitally represented and connected, the ability to integrate high-resolution monitoring data, user feedback and predictive analytics will only accelerate. The results presented in this deliverable provides a solid foundation on which to build future SEBERG research activities, in particular scaling up digital twin solutions and occupant-centric management to full-scale pilot demonstrations. By combining occupant comfort, sustainability, and innovative research practices, the results of Task 1.2 contribute to the establishment of knowledge on the evaluation of indoor environmental quality assessment practices using advanced tools and methods, ensuring that future initiatives can draw on robust data-driven approaches for optimizing occupant well-being and building performance.

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