CETIEB - Final publishable summary

1. *Executive summary*

Overview

The Energy Performance of Buildings Directive (EPBD) leads to energy efficient buildings. In future net-zero-energy buildings will be the state of the art. Concerning existing buildings refurbishment to an energy-efficient standard leads to tight buildings and affects the indoor climate whereas users are not adapted to this new situation. The air exchange rates could be lower than required if no mechanical ventilation is installed or the system performance is not optimised. Then, in trying to increase the energy performance of buildings, the indoor environment quality is often degraded.

People in Europe spend more than 90 % of their time indoors. Improving the health and comfort of the European population in those spaces consequently creates a huge potential of economic and societal benefits, manifested in increased productivity, reduced sick leave and medical costs, but also by the prevention of potential liabilities. There is clearly a need for developing new methods for continuous detection of indoor pollution considering all key factors and for studying and identifying the best systems that allow an efficient control of the indoor environment.

Objectives

CETIEB addressed three main objectives:

- Development of monitoring systems (wireless and/or partly wired) to detect insufficient comfort and health factor. A modular version allows a cost-effective adaptation for different monitoring tasks.
- Development of control systems for indoor environments, using both passive elements like cost-effective photo-catalytic materials or phase change materials, and active systems which control the air flow rates based on the monitoring data. In addition, a plant based system was tested.
- Modelling of indoor environments to assess and validate monitored data and to optimise the control parameters and systems for energy efficiency.

Results and Impact

CETIEB developed cost effective, innovative solutions for better monitoring indoor environment quality and investigated active and passive systems for improving it. The focus was on developing cost-effective solutions to ensure a wide application of the resulting systems.

The project demonstrated in real buildings the efficiency of technologies and systems developed, and disseminated results and recommendations for new policies and regulations within the EU.

Consortium

The consortium included 15 partners from 6 European countries and Taiwan. It was well balanced between research organisations, universities, small and medium enterprises, and large industry, with a strong participation of technological oriented SMEs.

Key facts

Start date: 1st October 2011
Duration: 36 months
Total Cost: €3.5m
EC-Funding: €2.5m
EU-FP7 Cooperation project
Grant Agreement: 285623
Coordinator: University of Stuttgart, Germany

2. Summary description of the project context and main objectives

Project context

The Energy Performance of Buildings Directive (EPBD) leads to energy efficient buildings. New and refurbished buildings have to meet the requirements concerning thermal insulation and air tightness and also the primary energy demand for heating, ventilation and air conditioning and illumination. In future net zero energy buildings will be state of the art.

However, refurbishing of existing buildings to an energy efficient standard leads to tight buildings (whole envelope: windows, walls, etc.) and affects the indoor climate. Users are not adapted to this new situation. The air exchange rates could be lower than required if no mechanical ventilation is installed or the system performance is not optimised. Therefore, in trying to increase the energy performance of buildings, the indoor environment quality is often degraded due to the lack of exchange with the outdoor environment.

People in Europe spend more than 90% of their time indoors (living, working, and transportation). In more than 40% of the enclosed spaces, people suffer from health- and comfortable related complains and illness. Already in 1984 the WHO reported an "increased frequency in buildings with indoor climate problems". The complexity of the problem and the fact of building related symptom clusters were later described as "Sick Building Syndrome". Major symptoms of Sick Building Syndrome observed are allergy, lethargy, headaches, dry eyes, throat and skin. Office indoor air may also be associated with productivity and sick leave of the office occupants.

Improving the health and comfort of the European population in those spaces consequently create a huge potential of economic and societal benefits, manifested in increased productivity, reduced sick leave and medical costs, but also by the prevention of potential liabilities. There is clearly a need for developing new methods for continuous detection of indoor pollution considering all key factors and for studying and identifying the best systems that will allow an efficient control of the indoor environment.

Main objectives

The main objective of the project is to develop innovative solutions for better monitoring the indoor environment quality and to investigate active and passive systems for improving it. The focus lies on cost-effective solutions to ensure a wide application of the developed systems. CETIEB addresses three main objectives:

- Development of monitoring systems (wireless and/or partly wired) to detect insufficient comfort and health factors. A modular version allows a cost-effective adaptation for different monitoring tasks. However, this system can also be used by advanced users for detailed and continuous measuring or to control active systems like HVAC. For that purpose several upgrade options are available.
- Development of control systems for indoor environments using both passive elements like cost-effective photo-catalytic materials or phase change materials, and active systems which control the air flow rates based on the monitoring data. The effect and the influence of passive elements will be proved by the developed monitoring systems. In addition, a plant based system will be tested.
- Modelling of indoor environments to assess and validate monitored data and to optimise the control parameters and systems for energy efficiency. Identifying the new air flow patterns in energy efficient buildings taking into account high thermal insulation and air tightness and also low temperature heating systems. This gives hints for the placement of sensors and the development of monitoring systems. The influence of the position of sources and sinks were investigated. So the design of refurbishing can be improved.

Further objectives are the demonstration of the efficiency of technologies and systems developed in real buildings and the dissemination of results and recommendations for new policies and regulations within the EU.

These main objectives are addressed with the following scientific and technological tasks. During the first project period the focus was on the development and testing of the monitoring system, the development of models, active and passive systems. The demonstration of concepts and the further improvement of systems were the main tasks in the second project period.

Technologies for monitoring relevant parameters that affect comfort of interior spaces of buildings

Technologies for monitoring relevant parameters that affect comfort of interior spaces of buildings were investigated first.

A cost effective portable wireless monitoring system was developed, intended for assessing air quality and comfort parameters. It can be used as fast monitoring system but also as an add-on for active control systems.

It is characterised by:

- Small, lightweight and low cost system
- Wireless and autonomous (portable)
- Flexible sensors use and open for new sensor integration
- Open for data exchange for other analysis tools

The sensors that were integrated are on the one hand commercial ones for monitoring temperature, humidity, CO_2, light, UV and an air velocity sensor for monitoring efficiently air quality and comfort parameters.

On the other hand there was a need for additional cost-effective sensors with the ability to monitor health related parameters like Volatile Organic Compounds (VOC) and comfort parameters for temperature and light colour with a higher accuracy, precision and reliability than existing ones. Different types of new sensors were developed and integrated in the wireless system. The use in an active control system was demonstrated:

- One key challenge within the project was the detection and monitoring of volatile organic compounds (VOC) for the assessment of health related parameters. An advanced VOC sensor based on an IR spectroscopic approach for on-line detection of VOCs at low concentrations was developed. In particular the wavelength range of 3 – 5 µm was of interest. The challenge was to reliably detect and quantify harmful or toxic substances of low concentrations in a sample that is more or less unknown composed. The development is based on a low resolving, robust and low cost micro spectrometer for the mid wave infrared range. A long wavelength range version (8 – 11 µm) is possible as well. The hybrid integration of a bulk micro machined high finesse Fabry-Perot Filter (FPF) and a pyroelectric detector resulted in a very compact spectrometer module. The integration in a long path multi-reflection absorption cell allowed the detection of VOCs down to 5 to 10 ppm. A further improvement with a photodiode as detector achieved a sensitivity of 2 to 5 ppm. One goal is that existing instrument designs can be easily adapted to such a MEMS based tunable detector.
- Additional a low cost TVOC sensor system based on suitable MOX sensor array was developed for sensitivities below ppm level. It consists of four different sensors which allow discriminating different substance classes by a pattern recognition analysis.
- Low-cost infrared vision system to monitor radiating temperatures and energy fluxes with real-time extraction of comfort parameters (as MRT and PMV), people detection, fire alarms, etc. by image post-processing. The cost of the system is in the order of 1/10 of a traditional infrared camera. A patent was applied for this development.
- A sensor for light monitoring and its characterization with respect to comfort evaluation was developed based on a RGB-colour sensing device in the visible light range. The intention was to build a low cost version to control light comfort compared to existing solutions.

The robust wireless sensor network system has the possibility to include all developed and commercial sensors in different nodes of the network. It has a user friendly software that allows for practitioners to work with it without having advanced hard- and software knowledge. The system provides features like self-organisation and self-reorganisation, sufficient time synchronisation, flexible monitoring task programming etc.. Additional a Graphical User Interface for data analysis and assessment was developed. With a corresponding market request the system could be available starting with a base version (temperature, humidity, CO_2) for around 200 € with upgrade possibilities including the developed sensors.

Active methods for ensuring a high quality indoor environment

The activities with focus on HVAC and lighting systems developed optimal active systems control algorithms, particularly in relation to energy-efficient buildings:

- Definition of optimal operational methodologies and control algorithms for lighting. The objective was to develop innovative operational methods for the integration of an advanced dynamic lighting system.
- Definition of operational methodologies and control algorithms for HVAC system. The objective was to identify the most important functions and define the operational methodologies of HVAC system in order to maintain comfort in every building. The control system has the ability to control heating, ventilation, air conditioning and perform the correct balance between the values of the parameters monitored by the sensor system.
- Definition of operational methodologies for a Plant Based air quality control, to be integrated with HVAC system. A prototype of air bio filter was developed to form part of a ventilation system for energy efficient buildings. This air bio filter was tested for its performance and its integration into the proposed monitoring and controlling kit.
- Design, development and validation of an Intelligent Control Platform as middleware able to implement the operation methods and the control algorithms developed.

The objective was to design and develop a SW architecture, able to gather data from the monitoring system developed and, implementing the operational methods and the control algorithms developed during the previous Tasks, to actually control the indoor environment providing a meaningful output to the Building Control Systems or the different subsystems installed inside a building. The system was demonstrated in two case studies.

Passive systems for ensuring a high quality indoor environment

There are cases where it is not possible to install active systems to control the air quality or when they are not efficient enough. For this case a passive plaster system was developed which includes cost effective building materials that will significantly contribute to the improvement of the indoor environment.

The final plaster system contains three functional layers:

- Lightweight thermal insulating plaster: The **first functional layer** is a mineral based lightweight thermal insulation plaster, using expanded perlite as lightweight aggregate, developed to achieve a competitive mineral plaster system with a low thermal conductivity without the use of synthetic insulation materials like polystyrene. The aim was to reach comparable values for the thermal conductivity like products based on polystyrene as insulating component. This was achieved.
- Lightweight thermal insulating plaster with high heat storage capacity: The **second functional layer** was realized by incorporating of phase-change materials (PCM) (Micronal) into the thermal insulation plaster to increase the thermal storage capacity. Expanded perlite inhibits the transfer of heat from inside to outside and vice versa and therefore the variation between maximum and minimum indoor temperature will be decreased in comparison to regular plasters used. With the addition of PCM, the heat capacity of the plaster was increased and walls adsorb or release energy (heat) from the indoor environment creating much easier a comfortable environment for humans. Due to expanded perlite and the decreased variation between maximum and minimum indoor temperature, smaller weight

percentages (around 5 wt-%) of PCMs were needed to keep the temperature in a range of 21-26°C than the 20-40 wt-% reported in the literature leading to a cost effective multifunctional building material.

- Photocatalytic plaster finish: The **third functional layer** contains photo catalytic perlite doped with titania that contributes to a cleaner and healthier environment by oxidizing and safely removing air pollutants and pathogenic from the air and the building surfaces. Although titania has already been applied in numerous fields as photo catalyst, there are still major drawbacks that restrain its wide practical application: low efficiency and high costs. The aim was to work on specifically modified titania in order to increase its efficiency. This was achieved by dispersion of TiO_2 on the expanded perlite's surface for enhancement of the activity and the efficiency creating in this way a new generation of building material for indoor use. The effect was proven for NO_x but not for VOCs.

3D-modelling and -simulation of the indoor environment

The objective was to focus on 3D-modelling and -simulation of the indoor environment including room air flow, the distribution of selected pollutants indoors taking into account all sources and sinks of this pollutants. This was done by an example room with clearly defined boundary conditions for the chosen use cases. The room air flow pattern was analysed regarding completely new indoor conditions due to the focus on highly insulated and very airtight energy efficient buildings. Older investigations didn't take into account these new indoor conditions. To evaluate the models a few large scale experiments in a test chamber were done. The influence of passive systems on indoor air conditions was investigated as well. The results of the simulation gave hints to the new air flow patterns and the distribution of pollutants and to the best and a practicable positioning of sensors. New in this project was the full integration of air pollutants including sources and sinks into normal 3D-room-simulations. Therefore models for sources, sinks and the distribution of air pollutants were developed and integrated in 3D-simulation.

Demonstrating the concepts

The objective was to execute a detailed monitoring and metering programme of interior air quality in order to verify the final performance of the developed systems, and create models for a further use of advanced monitoring. The principal aims were:

- To assess indoor environment quality with respect to comfort and health related parameters by the use of an advanced and robust monitoring system which includes new developed sensors.
- To improve thermal and lighting comfort by an active system platform which generates control parameters for HVAC and lighting system by the use of PMV and light colour data from the monitoring.
- To improve air quality by the use of an Air BioFilter reducing pollutants in the air.
- To improve indoor environment quality of buildings through the implementation of a passive plaster system with three functional layers.
- To define retrofitting guidelines for further retrofitting projects based on experience acquired in CETIEB.
- To deliver regular input to the EC databases.
- To validate the developed sensors and systems by the use of advanced modelling in simulation which includes models for sources, sinks and the distribution of air pollutants within a 3D-simulation.

3. Description of the main S&T results/foregrounds

CETIEB has identified the need for an affordable, cost-effective tool which allows real-time analysis and monitoring of indoor environment qualities and subsequent control of the HVAC and lighting systems to deliver the required best practice indoor environment standards in existing buildings being retrofitted.

The main results in the scientific work packages achieved are:

WP2 Definitions and requirements

Taking into consideration current regulations, knowledge and technology gaps in the market the project developed a tool and guidelines for ensuring existing buildings are retrofitted for energy efficiency while maintaining or improving the indoor environmental qualities.

Providing a system to measure and monitor indoor environment quality helps putting value to the improved indoor environment and thus stimulating the retrofitting market. The project has identified relevant stakeholders who will benefit from the developed technologies and who can help the wide dissemination of the technology. The specific needs of these stakeholders have been identified together with current regulatory, technology and market gaps.

Methodologies and benchmarks for performance assessments were defined. The following describes the main results achieved along the performed tasks:

Indoor environment quality and impact of building retrofit

This task delivered a comprehensive report accompanied by the matrix in an Excel spread sheet which set out and described a generic retrofitting process of measures which together could achieve a 'deep retrofit' which would most likely achieve the EU's 2050 energy efficiency targets.

The report describes the impacts of typical retrofit measures and emphasises the importance of human behaviour on the efficacy of retrofitting and the need for occupants to be involved in the preparation of the retrofit brief and also the handover of the completed building. People use energy, not buildings and the research shows clearly that human behaviour affects the energy use in a building by an average of 30%.

The Matrix went into considerable detail for each of the four building types CETIEB was focussing on and provided a very detailed list of measures under the categories of measures described in the report. These were then rated and colour coded to show their impacts so that a priority could be established by interrogating the matrix. The impacts were distinguished by whether they could be perceived by people or perceived by sensors.

Addressing regulatory gap

The review of regulations and standards generated a significant amount of information which was summarized in a series of 6 Excel worksheets. There are drop down filters to assist in accessing the information to suit specific enquiries which make this matrix of information extremely accessible and useful. The worksheets outline the regulatory information relevant to Indoor Environmental Qualities from a variety of international sources, divided into the following headings: 1. Air Quality Classification; 2. Contaminants; 3. Ventilation; 4. Thermal Comfort; 5. Illumination; and 6. Noise. Regulations and standards are reviewed by country and by building type.

The information is organised according to: Document Source Details; Document Content Details; Building Type and Comments. This allowed us to identify gaps in the regulations in Europe by comparing the regulatory environment in other jurisdictions.

The main conclusions of this task are that the regulatory gap should be closed with mandatory requirements for retrofitting that include:

1. an integrated retrofitting process
2. IEQ assessment via Post Occupancy Evaluation

3. IAQ monitoring
4. eco-cleaning products specifications
5. airtightness testing
6. energy assessment, monitoring and feedback
7. a '*Soft Landings'* type of process for continuous improvement of our building stock.

Identification of indoor environment quality parameters

The aim of this task was to declare parameters which are easy to measure and define where a real need to develop new sensors for air quality science is. The task report describes currently available commercial solutions; identifies performance indicators for the monitoring systems and identifies clearly the technology gap for the indoor environment monitoring and control. Selection criteria are based on the parameters to be measured. In all cases, low-cost equipment was taken into account in order to reduce the costs of the overall solution.

A database of all the parameters of interest concerning IEQ (Indoor Environmental Quality), and their relative operative range, as expected from the category of building (provided by ISO EN 15251), was provided.

Strategies for indoor environment enhancement

The research for this task clearly shows that adequate ventilation is the single most important retrofit measure that affects IAQ and therefore IEQ. The respective deliverable provides a review of several ventilation strategies available in the market to achieve good ventilation within retrofitted buildings (i.e., mechanical supply and exhaust ventilation systems with heath recovery, mechanical exhaust ventilation system, natural ventilation systems, etc.). The efficiency of heat recovery ventilation systems is discussed.

From the perspective of an occupant of a building, the ideal situation is an indoor environment that satisfies all occupants (i.e. they have no complaints) and does not unnecessarily increase the risk or severity of illness or injury. The desire is that the air be perceived as fresh and pleasant, that it has no negative impact on occupants' health, and that the air is stimulating and promoting their activities.

This deliverable has dealt with the problem of indoor air quality, particularly in new and refurbished buildings, and has investigated and summarized the solutions for its improvement. One focus was on systems to ensure an acceptable level of indoor quality in those buildings, where, owing to the higher degree of airtightness, air leakages are not enough to dilute the contaminants and designed ventilation systems are needed. The deliverable summarizes the main features of natural and mechanical ventilation systems, their most common configurations and their components, outlining how they work and their performances.

The IAQ issue has been approached with particular reference to the problem of energy saving: the benefits and the limitations of the ventilation systems from this point of view have been highlighted and an analysis of the main energy recovery devices and their performances has been carried out.

Indoor environmental quality guidelines

The *Guidelines for Retrofitting* have been prepared as main result in WP2 based on the different tasks and experience in the field. A series of individual Guidelines were developed for each category of retrofit measure which identifies their impacts; the relevant policies and regulations; the IEQ standards and parameters; and whether they are passive or active measures.

The Guidelines are comprehensive and provide a very useful prioritised strategy and methodology for retrofitting based on the WP-leader's experience operating a retrofitting contracting company and developing software for managing the retrofitting process. The measures include the activities at the beginning and end of an ideal retrofitting process which engage with the building occupants and users to create a feedback system for creating further knowledge about retrofitting. The retrofitting industry is still in its infancy with many working in the field still lacking important knowledge and experience.

Of critical importance is the understanding of the non-energy benefits of retrofitting as these have been proven to be more valuable than the energy saved by retrofitting. In order to make the economic and financial case for retrofitting this knowledge and information needs to be widely disseminated and developed as one of the main barriers to retrofitting is that stakeholders in the retrofit industry don't know the real value of better buildings.

The main annexes of the Guidelines describe the developed passive and active measures in terms of their benefits for individual stakeholders: building owner, building user, facilities manager, construction industry professional, etc. The descriptions include information for the general public, technical descriptions of the operation for stakeholders and financial cost-benefit analyses and business plans.

WP3 Monitoring

The objective of this WP was to develop technologies needed for monitoring relevant parameters that affect indoor environment quality. The idea was to go beyond the traditional and existing environmental temperature and humidity monitoring systems, extending the possibilities to monitor human health and well-being factors inside buildings. The technologies developed within this work package were a step forward in terms of:

- Provision of cost-effective and simple to use monitoring systems that allow for monitoring of a large variety of indoor environmental factors
- Provision of advanced sensor technologies to better measure and assess indoor environment factors with respect to human health and well-being
- Provision of data collection and analysis software that could be used to better monitor, assess, evaluate and control the indoor environment.

Development of cost-effective portable wireless monitoring system

Wireless systems have no central data acquisition unit but one or several sensors are connected to a (usually) small data acquisition unit, which is called a measurement node. The complete measurement system consists of several independent nodes, linked to each other by a radio communication link, hence building a wireless sensor network. Additional elements of the system are the gateway, which relays the measurement data to a long-distance network for remote access, and a database to save data storage for later retrieval and optional post-processing. The WSN is operated remotely either from a Smartphone or PC (basic functions only) or an operation and maintenance terminal (O&M).

Figure 1 gives a more detailed view on the general system layout. The autonomous wireless sensor nodes are depicted deployed in a building, sending their information either via a gateway (SmartGate) to a central server into a SQL-Database or optionally directly into a locally installed base station (SmartBase), which directly stores the acquired data in a SQL-database. The SmartGate includes a wide area mobile connection, used for controlling the system and for sending data to the central database and web server (Smartserver) within the operator's premises. Depending on the preferred solution (SmartGate with decentralized server or the locals solution with the SmartBase), the customer can then access the information via a web access (e.g. by Smartphone etc.).

The developed middleware including the database and the web application have undergone an extensive redesign during the second half of the project to cope with the demands of some of the advanced use cases in an efficient and state-of-the art fashion. Further improvements and additions were implemented during the demonstration phase to include third party systems in place at the demonstration site with the middleware.

The results of the CETIEB project will be used to develop a cost-effective version of smaller size for the market. Starting with a base set of sensors (temperature, relative humidity, CO_2) costs of around 200 € are visible depending on request.

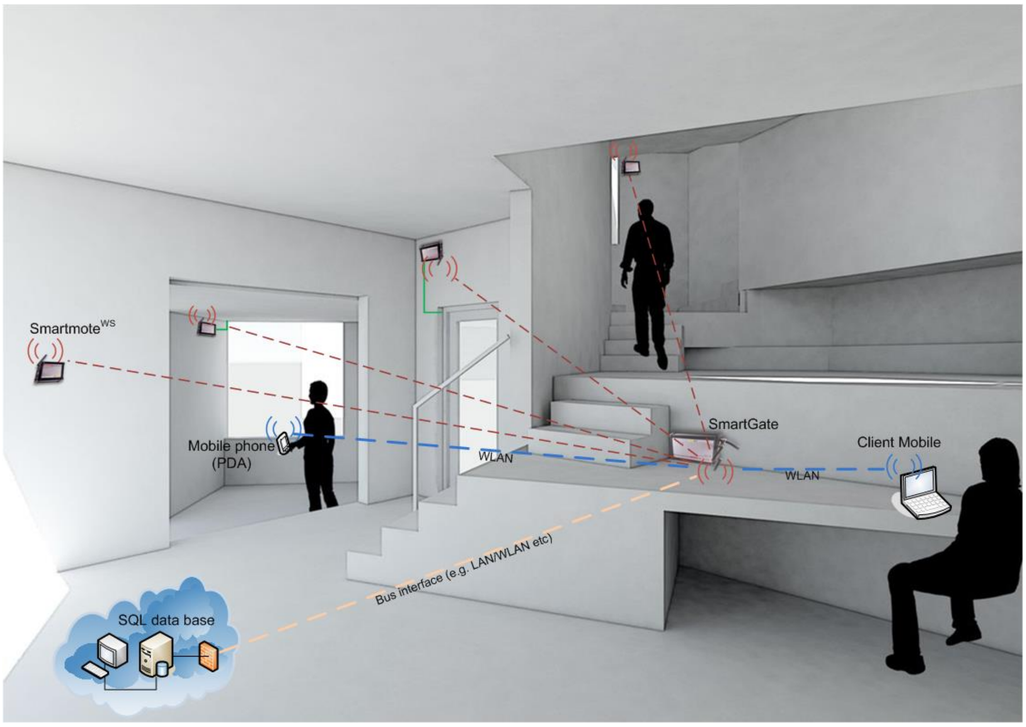

Figure 1: Principle sketch of the wireless sensor network system

Development, evaluation and integration of new sensor technologies

The objective was to develop, evaluate and integrate new sensor technologies, going beyond traditional and existing technologies, focusing on human health and well-being whilst being low cost. The following sensor technologies were integrated:

- Advanced IR spectrometric VOC sensor
- (Total) TVOC MOX sensor array for sub-ppm detection of VOCs
- RGB light sensor measuring intensity and colour temperature of light
- Infrared based vision system to monitor radiating temperatures and energy fluxes.

a. Advanced IR spectrometric VOC sensor

The advanced IR spectrometric VOC sensor is based on the tunable filter technology from ITC and a multi-reflection gas cell from Fraunhofer. It can detect and distinguish between individual VOCs or substance classes. Figure 2 shows the measurement principle, the spectral response and the MEMS based detector.

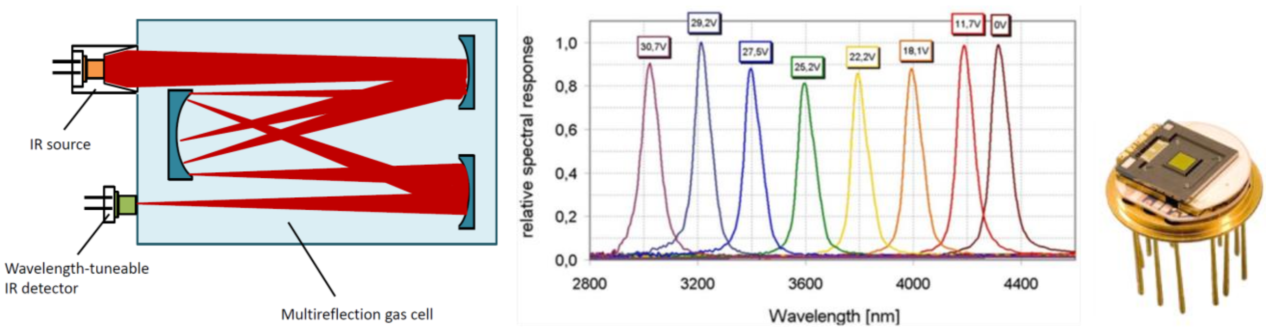

Figure 2: Left: Measurement principle. Middle: Spectral response. Right: Tunable MEMS sensor.

Figure 3 provides the technical outline and a spectra series from laboratory evaluation.

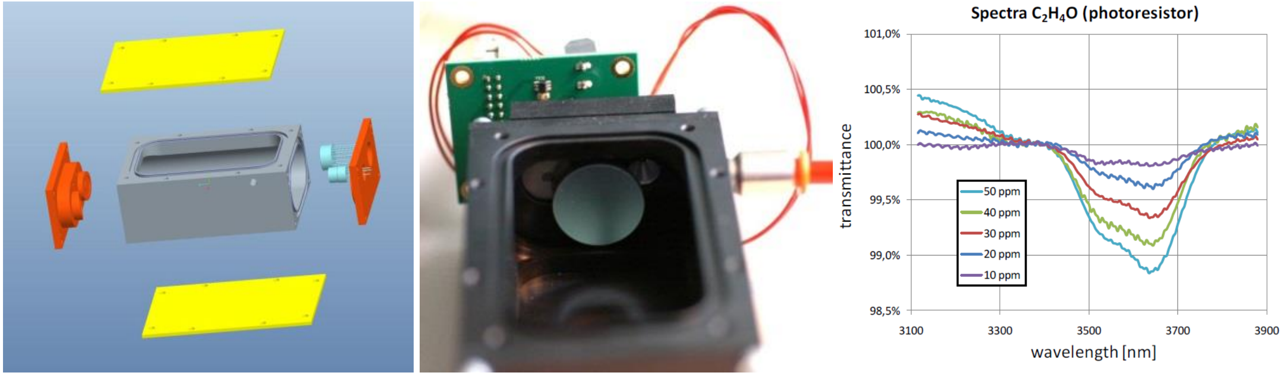

Figure 3: Left: Technical outline and view of the opened multi reflection cell. Right: Spectra series for Acetaldehyde from laboratory evaluation.

To enhance the sensitivity several detectors were evaluated with different methods (pulsed or chopping excitation). Table 1 gives an overview of the achieved results.

Table 1: Overview on achieved sensitivities

	Pyroelectric	Photoresistor	Photodiode
Recording time	~ 5 min	~ 1 min	~ 1 min
Chopping frequency	10 Hz, pulsed	63 Hz, mechanical	25 Hz, pulsed
Sensitivity (C_2H_4O)	10 ppm	5…10 ppm	2…5 ppm
Spectral resolution	50…70 nm	50…70 nm	25…35 nm

The system was demonstrated in a real building within a safety application for a national research project (Exemplary conservation of the St. Salvator rock chapels in Schwäbisch Gmünd[1]). There was a need to monitor ethanol emissions which were generated by the reaction of the conservation product during the conservation treatment of a figurative relief – a Mount of olive representation from 1620 – in the upper rock chapel of St. Salvator in Schwäbisch Gmünd. The concentration reached more than 2500 ppm. Due to the spectral resolution a separation of major compounds was possible (here: ethanol and CO_2). Figure 4 shows difference spectra compared with the spectrum before treatment.

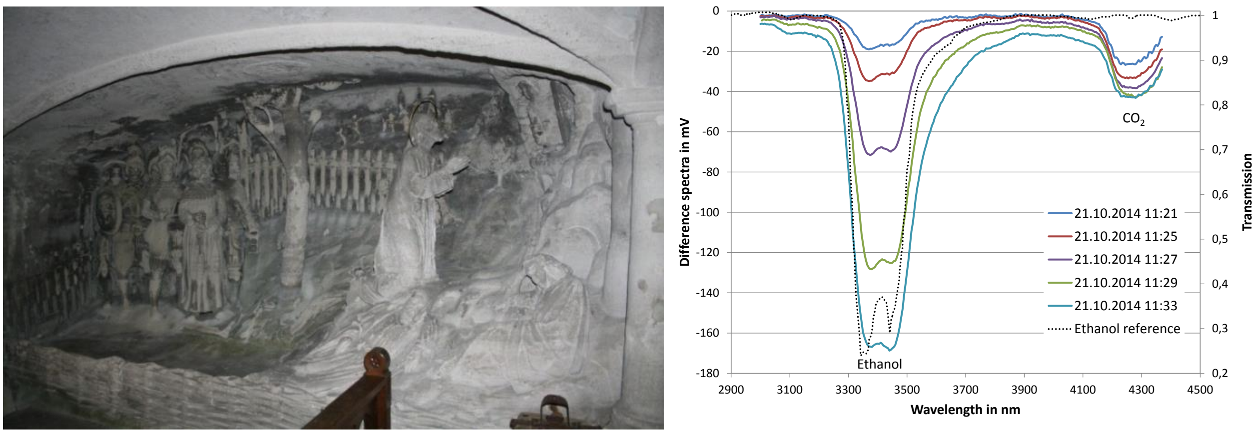

Figure 4: Left: Mount of olive relief which was treated. Right: Rise of ethanol concentration (difference spectra compared to spectrum before treatment). An Ethanol reference spectrum derived from IR data from NIST[2] is shown.

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[1] funded by the Deutsche Bundesstiftung Umwelt, the Deutsche Stiftung Denkmalschutz and the heritage preservation in Baden-Württemberg.

[2] National Institute of Standards and Technology (NIST), http://webbook.nist.gov/cgi/cbook.cgi?ID=C64175&Type=IR-SPEC&Index=2#IR-SPEC (accessed 18-12-2014)

The corresponding measurement with a sampling chip (Dräger Chip-Mess-System CMS Analyzer with Analyzer Ethanol 100-2500 ppm) at 11:35 was above 2500 ppm (detection limit). From the laboratory validation a concentration of around 4000 ppm can be estimated.

b. TVOC MOX sensor array

MOX sensors are not selective, but highly sensitive. Therefore only the sum of VOCs is measured which is called total VOC (TVOC). The idea of the MOX sensor setup is to use different MOX sensors in one node. With pattern recognition it is possible to differentiate between VOCs which are present in the room. Figure 5 shows a picture of the sensor node.

Figure 5: Left: Aluminum MOX sensor node box with integrated MOX sensors. Right: Open MOX sensor node with four MOX-sensors, PCB board and microcontroller.

The reaction of the sensors is different in dependence on different typical VOCs. The individual sensors show less response, faster increase or decrease because of their active sensing material. Catalytic surface effects lead to different sensor reactions. This individual behaviour was analysed with laboratory measurements (Figure 6). Figure 7 shows measurements during a meeting as first demonstration.

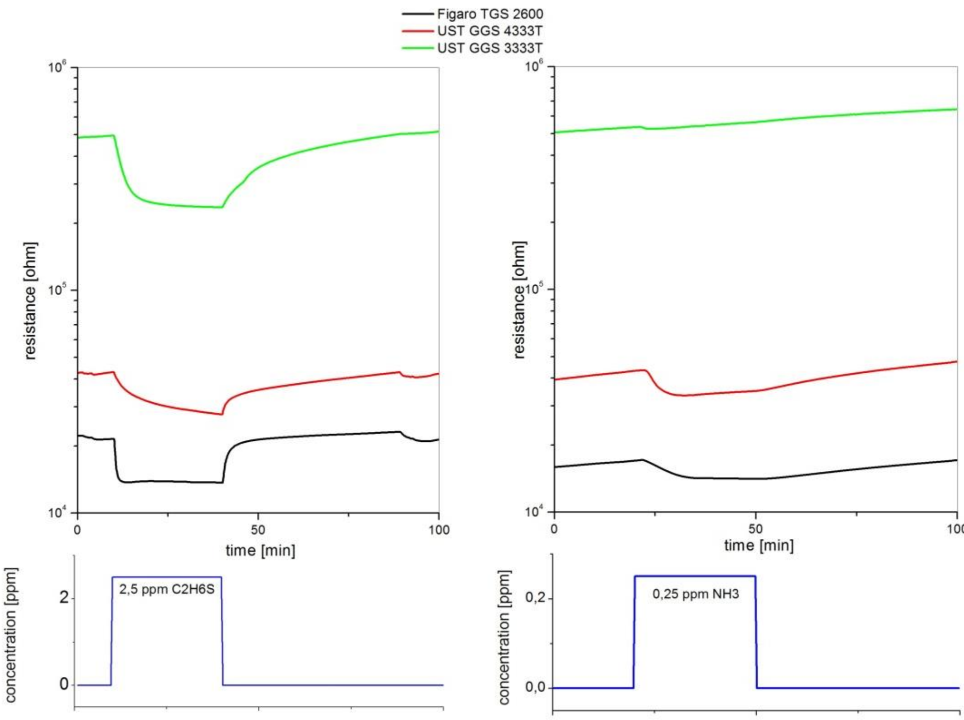


Figure 6: Gas measurements to analyse patterns with various MOX-sensors.

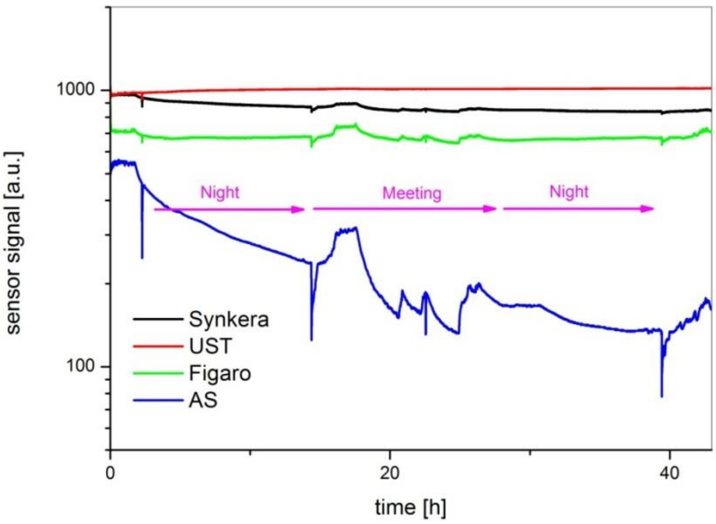


Figure 7: VOC-monitoring in a meeting room at Fraunhofer IPM.

c. RGB light sensor

A low-cost sensor solution for light intensity and light spectra was realised. The RGB sensor has been developed to determine the Colour or Correlated Colour Temperature of ‘white light’ with the objective to simulate the natural colour temperature of daylight in function of the time of the day and the latitude of the location. Within an office situation the RGB sensors were used to monitor the light colour and the signal was used for the control system. Figure 8 shows the sensor compared with other light sensors, spectral responsivity and a test window of the light control system during the test with a cool white source.

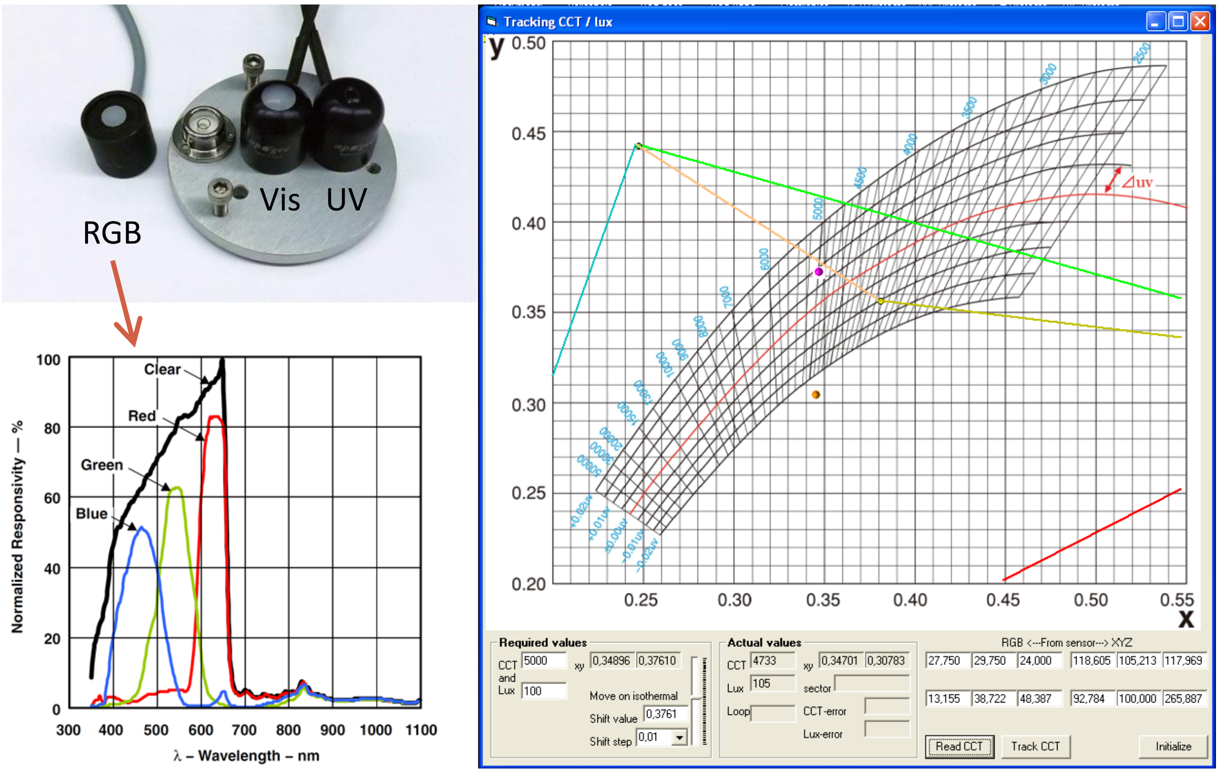


Figure 8: Left: RGB sensor in developed casing and spectral responsivity[3] compared with commercial sensors (VIS, UV). Right: Test window of light control system with a cool white source (pink: required values, orange: actual values).

[3] TAOS TCS 3414 CS datasheet, http://www.ams.com/eng/Products/Light-Sensors/Color-Sensor/TCS3414

d. Infrared based vision system

The objective was to develop an IR-based vision system for indoor thermal comfort monitoring. The system is able to perform real-time and spatial measurement of indoor thermal comfort, by taking into consideration the effect of indoor solar radiation in the mean radiant temperature calculation. The system was evaluated and tested in different scenarios (office, laboratory, classroom), for instance in collaboration with USTUTT-IGE in a test chamber, and demonstrated at some of the demo sites. During laboratory evaluation data were assessed concerning the measured parameters (Air Temperature, Relative Humidity, Mean Radiant Temperature (MRT), Predicted Mean Vote (PMV)) and compared to that acquired by commercial thermal microclimate stations which matches very well. At the demo sites the information provided by the system, together with data retrieved by the sensors installed, led to a detailed assessment of the indoor comfort in the classroom, for both students and teacher. In particular, it was found that the teacher perceives a higher thermal sensation with respect to students and this was due to the different metabolic profiles (see Figure 9).

The advantage of the system is the provision of the spatial distribution of MRT and PMV at costs which are 1/10 of a commercial micro-climate station measuring only at one point. A patent was applied for the system and partner UNIVPM is thinking of creation a spin-off company to commercialize the results.

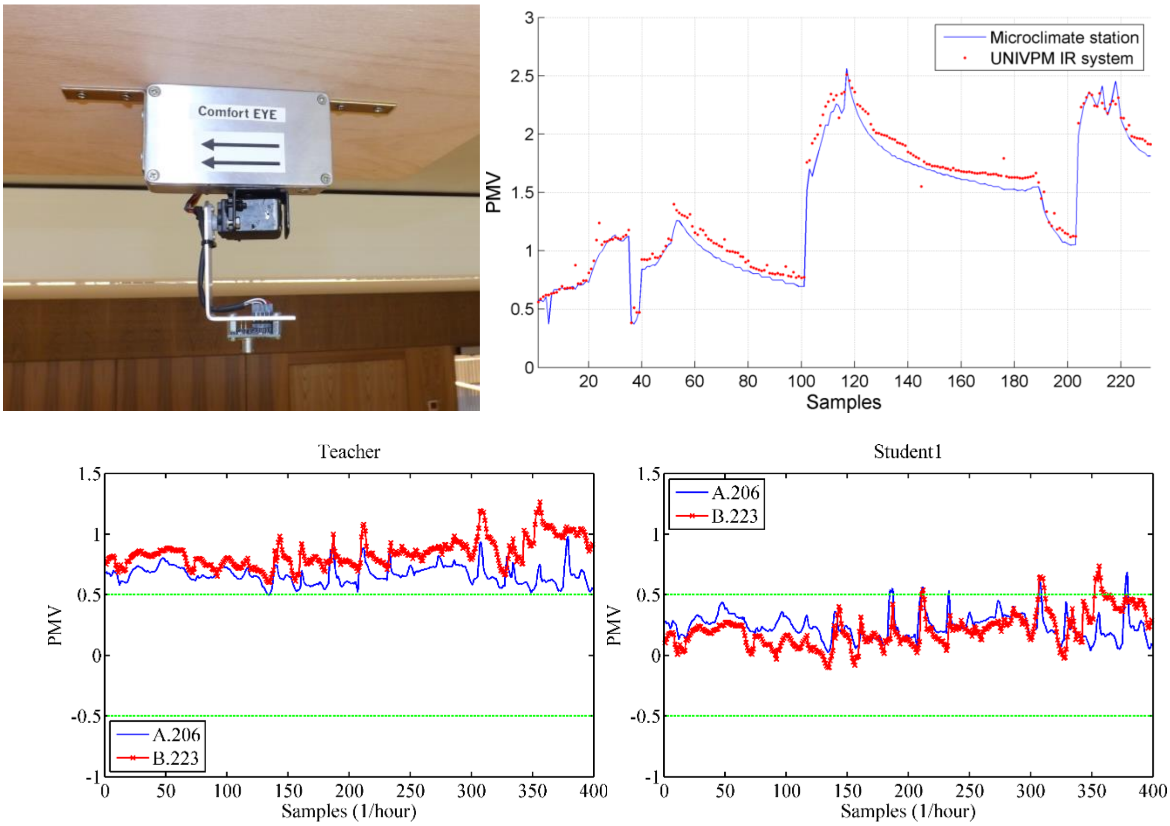


Figure 9: Top: IR vision system installed at demonstration site in Öhringen, Germany (left) and comparison of laboratory evaluation of PMV in comparison with a micro-climate station (right). Bottom: Differences for calculated PMVs for a teacher (left) and students (right).

WP4 Active Systems

The overall project objective of ensuring a high quality indoor environment is approached in the present work package through the analysis of the HVAC and lighting systems. Human thermal comfort is defined as the state of mind that expresses satisfaction with the surrounding environment. Maintaining thermal comfort for occupants of buildings or other enclosures are therefore one of the important goals of HVAC design engineers. Indoor thermal conditions are important for health and comfort, although individuals vary in their temperature requirements. At the same time artificial lighting influences human biological needs, for example, interfering with melatonin secretion at night and modifying human level of attention and brain response. Dynamic lighting systems are, thus, of primary importance for the quality of indoor environment. These active systems are based on three basic components, a sensor system that monitors the physical parameters associated with the different phenomena, a control system that analyses data from the sensors and, based on specific control algorithms, manages the active component. The activities focused on the definition of the optimal active systems control algorithms, particularly in relation to energy-efficient buildings:

- Definition of optimal operational methodologies and control algorithms for lighting.
- Definition of operational methodologies and control algorithms for HVAC systems.
- Definition of operational methodologies for a Plant Based air quality control, to be integrated with HVAC system.
- Design, development and validation of an Intelligent Control Platform able to implement the operation methods and the control algorithms developed within the work package.
- Development of a smart Natural Light Illumination System. A sun light collecting and transmitting system will be combined with an automatically turn-on quasi-sunlight system if outdoor sunshine is weak. According to specific needs it will be turned to a "smart mode" to adjust colour temperature, colour rendering index, glare rating etc.

Intelligent Control Platform

An intelligent architecture for active systems to control natural ventilation whilst improving indoor air quality and optimising air flow in buildings was set-up and evaluated. The system was demonstrated within a passive house at the INCAS platform at CEA INES in France. Figure 10 shows the principle of the main core of the software used.

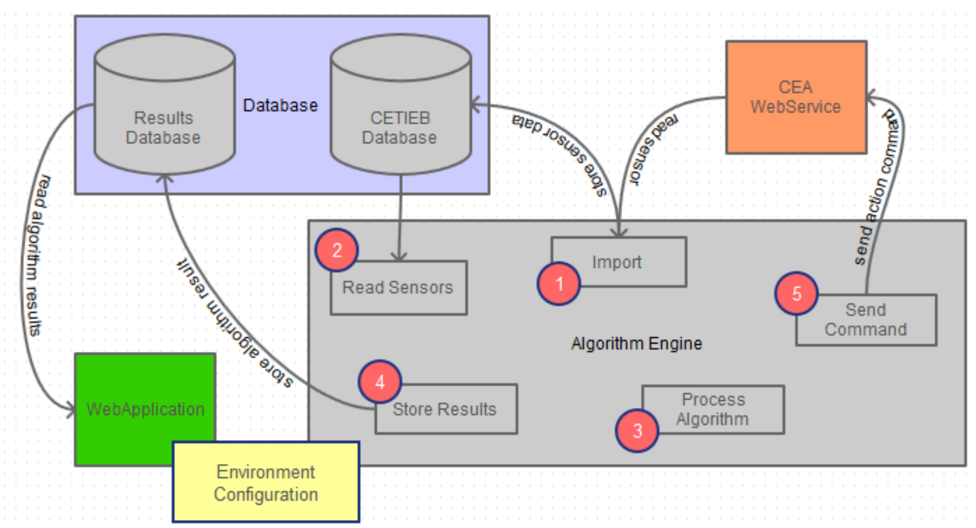


Figure 10: Principle of the main core of the software developed.

Figure 11 shows the improvement of MRT and PMV achieved (right part of diagram) compared to the reference room where a constant set-point was applied. Results show that in the test room the thermal perception was 1-point scale inferior with respect to the reference room (where a hot sensation is observed). Moreover, the energy saving of HVAC control by adopting the PMV information was improved by 15%.

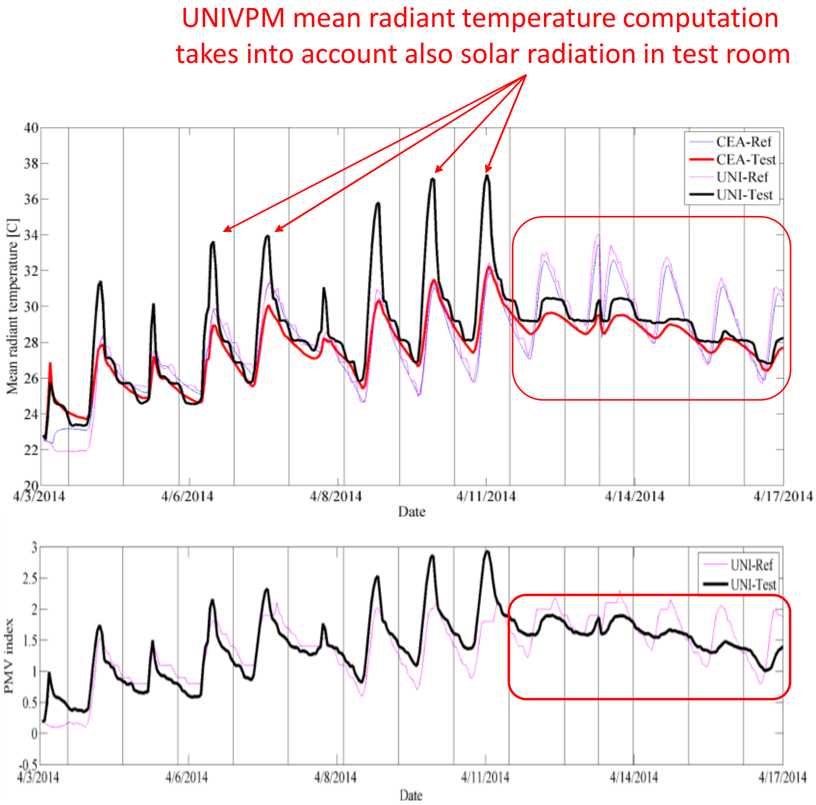


Figure 11: MRT and PMV in test room and reference room at CEA INES.

Air BioFilter

Biofiltration is the use of microbes to remove or neutralise contaminants. For filtration a contaminated medium, water or air, is passed through a biologically active substrate e.g. a designed root zone material, moss, soil, or plants, where contaminants are absorbed into a liquid phase and are consumed by microbes in the substrate and converted into benign constituents: carbon dioxide, water and salts. Unlike conventional filters that physically remove contaminants there is no accumulation in the bio-filtration system as all contaminants are broken down.

The developed Air Biofilter is a vertical hydroponic green wall structure containing a range of specifically selected plants. The plant roots are embedded between two layers of woven, porous material similar to that of a kitchen-scrubbing pad. Nutrient rich water trickles down in this material, into which the roots of the plants are intertwined, providing plant roots with nutrients and hydration. The water is key to filtering the air: Fans running behind the wall continuously pull contaminated indoor air through the bio-filter's porous root zone material. As a result, VOCs naturally dissolve into the water and become available to bacteria and fungi on the plants' roots. These microbes then consume and break down the VOCs into benign products, primarily carbon dioxide and water. As the microbes remove VOCs from the water, more VOCs can be absorbed from the circulating air, and the cycle continues.

The removal of VOCs from indoor air is a significant improvement of IAQ and IEQ leading to health benefits. The visual and psychological effect of having attractive plants in a working environment is important to occupant satisfaction. The recycling of the 'cleaned air' can reduce the amount of outside air which is brought into the building by the HVAC system and this can create energy savings. Experiences from a cold climate showed possible energy savings up to 60%. The portable prototype built to demonstrate the system in this project is ideal for retrofitting projects as it is an independent system requiring only an electrical plug connection and manual top ups of water and nutrients.

The final design and operation principle is shown in Figure 12. When air is drawn through the planted cylinder it filters, cleans, humidifies and re-oxygenates the air removing indoor pollutants and VOCs.

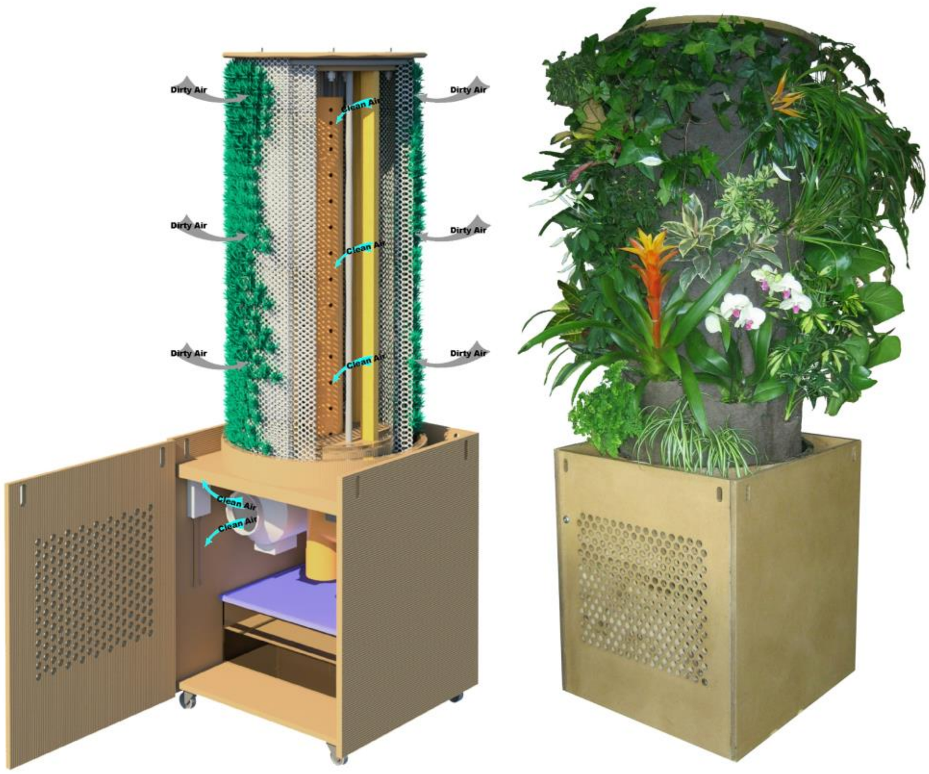


Figure 12: Operation principle (left) and final design (right) of the plant based Air BioFilter.

At the demonstration site Registrar's office at University of Stuttgart, Germany a reduction of the TVOC values of 50% after a certain period was observed compared to reference samples (see Fig 13).

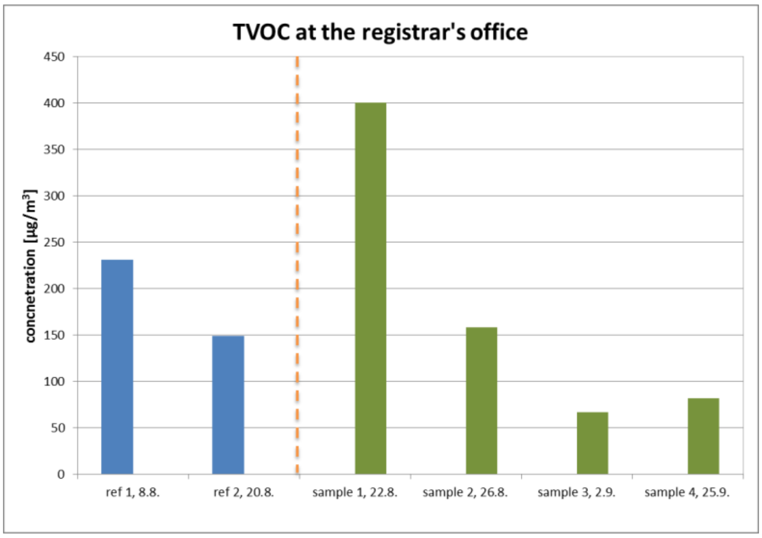
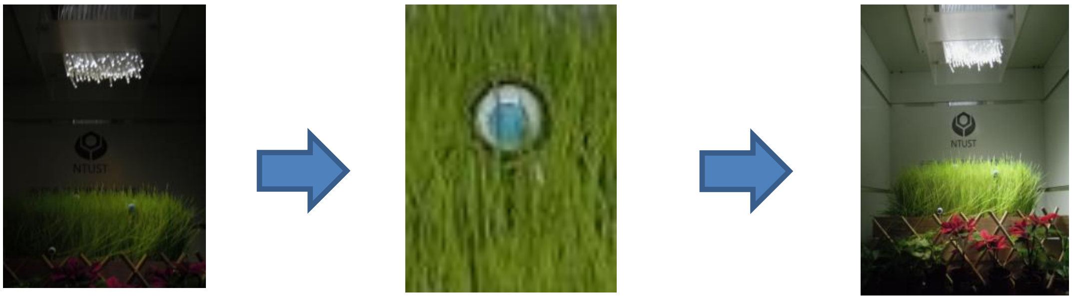


Figure 13: TVOC results of tube sampling at the demo site.

Natural Lighting Illumination System (NLIS)

The main objective was to develop a smart Natural Lighting Illumination System (NLIS). NTUST simulated several situations to find an optimal situation for energy-efficient buildings. Then a NLIS model house was constructed (see Figure 14) which was used to illustrate the major functions of NLIS (collecting, transmitting and emitting). Subsequently, NTUST integrated with a "ZigBee Sensor" the model towards a NLIS smart home model (see Figure 15), able to detect the current illumination and turn on the quasi sun-lighting system automatically. In addition, this sensor was not only applied for distant control, but could also be combined with an APP to monitor the situation simultaneously.

Figure 14: Energy-Efficiency Sample Building



Once the indoor nature lighting is getting weak …	… the ZigBee sensor can detect the indoor illumination, temperature, humidity, colour temperature, colour rendering index and glare rating (depends on the parameters setting).	Then the sensor can turn on the quasi-sunlight system to balance the indoor illumination in order to maintain a stable situation.

Figure 15: The illustration of ZigBee Sensor Integration

Natural Light Illumination System (NLIS) is a cascadable and modulated system to gather nature light for indoor illumination. There are three sub-systems of NLIS, collecting, transmitting and emitting sub-system. The illustration diagram of NLIS is shown in Figure 16 (left). Regarding to the collecting sub-system, it uses prismatic concept structure, named “SunLego®,” installed on the roof or wall, to collect sunlight. Furthermore, the transmitting components include the fibre and light pipe to transmit the sunlight from SunLego®. The emitting components are the optical lens based on freeform design concept and connected to the light pipe. Figure 16 (right) shows the structure of NLIS. It can be seen that the sunlight is collected by the SunLego® and being transmitted in the system by optical fibres and light pipes. Finally, the sunlight will distribute over the indoor space by emitting components.

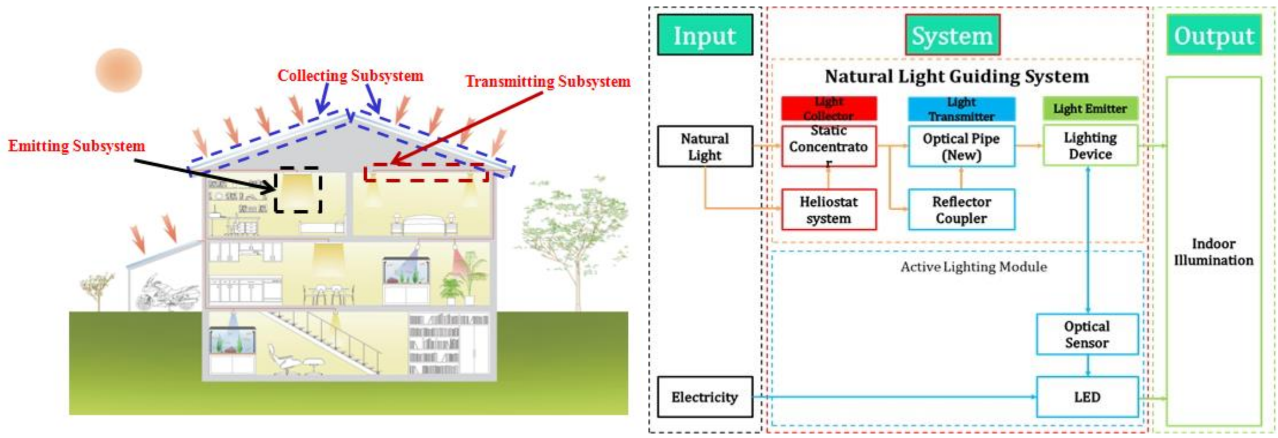


Figure 16: Illustration (left) and structure (right) of the Natural Light Illumination System

The demonstration of the Natural Light Illumination System (NLIS) was performed by partner NTUST in a prominent university building in Taipei, Taiwan. The Taiwan Building Technology Center (TBTC) located on the campus of NTUST provides a real-world laboratory for testing and exhibiting the ideas and results of the Centre's projects, thus assisting the TBTC in taking its place on the world stage as a leading research centre for intelligent green building technology. Figure 17 shows the installation.

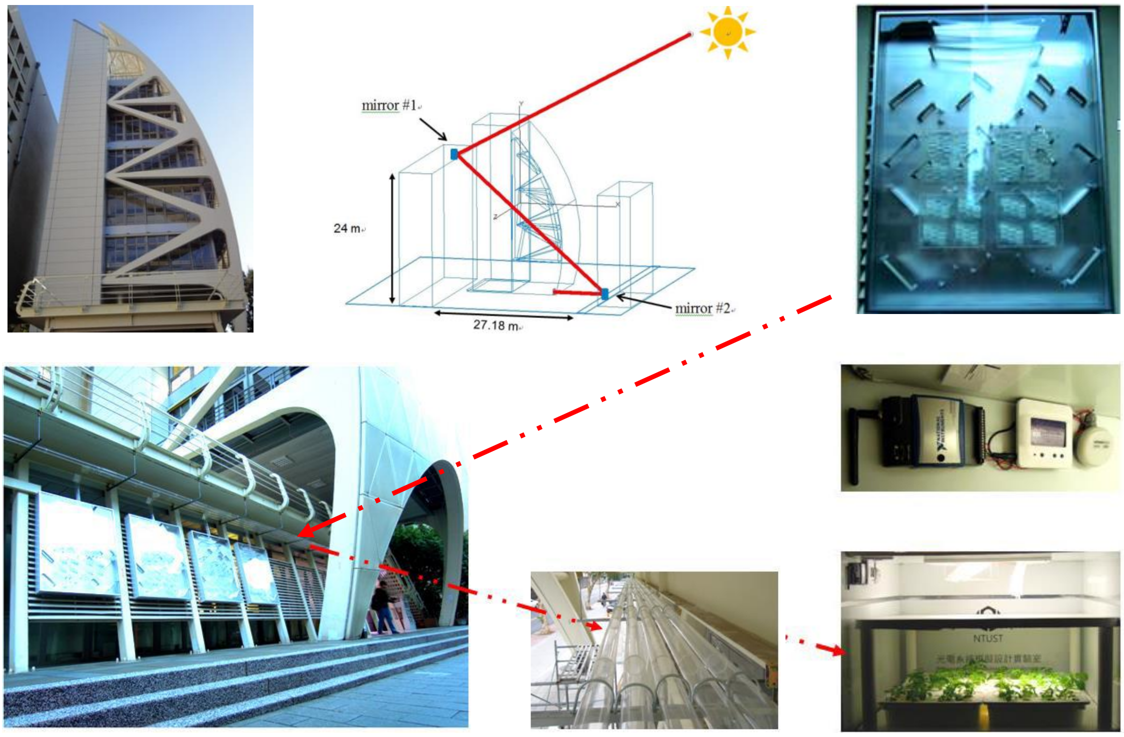


Figure 17: Installation and components of the Natural Light Illumination System installed in Taipei, Taiwan.

The total system development is based on a series of several patents. During the CETIEB project the following patent applications were achieved:

Subsystem	Patent	Patent No.	Country	Application Date
Collecting	LIGHT COLLECTION DEVICE	3734902	China	2013/11/03
	LIGHT ENGINE DEVICE	M483388	Taiwan	2013/12/31
Transmitting	MOBILE LIGHT SUPPLYING SYSTEM	M483432	Taiwan	2013/12/31
Emitting	MULTI-SOURCES FREEFORM LENS	M493651	Taiwan	2013/12/31

WP5 Passive Systems

The aim was the development of wall materials (Passive Plaster System) that provide significant improvement to the indoor air quality. The main properties of such a system (Figure 18) are the reduction of indoor temperature variations, humidity storage abilities (Phase-change materials) and photo-catalytic activity for the removal of indoor air pollutant.

The final Passive Plaster System (PS) was built as a sandwich-system. The aim to be suitable for gypsum containing and cementitious substrates was accomplished with a ternary system based on a mixture of calcium aluminate cement, calcium sulphate and Portland cement as binding agents. The system contains the following layers:

- First layer aims to improve the adhesion of the following thermal insulation plaster layer on the underground.

- The 1st functional layer is a lightweight thermal insulation plaster.
- The 2nd functional layer is a storage plaster, containing phase change material (PCM) for better adjustment of heat absorption capacity, helping thus to keep the indoor temperature more constant.
- The 3rd functional layer is either a photo catalytic paint containing TiO_2 coated expanded perlite or a spackle finishing layer with photoactive perlite. Both of these layers require UV–light (incoming sunlight) for evolving the catalytic property that aims at improving indoor air quality by VOC and NO_x removal.

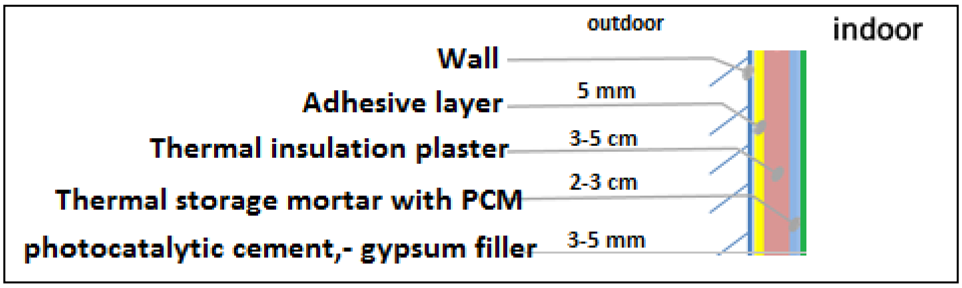


Figure 18: Functional layers concept of the Passive Plaster System

First and second functional layer: Thermal insulation and thermal storage plaster

The **first functional layer** is a mineral based lightweight thermal insulation plaster, using expanded perlite as lightweight aggregate, developed to achieve a competitive mineral plaster system with a low thermal conductivity without the use of synthetic insulation materials like polystyrene. The **second functional layer** is the incorporation of phase-change materials (PCM) (Micronal) into the thermal insulation plaster to increase the thermal storage capacity.

The innovative plaster system, developed by Schwenk Putztechnik GmbH, maintains the following physical and mechanical properties:

- Thermal conductivity of thermal insulation plaster: 0.067 W/(m*K) comparable to commercial plasters (< 0.066 W/(m*K)) with polystyrene as lightweight material
- Thermal conductivity of energy storage plaster: 0.074 W/m*K
- Energy storage capacity: 48.87 kJ/m^2 for a thickness of 2 cm
- Mechanical Strength: more than factor 2 compared to commercial plaster with polystyrene
- Water vapour resistance factor: factor 2 or 3 lower compared to a commercial plaster with polystyrene
- Thermal insulation plaster and energy storage plaster have a high humidity storage capacity, 12 mass-% and 6 mass-%, respectively.
- The developed plasters show a very wide pore size distribution.

The plaster system with insulation and thermal storage was demonstrated at Colegio El Porvenir in Madrid, Spain (see Figure 19). The effect of the thermal storage can be seen in Figure 20 (first two weeks). The day/night changes of the temperature in the plaster room are smaller than in the reference room and temperature peaks are reduced. This is due to the phase change material included. In general the temperature fluctuations in the plaster room are smaller and the relative humidity reaches the same values as for the reference room after curing of the plaster (see Figure 21). Additional during a sunny period in December the relative humidity kept slightly higher than in the reference room, which was at that time more comfortable (relative humidity below 30 % is too low). This might be due to possible moisture storage ability of the plaster because of the high porosity.

Figure 19: Installed plaster system in the test classroom.

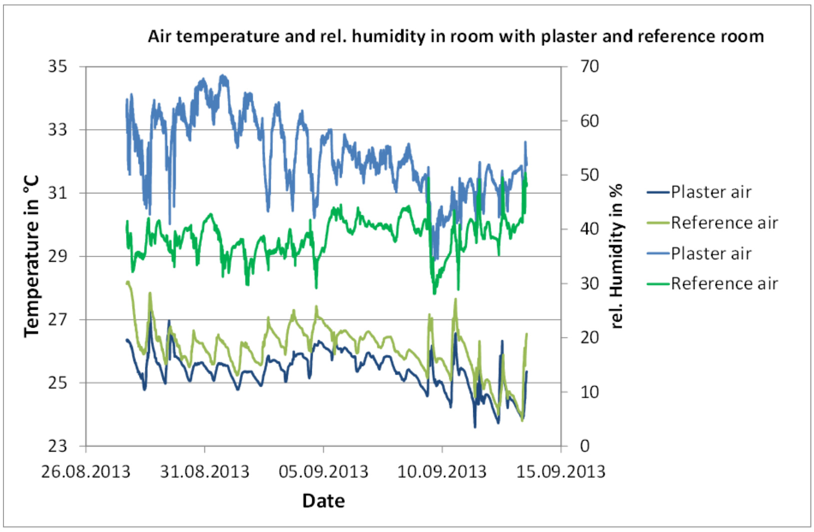


Figure 20: Temperature and relative humidity in Colegio El Porvenir

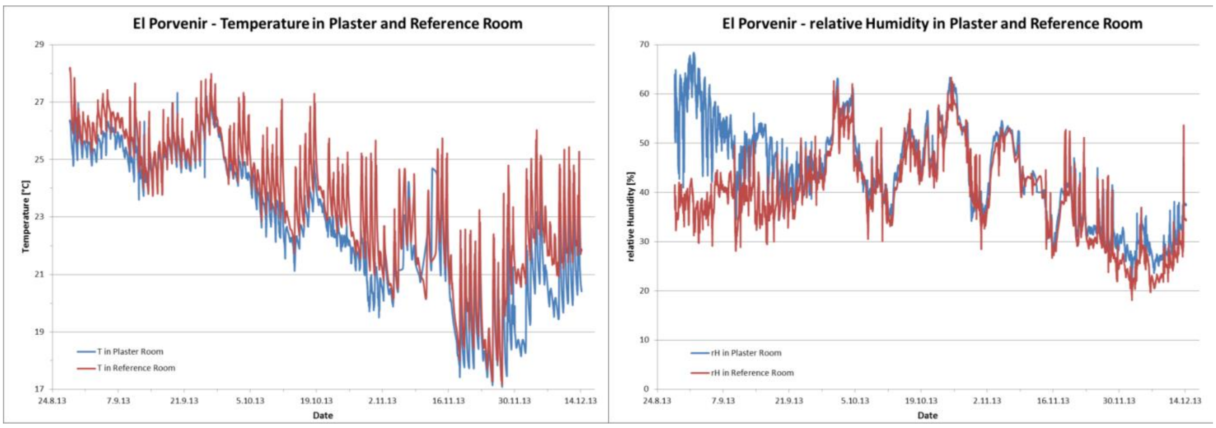


Figure 21: Temperature and relative humidity monitoring in Colegio El Porvenir.
(blue: plaster room, red: reference room).

The commercial use of the two products is under consideration. The insulating mortar (based to 99% on mineral materials) is a very promising product, especially for retrofitting buildings and has an acceptable price. The lightweight energy storage material (including PCM), despite its good physical properties, is considered as cost inefficient, with limited commercial applicability. The material costs increase by a factor of 2.3 with 5 mass-% PCM in the dry product, this lead to end-costs of minimum a factor of 1.5 compared to the insulation plaster without PCM.

Third functional layer: Plaster finish containing photo-catalytic perlite/titania

The first step was the development of photo-catalytic plasters for air purification from NOx, VOC and other pollutants. The development of such a plaster is relied on the selection of the nano-TiO_2 coated expanded perlite. It was found out in Lab scale that the optimum expanded perlite grade is below 100 µm (µ-spheres), with 40% (absolute loading) of catalytic powder. The specific blend exhibits 1.5-1.6 times higher efficiency, in NO_x reduction, with much less active titania.

The aim of development of a plaster system, suitable for gypsum containing and cementitious substrates was accomplished with a ternary system based on a mixture of calcium aluminate cement, calcium sulphate and Portland cement as binding agents. The expanded perlite/photocatalytic titania system can achieve the same photocatalytic effect with 35% less titania in case of NO_x, something which is proven in case of VOCs, as well. The mortar system containing 3.5% active titania as a layer on expanded perlite, has the same photo-catalytic activity as the one with 5% commercial powder only.

Industrial Scale

The pilot scale production line installed in Ritsona plant (S&B) consists of the following sectors:

- Expansion – Air circulation: Furnace for µ-spheres production, raw perlite feeder and the fan.
- "Spraying" section: Hydrophobising of the expanded perlite surface by solutions of siloxanes
- "Drying" sector: Electrical Furnace for drying the hydrophobised material after spraying
- "Sieving" sector

The aim of the industrial trials was to maximize the titania loading on the perlite substrate, improve the coating, avoiding coagulates, without blocking the nozzle during the spray.

The industrially achieved loading (≈8-9%) is much lower than the one (≈ 28-29%) required at lab scale for sufficient photo-catalytic activity, however the industrial sample with 8.7% nano-titania, exhibits slightly lower NO_x reduction than the commercial powder P25. The usage of slurries with increased solid contents (≥ 15 %) was not feasible.

The low titania loading of the industrially produced photo-catalytic perlite resulted in plasters with increased content of lightweight aggregates, and, consequently the physical properties of these mixtures were degraded. Finally, the prepared samples showed a good photo-catalytic activity with respect to NO_x, but the same behaviour wasn't observed for the VOCs.

WP6 Integration and assessment

The objective was to focus on 3D-modelling and -simulation of the indoor environment including room air flow, the distribution of selected pollutants indoors taking into account all sources and sinks of this pollutants. This was done by an example room with clearly defined boundary conditions for the chosen use cases. The room air flow pattern was analysed regarding completely new indoor conditions due to the focus on highly insulated and very airtight energy efficient buildings. Older investigations didn't take into account these new indoor conditions. To evaluate the models a few large scale experiments in a test chamber were done. The influence of passive systems on indoor air conditions was investigated as well. The results of the simulation gave hints to the new air flow patterns and the distribution of pollutants and to the best and a practicable positioning of sensors. New in this project was the full integration of air pollutants including sources and sinks into normal 3D-room-simulations. Therefore models for sources, sinks and the distribution of air pollutants were developed and integrated in 3D-simulation. Two examples are given in the following section.

Office room with mixing ventilation

The test room was modelled in a correlation to the test chamber of the IGE. The numerical model was developed in ANSYS FLUENT. Figure 22 shows the test room with all sources and sinks both for heat and contaminants. The thermal load from all heat sources in the room was 27 W/m^2. Tracer gas nitrous oxide (N_2O) was used as an assumed contaminant. Other gaseous contaminants will be spread in a room in a similar way. The source inside the table emitted $6.3 \cdot 10^{-3}$ kg_{N2O}/h of the tracer gas. The back green wall was defined as de-contaminating sink reducing the contaminant. The reduction rate of the surface was defined $1.1 \cdot 10^{-3}$ kg_{N2O}/h.

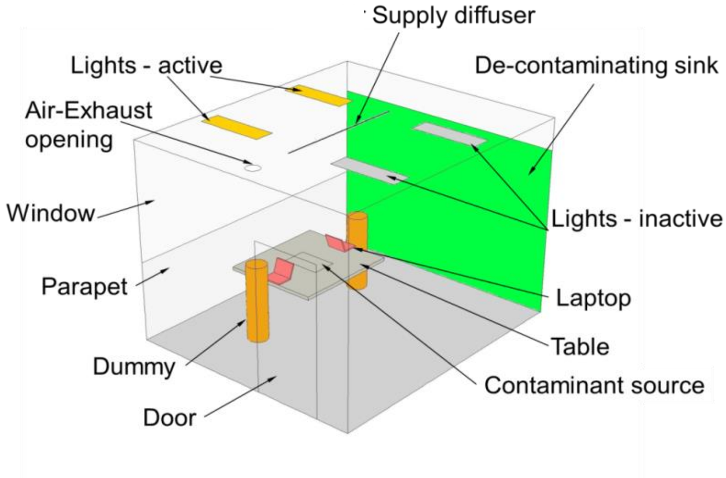


Figure 22: Model of the Test room with mixing ventilation, general view

The room was ventilated mechanically by mixed ventilation. Air exchange rate was 1.8 h^{-1}. The supply diffuser and the exhaust opening were located on the ceiling.

Figure 23 shows the distribution of the tracer gas in a room section through the dummies (persons). The left picture shows the concentration in the room without a sink; the right one the concentrations in the room with a sink. In presented sections the sink is located on the right wall. The simulation showed that the concentration of tracer gas in the room with the sink decreased not only in front of the sink surface, but also inside the whole room on 14%.

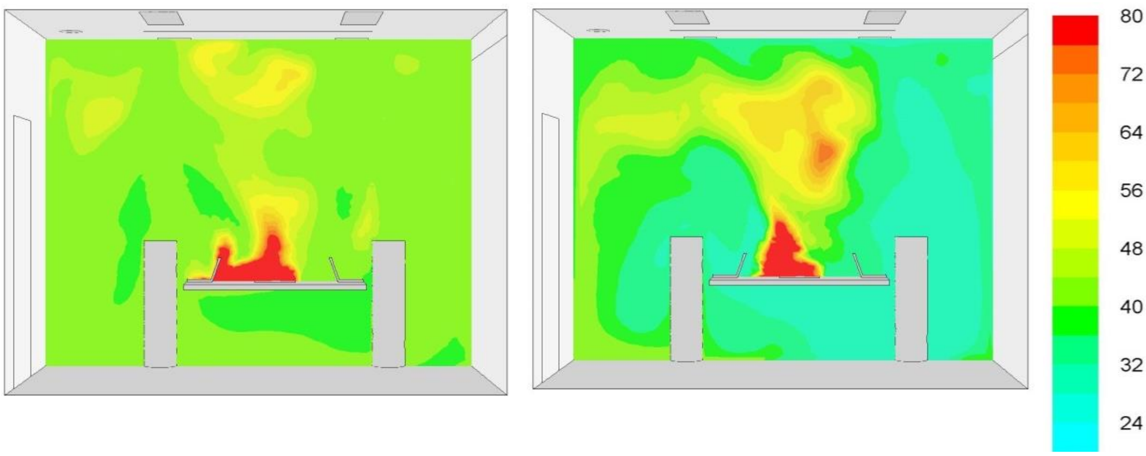


Figure 23: Simulated tracer gas concentrations (ppmv) in the room with an inactive (left) and with an active de-contaminating sink (right). Longitudinal section through the dummies and the contaminant source

It can be concluded that in rooms with mixing ventilation de-contaminating walls can be applied for the improvement of the indoor air quality. However, for the improvement of the indoor air quality not only in front of a de-contaminating surface but also inside the whole room a good air-intermixing is necessary. The reason for this lies in the fact, that in the rooms with mixing ventilation gaseous contaminants are spread by the moving air. Mixing enables the transport of the contaminants towards the wall and the recirculation of de-contaminated air.

Office room with displacement ventilation

A second model of a room with displacement ventilation was developed. The location and the intensity of heat and contaminant sources remained the same. The properties of the sink also remained the same.

Air exchange rate was 2.0 h^{-1}. The geometry and arrangement of the supply diffuser (inlet) was changed. In the second model the inlet is located above the floor (Figure 24). The geometry of the inlet was approximated to the form of a rectangle. The exact contour of the inlet was adjusted to the numerical mesh on the wall.

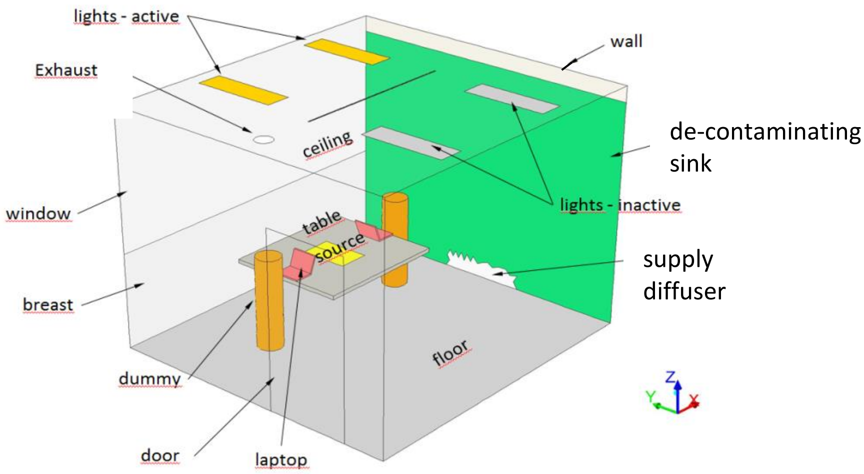


Figure 24: Model of the Test room with displacement ventilation, general view

Figure 24 shows a longitudinal section through the middle of the room without (left) and with a sink (right). A de-contaminating effect of the sink was visible on the right picture in the region in front of the sink (right wall). Under the investigated side conditions the activation of a de-contaminating sink caused a reduction of the tracer gas concentration in the studied room.

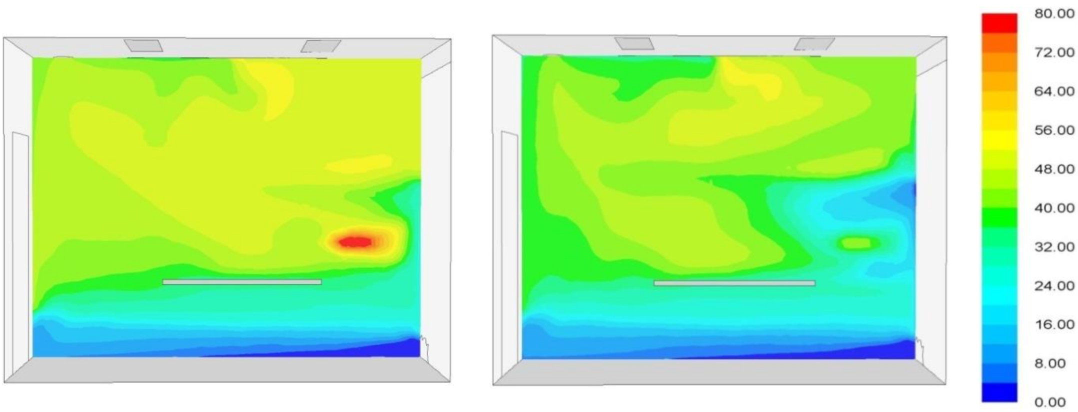


Figure 25: Simulated tracer gas concentrations (ppmv) in the room without (left) and with a de-contaminating sink (right). Longitudinal section through the middle of the room.

It can be concluded that in rooms with mechanical ventilation de-contaminating materials can be applied for the improvement of the indoor air quality and the reduction of supply airflows. Tests of de-contaminating materials performed in small test boxes do not provide comprehensive information about the impact of de-contaminating surfaces on the indoor air quality. The impact of de-contaminating surfaces on the indoor air quality is strongly influenced by the ventilation systems. This relationship should be considered for the application of de-contaminating surfaces.

WP7 Demonstration

Main objective was to demonstrate the concepts of the CETIEB project in diverse real building contexts. It was the principal, visible demonstration activity of CETIEB, and its accomplishment determined the success of the project. The installation works target to accomplish the plans prepared in WP2, the materials researched in WP5, the active systems developed in WP4 and the Monitoring Kit from WP3. This was performed in the following case studies.

- INCAS platform at CEA INES, Le Bourget du Lac, France:
  Real scale test of passive system (January to May 2013)
- Colegio El Porvenir, Madrid:
  Demonstration of monitoring system and passive system (September to December 2013)
- Lesson room at University of Stuttgart (IFK), Germany:
  Validation and comparison of CO_2 sensors (20th January till 16th February 2014)
- Office of RED, Padova, Italy:
  Real scale test of the intelligent light control system (February 2014)
- INCAS platform at CEA INES, Le Bourget du Lac, France:
  Real scale test of the intelligent control system (March 2014)
- INCAS platform at CEA INES, Le Bourget du Lac, France:
  Test of the Air BioFilter (23rd to 29th April 2014)
- Richard-von-Weizsäcker school in Öhringen, Germany:
  Demonstration of monitoring system (from 5th March 2014 until end of project)
- Taiwan Building Technology Center (TBTC) in Taipei, Taiwan.
  Demonstration of the Natural Light Illumination System (NLIS) (installed 2014)
- Registrar's office University of Stuttgart, Germany:
  Test of Air BioFilter in an large office environment (August to September 2014)
- Rock chapel of St. Salvator in Schwäbisch Gmünd:
  Detection of harmful ethanol concentrations in the air during a conservation treatment of rock sculptures (October to November 2014)

A system demonstration of the Natural Light Illumination System in Europe is planned in the frame work of the ECO-shopping project (http://ecoshopping-project.eu/) in Sopron, Hungary (Figure 26).

Figure 26: Planned installation side for the NLIS.

Three of the case studies were developed in existing buildings with students, teachers or employees present.

Colegio El Porvenir in Madrid, Spain

The first one of these was the demonstration of the monitoring system and passive system at the Colegio El Porvenir in Madrid. The El Porvenir school consists of one building constructed in the late 19th century in a neo-gothic and neo-mudejar style which is used for secondary education. A second new building was erected by FCC CO, intended for preschool and primary education, with 7,150 m^2 of constructed surface area. The works completed in summer 2013 (see Figure 27). The new building has a modern HVAC system, making it interesting for comparison of systems and materials developed in the CETIEB project.

Figure 27: Top: Overall plan of Colegio El Porvenir (left) and existing old building (right). Bottom: New building nearly finished (left) and floor plan of the new building.

Two neighbouring class rooms with identical exposition were chosen for demonstration. One was equipped with the passive plaster system (two walls with thermal insulation plaster and thermal storage plaster) as test room (see Figure 19) and one remained as reference. Both rooms were equipped with the monitoring system. The temperature variations were reduced in the test rooms due to the thermal storage ability of the plaster. Figures 20 and 21 show some of the results.

Richard-von-Weizsäcker School in Öhringen, Germany

The Richard-von-Weizsäcker School in Öhringen consists of three buildings. Two newer one built in passive house standard and one older built in energy-efficient standard (see Figure 28). Due to a technical problem the windows in the passive house part couldn't be opened. The only air exchange was provided by the central HVAC system. Students and teacher claimed about irritations, headache and cold air streams. This was a clear hint of indoor environment problems and therefore an ideal case for monitoring and assessment.

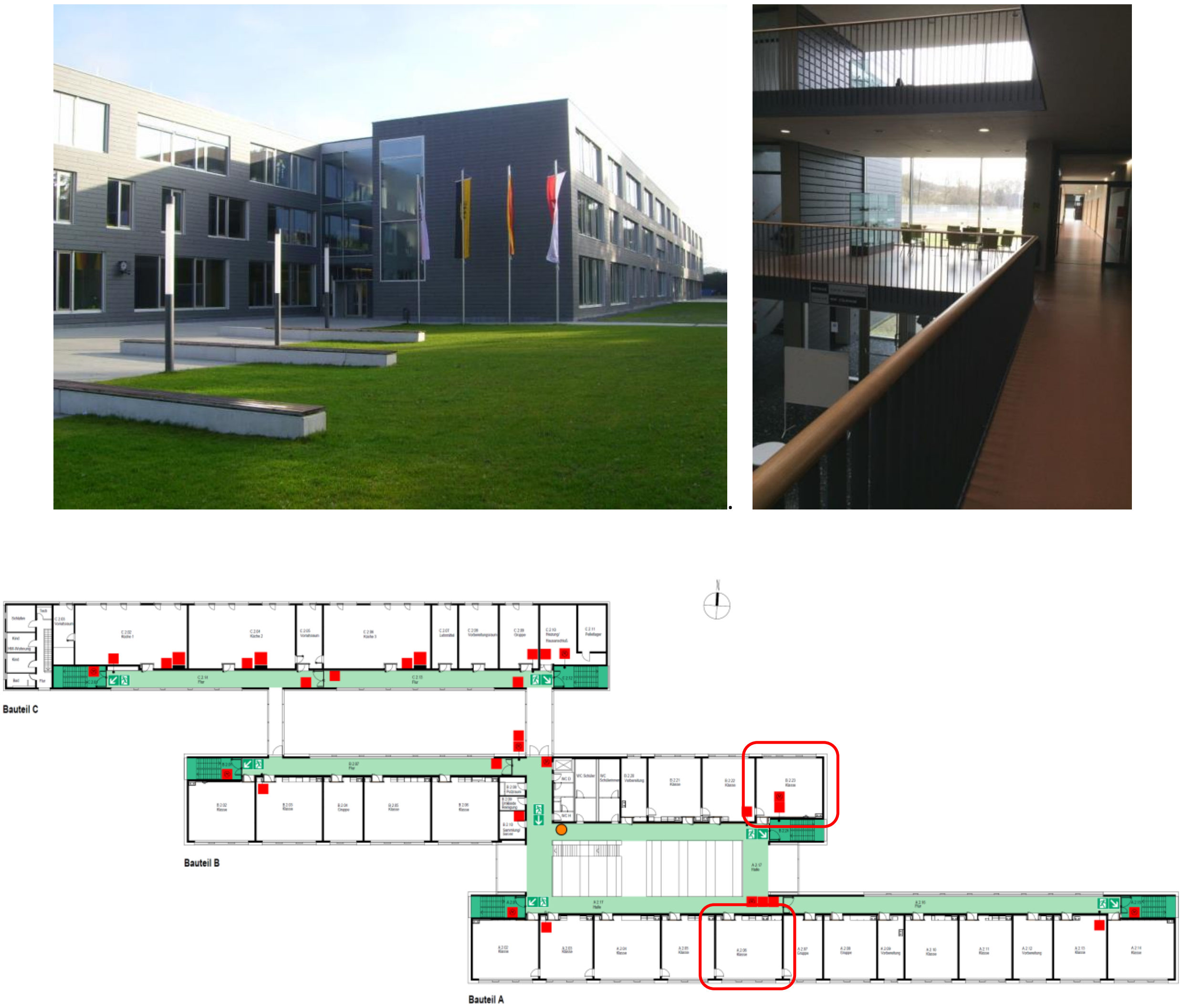


Figure 28: Top: Passive house part of the Richard-von-Weizsäcker School. Bottom: Floor plan of second floor. The two selected class rooms for monitoring are marked.

The results of the monitoring showed that the relation between temperature and relative humidity was not always in a satisfactory range. Figure 29 gives two examples from spring and summer. In winter and spring season the relative humidity went below 30% which could cause irritations like dry eyes. In summer times the opposite with too humid periods occurred. The air exchange rate is high enough. The CO_2 levels exceed 1500 ppm only very seldom and 2000 ppm was not reached. Interesting is as well the different thermal comfort level for students and teachers. It was found that the teacher perceives a higher thermal sensation with respect to students and this was due to the different metabolic profiles (see Figure 9).

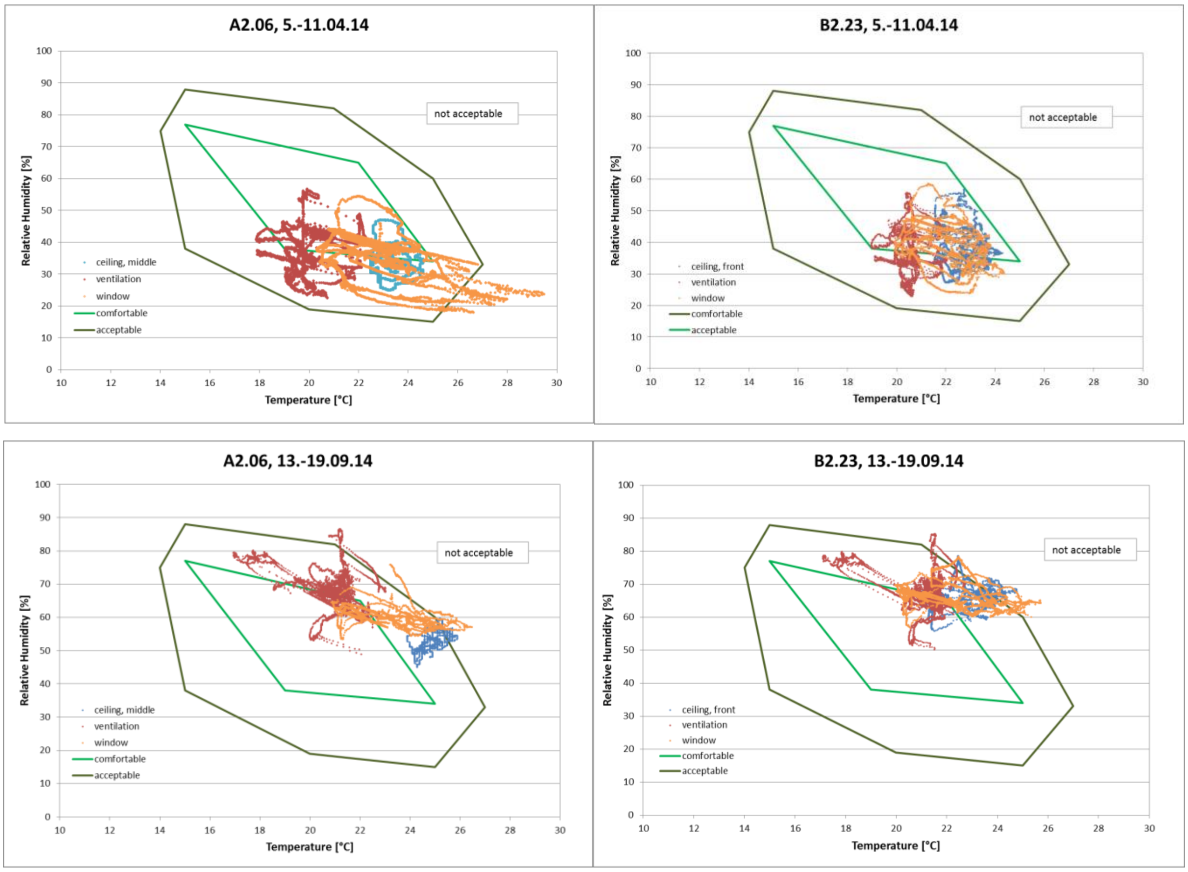


Figure 29: Correlation between relative humidity and room air temperature.
Left: room A2.06 (south oriented); right: room B2.23 (north oriented).

University of Stuttgart, Germany

At University of Stuttgart the effect of the Air BioFilter was tested at the registrar's office, a large office with 5 to 8 employees which has opening hours for students every day. The Air BioFilter (see Figure 12) led to a reduction of the VOC level of around 50% compared to the values before within a few days of operation. The results are shown in Figure 13.

A second demonstration was performed in a lesson room to compare low cost CO_2 sensors used in the monitoring system with an analytical instrument. The performance was acceptable with a high correlation within the detection limit of 2000 ppm of the low cost sensors. In general at lot of lessons reached the threshold of 1500 ppm and even the value of 2000 ppm (analytical instrument) were exceeded. The maximum value reached 3500 ppm (see Figure 30). Values above 2000 ppm are inacceptable according to German guidelines[4]. Therefore a better ventilation of the room during lessons is recommended.

[4] Leitwerte für Kohlendioxid in der Innenraumluft (2008). Quelle: Umweltbundesamt. http://www.umweltbundesamt.de/themen/gesundheit/kommissionen-arbeitsgruppen/ad-hoc-arbeitsgruppe-innenraumrichtwerte

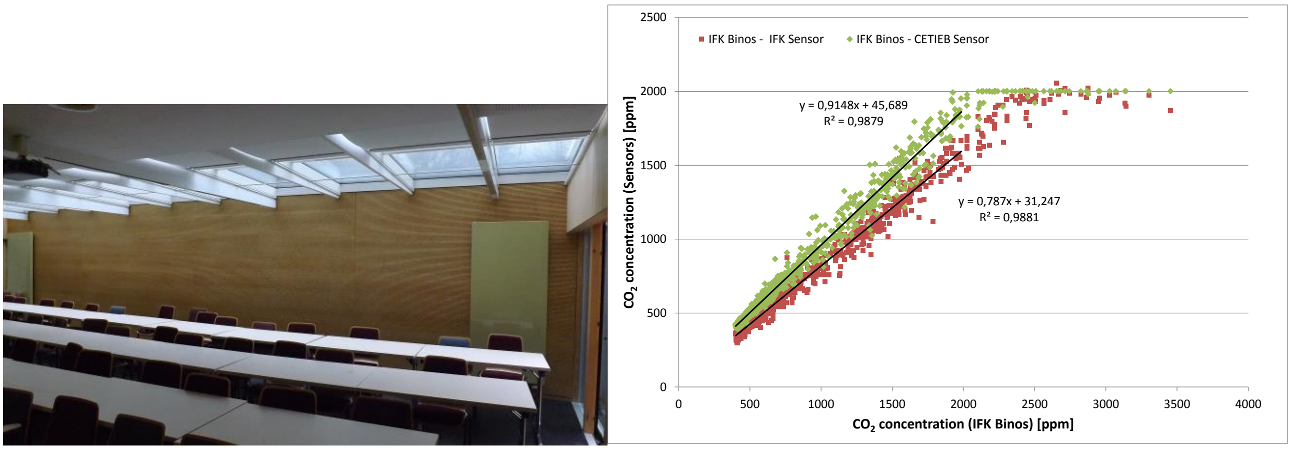


Figure 30: Left: Lesson room at University of Stuttgart for the CO_2-monitoring. Right: Correlation of low cost sensors with analytical instrument. Values above 2000 ppm are only measured by the analytical instrument.

4. Potential impact and main dissemination activities and exploitation of results

CETIEB products

Assembling the right team is essential to generating effective new business model ideas. Members should be diverse in terms of experience level, business unit represented, customer knowledge, and professional expertise. The consortium has been composed of 15 organizations from 7 different countries: Germany, Italy, Spain, Ireland, France and Greece, and the non-EU member Taiwan, and as a whole is well defined, taking into account the above mentioned terms and geographical location, where different changes of climate request different technological applications in relation to energy efficient buildings.

The Industrial "core" of the CETIEB project has been based on Large Industrial companies, such as: **S&B**, **Schwenk**, and **FCCCO** representing the whole value chain for construction from raw materials, building products, engineering and construction. Moreover, in the consortium have been included SMEs, such as: **DWE**, **SOL**, **RED**, **TTI**, **ITC**, and **STAM** – as innovative technology providers (TTI, ITC, RED and STAM) and supporting partners (DWE, SOL), increasing the value of project results.

The Academic "shell" of the CETIEB project has been based on: **USTUTT**, **UNIVPM**, **Fraunhofer-IPM**, **CEA**, **Consorzio TRE** and **NTUST** – as responsible for providing their knowledge during the development of systems and components, simultaneously increasing their know-how.

There are eight CETIEB products, defined during the execution of the project, such as: Infrared Thermal Comfort Monitoring System, VOC IR Sensor, RGB Lighting System, Monitoring System Platform, Active Control System, Air BioFilter, Natural Light Illumination System (NLIS), and Multi-Functional Plaster System, which are characterized by positive Value Properties for Retrofitting of Buildings:

- **Infrared Thermal Comfort Monitoring System**, which is characterized by the following Value Properties:
  - Provides multi-point thermal comfort monitoring for optimal assessment and control strategies, to improve in cost effectively way indoor environment quality. The system exists as a stand-alone solution and as an integrated version within the monitoring system.
  - Helps to achieve higher energy efficiency requirements of Building Regulations, imposed by EU/National Directives, and reduces energy use of HVAC system.
  - A patent was applied for the system, which is in evaluation state. UNIVPM evaluates now the possibilities to found a spin-off to commercialize the development.
- **VOC IR sensor**, which is characterized by the following Value Properties:
  - A tunable IR optical gas sensor for VOCs at lower ppm levels based on MEMS technology in combination with long path absorption cell which provides the possibility to distinguish between different VOCs and other IR active pollutants. A safety application was demonstrated within a national project in Germany.
  - Helps to improve the health related indoor environment quality by assessing of IR active air pollutants. The system exists as a stand-alone solution and as an integrated version within the monitoring system.
  - ITC collaborates with leading companies for air quality sensing, medical gas analysis as well as for health and safety technology on a pre-competitive level for a future product launch.
- **RGB Lighting System**, which is characterized by the following Value Properties:
  - Responsive light assessment and lighting system that provides colour corrected electric lighting that mimics daylight for more healthy indoor environments.

    - Valuable for museums, offices, retail and health providers (hospitals and nursing homes) to improve indoor light comfort and reduce the health and recovery time of patients thus reducing health care costs. The system exists as a stand-alone solution and as an integrated version within the monitoring system.
    - Reduces energy use by controlling and optimizing the amount of electric lighting that is used.
- **Monitoring System Platform**, which is characterized by the following Value Properties:
    - The monitoring system combines a wide variety of sensors (wireless and partly wired) in a data acquisition system based on data base driven single middleware platform. It is open for the integration of new sensors.
    - It provides the ability to monitor comfort and health related parameters in indoor environments. The data assessment supported by the middleware services helps to improve indoor environment quality by provision of control related information.
    - TTI Smartmote considers a commercialisation by licence or technology transfer.
- **Active Control System**, which is characterized by the following Value Properties:
    - Middleware platform for provision of control strategies and algorithms for HVAC systems.
    - Cost effectively the system helps to achieve higher energy efficiency requirements of Buildings Regulations.
    - STAM plans to provide both standardized and customized control systems to HVAC system manufacturers and building managers. Revenues will come from sales of the control system, provision of licences to HVAC system manufacturers and maintenance services to building managers.
- **Air BioFilter**, which is characterized by the following Value Properties:
    - Attractive internal feature which cost effectively improves indoor air quality and indoor environmental quality.
    - Cost effectively helps achieve higher energy efficiency requirements of Buildings Regulations.
    - Reduces energy use of ventilation system.
- **Natural Light Illumination System**, which is characterized by the following Value properties:
    - Advanced dynamic indoor lighting system
    - Valuable for buildings in which the natural light is limited
    - Reduces energy use of electric lighting
    - Four patents were applied during the project which are in evaluation state.
- **Multi-Functional Plaster System**, which is characterized by the following Value Properties:
    - High performance multi-functional mineral plaster system for new and retrofit projects.
    - Cost effectively the system helps to achieve higher energy efficiency requirements of Buildings Regulations.
    - Flexible family of products to meet customers’ requirements. Added functions increase options: improved insulating performance of envelope; thermal storage properties, and improved IEQ (only achieved for NO_x).
    - As a first product Schwenk will commercialise the developed thermal insulation plaster for indoor applications.

Indoor environmental quality guidelines

The *Guidelines for Retrofitting* have been prepared as main result in WP2 based on the different tasks and experience in the field. A series of individual Guidelines was developed for each category of retrofit measure which identifies their impacts; the relevant policies and regulations; the IEQ standards and parameters; and whether they are passive or active measures.

The Guidelines are comprehensive and provide a very useful prioritised strategy and methodology for retrofitting based on the WP-leader's experience operating a retrofitting contracting company and developing software for managing the retrofitting process. The measures include the activities at the beginning and end of an ideal retrofitting process which engage with the building occupants and users to create a feedback system for creating further knowledge about retrofitting. The retrofitting industry is still in its infancy with many working in the field still lacking important knowledge and experience.

Of critical importance is the understanding of the non-energy benefits of retrofitting as these have been proven to be more valuable than the energy saved by retrofitting. In order to make the economic and financial case for retrofitting this knowledge and information needs to be widely disseminated and developed as one of the main barriers to retrofitting is that stakeholders in the retrofit industry don't know the real value of better buildings.

The main annexes of the Guidelines describe the developed passive and active measures in terms of their benefits for individual stakeholders: building owner, building user, facilities manager, construction industry professional, etc. The descriptions include information for the general public, technical descriptions of the operation for stakeholders and financial cost-benefit analyses and business plans.

Cluster activities

The CETIEB partners have been involved in different clustering/networking activities and other research projects as well as activities not coordinated by the project with an essential impact on the dissemination of foreground.

EeB PPP Impact Workshops: CETIEB participated at the EeB PPP Impact workshops (2012, 2013 and 2014) and contributed to the development of an impact strategy of the EeB projects. One result was the formation of the AMANAC cluster (see below). The CETIEB project contributed to the EeB PPP Project Reviews 2012, 2013 and 2014 provided by E2BA and ECTP.

Advanced Material and NAnotechnology Cluster (AMANAC): The cluster was formed out of the EeB Impact Workshops. The European AMANAC-Cluster brings together up to now 27 related FP7 projects that use Nanotechnology as a Key Technology in order to develop high-performance insulation materials/products and HVAC systems to significantly enhance the energy efficiency of buildings. The Cluster includes Large Enterprises, SMEs, R&D entities. The developments of FP7 funded research projects and the cooperation potential established and provided by the AMANAC-Cluster formulate a platform that supports the EU efforts and objectives of enhancing the competiveness of our industry and strengthening our society. CETIEB is included in the group: "Technologies and materials for a healthier indoor environment" which consists of the projects: INTASENSE, CETIEB, H-HOUSE, BRIMEE, OSIRYS, and ECO-SEE. A first meeting was organized on 8th April 2014, in Athens (Greece). The second meeting was on 9th/10th October 2014 in Chambéry at CEA-INES in France. The third meeting is planned for 27th/28th May 2015 at the VII INTERNATIONAL CONGRESS ON ARCHITECTURAL ENVELOPES in San Sebastian, Spain. A core group of AMANAC contributes since 2015 as CSA-project within HORIZON 2020 to enhance the EeB PPP impact.

Indoor Environment Quality (IEQ) Cluster: The IEQ cluster was initiated by USTUTT-MPA on behalf of the CETIEB consortium at the ECTP-conference 2014 in Brussels within a dedicated session for Indoor Environment Quality (19th June 2014). The idea was to connect the group "Technologies and materials for a healthier indoor environment" within the AMANAC cluster with other ongoing European and national activities for Indoor Environment Quality and possibly to enlarge the cluster. As a first result the IEQ cluster contributed in July 2014 with research ideas to the European roadmap for "Renaturing Cities: Addressing Environmental Challenges and the Effects of the Economic Crisis through Nature-based Solutions" and "Materials & technologies for improved Indoor Environment Quality" within EU Horizon 2020. The research ideas paper and all session presentations are available for download at CETIEB homepage (www.cetieb.eu). The second meeting of the IEQ cluster was hosted by the Cost action TD 1105 EuNetAir at their 3rd Scientific Meeting organized by GEBZE Institute of Technology at Bahcesehir University in Istanbul 3rd and 4th December 2014. The IEQ cluster contributed with several presentations and posters to the workshop. The presentations will be soon available for download at the EuNetAir homepage (www.eunetair.it). The 3rd meeting of the IEQ cluster will be hosted by AMANAC cluster at their 3rd meeting at 27th/28th May 2015 at the VII INTERNATIONAL CONGRESS ON ARCHITECTURAL ENVELOPES in San Sebastian, Spain. The IEQ cluster will contribute with presentations and a special IEQ cluster session. It is planned in 2015 to establish the IEQ cluster as open group in the ECTP to formalize the work and get support from the ECTP internet platform.

European conference series for Renaturing Cities with nature based solutions: The CETIEB project supports the lounge of the EC research activity for "Renaturing Cities with nature based solutions" within Horizon 2020. A conference series was initiated by the EC to serves as showcase to demonstrate how Europe is leading the process of renaturing cities and how this European expertise could be up-taken at the international level. The CETIEB coordinator contributed with a presentation as discussant and a poster to the two conferences. The 1st conference was at 13th/14th May 20145 in Brussels with the theme "Renaturing Cities: Addressing Environmental Challenges and the Effects of Economic Crisis Through Nature-Based Solutions" and the 2nd was in Milan at 1st/2nd December 2014 with the theme "Renaturing Cities: Systemic Urban Governance for Social Cohesion". The third conference will be held in Berlin, Germany in May 2015. The activity of CETIEB and the IEQ cluster shows the contribution of the indoor environment quality sector to develop a research agenda for this new research field within Horizon 2020.

Cluster Smart Home&Living in Baden-Württemberg: USTUTT and TTI contributed to the regional initiative to establish the cluster Smart Home&Living in Baden-Württemberg. The cluster comprises all stakeholders for the development of Smart Homes with respect to comfort issues for the active generation and improvements for an assisted living for the elderly. CETIEB contributed with the results for comfort and health related parameters to identify a research agenda for the cluster. The CETIEB coordinator is member of Executive Board of Smart Home&Living.

Main dissemination activities

The CETIEB partners disseminated the project results through different publications and conferences. The main scientific publications are listed in the following:

International journals

- Revel, G. M., Arnesano, M., Pietroni, F., Frick, J., Reichert, M., Krüger, M., Schmitt, K., Huber, J., Ebermann, M., Pockelé, L., Khanlou, A., Ekonomakou, A., Balau, J., Pascale, C., De Falco, F., Landò, R., Battista, U., & Stuart, J. (2013). Advanced tools for the monitoring and control of indoor air quality and comfort. *Environmental Engineering and Management Journal*, 12(9);
- Revel, G. M., Arnesano, M., & Pietroni, F. (2014). Development and validation of a low-cost infrared measurement system for real-time monitoring of indoor thermal comfort. *Measurement Science and Technology*, 25(8), 085101;

International conference proceedings

- Revel, G. M., Arnesano, M., & Pietroni, F. (2014). A Low-Cost Sensor for Real-Time Monitoring of Indoor Thermal Comfort for Ambient Assisted Living. In *Ambient Assisted Living: Italian Forum 2013* (pp. 3-12). Springer International Publishing;

- J. Huber , R. Binninger , K. Schmitt , J. Wöllenstein (2013). Detection of bad indoor environment with a miniaturized gas sensor system. In *Proc. SPIE 8763, Smart Sensors, Actuators, and MEMS VI, 87632H (May 17, 2013).*
- Revel, G. M., Arnesano, M., & Pietroni, F. (2013). An innovative low cost IR system for real-time measurement of human thermal comfort. In *Proceedings International Conference IAQ2103 (Vancouver, October 2013);*
- Frick, J., Reichert, M., Baumbach, G., Song, S., Neuwirth, A., Krüger, M., Schmitt, K., Huber, J., Ebermann, M., Pockelé, L., Khanlou, A., Ekonomakou, A., Balau, J., Revel, G. M., Arnesano, M., & Pietroni, F. (2013). Monitoring and Improvement of Indoor Environments in Cultural Heritage. In *Conference proceedings EWCHP 2013: European Workshop on Cultural Heritage Preservation;*
- Revel, G. M., Arnesano, M., Pietroni, F., Schmidt, M., & Kaschtschejewa, O. (2014). Evaluation in a controlled environment of a low-cost IR sensor for indoor thermal comfort measurement. In *Proceedings International Conference QIRT 2014;*
- Alessi F. (2014). Impact of a photocatalytic layer covering the interior surfaces of a real test room: volatile organic compound mineralisation, risk assessment of by-product and nanoparticle emissions. In *Conference proceedings 35th AIVC 2014 in Poznan, Poland*.
- Revel, G. M., Arnesano, M. Pietroni, F., Frick J., Reichert M., Krüger M., Schmitt K., Huber J., Ebermann M., & Pockelé L. (2014). The monitoring of indoor air quality and comfort: the experience of the project CETIEB. In *Proceedings International Trade Fair ECOMONDO 2014, Procedia Environmental Science, Engineering and Management 1 (2014) (1) 87-92; November 2014*

National conference proceedings

- Revel, G. M., Arnesano, M., & Pietroni, F. (2014). Integration of real-time metabolic rate measurement in a low-cost tool for the thermal comfort monitoring in AAL environments. In *Conference proceedings ForitAAL 2014, (Catania, September 2014*);
- Revel, G. M., Arnesano, M., & Pietroni, F. (2014). A method to employ low-cost IR sensors for the indoor thermal comfort measurement. In *Conference proceedings of IX Congress of National Group of Mechanical and Thermal Measurements (Ancona, September 2014);*

Other publications

- Gu, B., Kaschtschejewa, O., Schlosser, T. (2013). Untersuchung der Schadstoffausbreitung in einem Büroraum. In *HLKBRIEF, Mitteilung 156 (www.vdf.info)*
- Schmidt, M., Kaschtschejewa, O. (2014). Verbesserung der Raumluftqualität mittels einer schadstoffsenkenden Wand. Teil 1: Experimentelle Untersuchungen. In *GI – GebäudeTechnik | InnenraumKlima, vol. 135, no. 05, pp. 280-289, 2014*

Training activities

In order to achieve the energy-efficiency in the buildings, and exploit it world-wide, the CETIEB project set up and performed various types of training activities for possible Stakeholders/End-Users.

On April 12, 2013 a training workshop at ACEN (Associazione Construttori Edili Napoli) was organized, which was attended by engineers and workers from private building industries and fellowship training students from the Universities in the Campania region of Italy. Few days later, the participants were asked to fill out a short questionnaire for the evaluation of the Training Workshop. Details are described in Deliverable D8.4. The workshop was appreciated by national and local media. Articles and a TV-Video (Julie News) are available at:
www.consorziotre.com/index.php?option=com_content&view=article&id=88&Itemid=62.

A second training workshop was performed at the 3rd European Workshop for Cultural Heritage Preservation (EWCHP) at 18th September 2013 in Bolzano, Italy. In focus were possible applications of CETIEB project results for use in the Cultural Heritage area. The workshop was attend by engineers, architects, restorers, cultural heritage supervisors, researchers and students from the region Trentino/South Tyrol and the international participants of EWCHP 2013. The audience was around 40 persons.

At the end of the CETIEB project execution, Günter Baumbach (USTUTT-IFK) organized the regional workshop “24th ALS Colloquium on Indoor Air Pollution” at 30th September 2014 at University of Stuttgart, Germany, at which achievements and outcomes of the CETIEB project were presented. The audience of the workshop was completed by Universities, Authorities, Large and Small/Medium Enterprises, Inspection Agencies, Engineering Consultancy, as well as Students of University of Stuttgart.

Student internships and theses

Individual student internships and theses were performed:

- MSc candidate Tommaso Recanatini from UNIVPM worked on his master thesis at the MPA Institute of the University Stuttgart (USTUTT-MPA, Germany) from 24/05/2013 to 31/10/2013.
- The students Dora Ya-Cie and Rongna Xiao-Rong from partner NTUST performed sensor and light studies at the MPA Institute of the University Stuttgart (USTUTT-MPA, Germany) from 19/08/2013 to 06/09/2013.
- MSc candidate Shuyang Song performed her master thesis at the IFK Institute of the University Stuttgart (USTUTT-IFK, Germany) from 01/12/2012 to 31/07/2013, working on photo catalysis.
- MSc candidate Marc Doyle performed his master thesis (2014) at Dublin Institute of Technology, School of Architecture, Architectural Technology with support and supervision of DWE. He worked on the construction principles of the Air BioFilter.

Fairs

The project participated at several fairs were the project results were disseminated. Own stands were provided at Building Test Expo (BTE 2013, Cologne, Germany and BTE 2014, Brussels, Belgium) and Mostra Convegno Expocomfort (MCE 2014, Milan, Italy). A presentation was given at Ecomondo 2013 (Rimini, Italy). The stand at the BTE 2014 in Brussels was together with the partner project INTASENSE from the same call and was visited by the EC project officer of the projects.

Figure: 31: Stands at BTE 2013 in Cologne (left) and BTE 2014 in Brussels.

Project website, video

CETIEB offers a website (www.cetieb.eu) and has implemented a group profile within LinkedIn.

The CETIEB project video was realized at the University of Stuttgart and at the demonstration site Richard-von-Weizsäcker School in Öhringen, Germany.

A low resolution web version is available for download at the CETIEB homepage www.cetieb.eu under "Download". A high resolution version and a DVD were provided to the project partners and the European Commission.

5. Address of public website and contact details

Public website:

www.cetieb.eu

CETIEB Coordinator contact details:

Dr. Jürgen Frick
Material Testing Institute – MPA
University of Stuttgart
Pfaffenwaldring 2b
D 70569 Stuttgart
Email: Juergen.Frick@mpa.uni-stuttgart.de
Tel.: +49/ 711/ 685-63381

6. Project logo

7. Diagrams, photographs, videos

Provided in the text.

8. *List of beneficiaries with contact names*

Participant no.	Participant legal name – Acronym	Country	Organisa-tion type*
1	University of Stuttgart – USTUTT - Materials Testing Institute (MPA), **coordinating institute** *Contact: Jürgen Frick; www.mpa.uni-stuttgart.de* - Institute of Building Energetics (IGE) *Contact: Günter Baumbach; www.ifk.uni-stuttgart.de* - Institute of Combustion and Power Plant Technology (IFK) *Contact: Michael Schmidt, Olga Kaschtschejewa; www.ige.uni-stuttgart.de*	Germany	RTD
2	DW EcoCo – DWE *Contact: Jay Stuart; www.delapandwaller.com/irelands_offices.php*	Ireland	SME
3	S&B Industrial Minerals S.A. – S&B *Contact: Christos Dedeloudis; www.sandb.com*	Greece	Industry
4	Solintel – SOL *Contact: Emil Lezak, www.solintel.eu*	Spain	SME
5	Università Politecnica delle Marche – UNIVPM *Contact: Gian Marco Revel, www.univpm.it*	Italy	RTD
6	RED S.r.l., Research and Environmental Devices – RED *Contact: Luc Pockelé; www.red-srl.com*	Italy	SME
7	TTI GmbH; TGU Smartmote – TTI *Contact: Markus Krüger; www.smartmote.de*	Germany	SME
8	Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V. – FRAUNHOFER *Contact: Katrin Schmitt; www.fraunhofer.de*	Germany	RTD
9	InfraTec GmbH – ITC *Contact: Martin Ebermann; www.infratec.de*	Germany	SME
10	CEA INES Institut National de l'Energie Solaire – CEA *Contact: Franck Alessi; www.cea.fr*	France	RTD
11	Stam S.R.L. – STAM *Contact: Roberto Lando; www.stamtech.com*	Italy	SME
12	Schwenk Putz und Mörteltechnik GmbH – Schwenk *Contact: Johann Balau; www.Schwenk-Putztechnik.de*	Germany	Industry
13	Consorzio TRE – TRE *Contact: Francesco De Falco; www.consorziotre.it*	Italy	RTD
14	FCC CONSTRUCCION, S.A. – FCCCO *Contact: Francisco Esteban Lefler; www.fccco.es*	Spain	Industry
15	National Taiwan University of Science and Technology – NTUST *Contact: Allen Jong-Woei Whang; www.ntust.edu.tw*	Taiwan	RTD