Teaching and researching the indoor environment: from traditional experimental techniques towards web-enabled practices

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Abstract

In this paper some of the recent developments and ongoing work at the Energy, Environment and Comfort research group of ADAI (Association for the Development of Industrial Aerodynamics), in the areas of Indoor Environmental Quality and Energy Efficiency in Buildings are presented. Summarily, it is showcased a state of the art of the Indoor Live Lab, developed at the Mechanical Engineering Department of the University of Coimbra.

The Indoor Live Lab (I2L) is a new platform for research and technology demonstration in Indoor Environmental Quality (IEQ). The main motivation for initiating this effort arose from the increasing necessity that researchers, educators and decision makers have for continuously available monitored data on all aspects of building functioning. This paper aims at presenting early developments at the I2L, as well as associated research projects which were at the centre of its creation. Firstly, the objectives of the I2L are presented. Secondly, ongoing research on both residential buildings and services buildings is exposed. After, the several IEQ parameters studies are discussed in particular. This is followed by the I2L description, location and specific features. Finally, a conclusion and future work section is presented.

Keywords

Indoor environmental quality; energy efficiency; tracer gas techniques; remote and virtual laboratories; building rehabilitation; hybrid ventilation.

Nomenclature

ADAI	Association for the Development of Industrial Aerodynamics (in Portuguese: *Associação para o Desenvolvimento da Aerodinâmica Industrial*)	IIC	Initial Investment Cost
ACH	Air Changes per Hour	LCC	Life Cycle Cost
AER	Air Exchange Rates	LCIA	Life Cycle Impact Assessment
DEHEMS	Digital Environment Home Energy Management System	Moodle	Modular Object-Oriented Dynamic Learning
DEM	Department of Mechanical Engineering at the UC	MV	Mechanical Ventilation
DHW	Domestic Hot Waters	NSA	Neighborhood Sustainability Assessment
ECTS	European Credit Transfer and Accumulation System	NV	Natural Ventilation
EE	Energy Efficiency	Q	Ventilation airflow rate (m^3/s)
EPBD	Energy Performance of Buildings Directive	REH	Regulation for the characteristics of thermal behavior of residential buildings (in Portuguese: *Regulamento de Desempenho Energético dos Edifícios de Habitação*)
GWP	Global Warming Potential	RH	Relative Humidity
HVAC	Heating, ventilation, and air conditioning	TC	Thermal Comfort
I2L	Indoor Live Lab	TPE	Total Primary Energy
IAQ	Indoor Air Quality	UC	University of Coimbra
IECB	E-learning course on Indoor Environmental Comfort in Buildings at the University of Coimbra	UNESCO	United Nations Educational, Scientific and Cultural Organization
IEQ	Indoor Environmental Quality	WS	Wind speed (m^3/h)
		3Es	Energy Efficient Schools project (in Portuguese: *Escolas Energeticamente Eficientes*)

Introduction

In Europe there is a growing awareness and concern towards how energy is used in buildings, especially with respect to people's quality of life and also to its repercussions on the environment and the economy. This interest and concern can be understood due to the increased population density in urban areas, since around 75% of the European population lives in cities [1], [2], and the pressures related to urbanization, pollution and depletion of natural resources are at the origin of significant differences in the quality of life across the European Union Member States.

To meet the targets for a Low Carbon Economy by 2050, all new and existing buildings must significantly reduce their energy footprint, and progressively make a transition towards low carbon energy supplies. In Europe, residential buildings represent 75% of the built area and in 2009 the residential sector was responsible "for 68% of the total final energy use in buildings"[3]. New buildings, and existing buildings that are undergoing renovation, are subject to minimum requirements for energy efficiency (EE), related to the European Union policy to achieve nearly zero energy buildings in the near future [4-8]. Satisfying these requirements, however, must not be favoured at the expense of the Indoor Environmental Quality (IEQ) and comfort of the building occupants and visitors [5], since "occupants spend over 85% of their time indoors" [6]. IEQ is a major factor conditioning the health and productivity of people [7] encompassing the thermal environment, the indoor air quality, as well as other health, safety and comfort aspects such as ergonomics, acoustics and lighting. Undeniably, these factors play an important role in energy performance of buildings [8].

One of the aspects of IEQ that greatly affects EE in buildings is the thermal environment, since HVAC systems in mechanical ventilated buildings consume significant amounts of energy when running. From a database presented in [9], the authors of [10] showed that space heating accounts for more than 45% of the energy use profile of secondary schools in the USA. Recently, in 2014, the authors of [11] showed the result of a thermal comfort study conducted in a secondary school in Cyprus unveiling that the representative secondary "typical school building *did* not provide the required indoor thermal comfort conditions for its occupants". In Ref. [12], it was reported that IEQ negative results in Portuguese secondary school buildings were mostly due to excessive CO_2 concentration indoors, i.e. poor Indoor Air Quality (IAQ).

Improving EE in buildings without considering occupants' comfort might have harmful effects on occupants' health and their productivity. Therefore, EE and IEQ have to be considered simultaneously throughout building design, construction and operation. To make their buildings places where people feel good and perform well, building designers and building managers must balance the selection of strategies that promote EE and energy conservation with those that address the needs of the occupants and promote well-being. Ideally, design and operational strategies would do both: the solutions that conserve energy, would also contribute to the best indoor environment. In reality, however, it is not possible to achieve a best indoor environment for all the occupants of a building, because people do not share the same preferences or the same expectations about their indoor environment. Therefore, it is not possible to satisfy every building occupant all of the time. It is possible, nevertheless, to satisfy the majority of the occupants most of the time, and it is this fine balance between the best achievable IEQ and the associated energy necessary to maintain it, that makes Indoor Sciences such a challenging and exciting field of research.

In this context, the authors present a summary of recent developments and ongoing work at ADAI's Energy, Environment and Comfort research group [13], in the areas of Energy Efficiency in Buildings and Indoor Environmental Quality. Centre stage is given to the Indoor Live Lab – I2L [14], a new platform for research, technology demonstration and IEQ teaching enhancement.

1. I2L: The Indoor Live Lab

There has been a tendency in building management research towards developing supervisory control systems for improving IEQ and energy efficiency in buildings [15]. In studies focusing on building energy and comfort management, conventional control systems are being replaced by intelligent controls [16]. It should be mentioned that many Live Labs have formerly been developed for many purposes in a variety of research areas. For instance, a project, known as the Digital Environment Home Energy Management System (DEHEMS) [17] has developed Live Labs in five European cities to assess the behaviour of the occupants on energy use as well as the advantages of energy monitoring.

The concept of the I2L has been proposed as an online platform for high availability of IEQ and energy data in an office setting, as well as the physical instrumented space where the data is acquired. It is a peculiar proposal in the sense that it is not intended to be a carefully controlled experimental setup. Rather, it is meant to be a permanent instrumented installation in an existing 6 person office, where the indoor and outdoor environmental conditions as well as energy use can be continuously monitored in the long term and in a non-intrusive way, as the office occupants go about their daily routine.

1.1 Research methodologies on IEQ, EE and Infiltration rates

Air infiltration through the building envelope is one of main mechanisms that directly affect both the energy performance of buildings and the quality of the indoor environment [18], [19]. Air infiltration is a term commonly used to designate uncontrolled and unintentional air flows through the building envelope, through holes, cracks, voids and unsealed joints. Some authors, particularly in the HVAC literature, distinguish between infiltration and exfiltration to mean the ingress of outdoor air into the building and the escape of indoor air out of the building, respectively [20], [21]. Herein, there is not a requirement to make such a distinction, and infiltration is used throughout to mean uncontrolled and unintentional air flow through the building envelope, regardless of direction.

In residential buildings, air infiltration provides the minimum air ventilation for the dilution and removal of indoor pollutants and the basic oxygen needs for human activities, when windows or vents are closed and mechanical ventilation (MV) systems are off. Air infiltration co-exists with installed natural or MV systems, and its unpredictable contribution to the total space ventilation often leads to an overestimation of the required ventilation rates, contributing to system overdesign and uncertainty in building simulation. Air infiltration represents heat loss in winter and excessive daytime heat load in summer [19], and affects the performance of mechanical or hybrid ventilation systems. Infiltration may represent a significant fraction of untreated air entering buildings with mechanical extraction, even with purposively designed inlet devices, or where unbalance is created by pressure differences in other types of mechanical systems.

To a large extent, the enhancement of the EE of buildings has been achieved by improving the thermal performance of the opaque envelope through the widespread use of thermal insulation systems [22], [23]. Yet, in contemporary residential buildings, more than 50% of the energy consumption is used for space heating and air conditioning in EU members [28-30], and the main mechanism through which energy is lost to the environment is associated with the renovation of indoor air. There is, therefore, a great potential for energy savings in buildings by controlling air infiltration through the building envelope. This potential is being explored in modern constructive solutions, through the use of window frames with high thermal performance and reduced air permeability. This has led, in some buildings, to an extreme reduction in effective ventilation rates, which is believed to be at the origin of health problems or symptoms of disease associated with permanency inside these buildings.

Lately, air infiltration through the building envelope became intrinsically a key issue in building regulations. When the EPBD recast [26] became into force, however, uncertainty persisted about the magnitude of the national minimum or reference infiltration rate in each Member State, in Portugal in particular, regarding air infiltration rates in existing and newly built dwellings.

Thereat, an experimental field research in the assessment of fresh air infiltration rates in 20 naturally ventilated dwellings in the district of Oporto (Portugal), under regular occupation, was performed. Using the transient techniques of the tracer gas method with the metabolic CO_2 released by its occupants. The time evolution of the CO_2 concentration at each dwelling was measured and recorded for at least 3 days. The obtained infiltration rates were compared with the current Portuguese regulation on the thermal performance of residential buildings (REH [27]). Subsequently, the short-term measurements were also adequate for evaluating the IAQ considering the metabolic CO_2 as an indicator.

The full results of this research, of which a summary is shown in **Figure 1**Error! Reference source not found., can be seen in [28], [29]. In all tests, the obtained infiltration rates varied between 0.03 ACH and 0.6 ACH, except for the dwelling #13 with a maximum of 0.86 ACH. The arithmetic mean infiltration rate varied between 0.46±0.23 ACH and 0.15±0.08 ACH and the geometric mean infiltration rates between 0.4 ACH and 0.12 ACH, both respectively, in the dwelling #13 and in the dwelling #20. In the Portuguese regulations regarding thermal performance buildings it is assumed that residential buildings have construction characteristics or ventilation devices that ensure a minimum ventilation rate of 0.6 ACH and that this is needed to maintain a good IAQ. While the former regulations [30] were based on a simplified calculation with standard values, where the infiltration rates by natural ventilation varied from a minimum requirement of 0.6 ACH up to 1.25 ACH, the current ones are based on the EN 15242 with some adaptations and simplifications. The dwellings with estimated infiltration rates closer to those measured are the ones with a single facade, eventually without cross ventilation solutions, with a low height above ground and located in high terrain roughness sites, which implies a low wind exposure of the dwellings. Dwellings with higher deviations between estimated and measured infiltration rates were those located close to the coastline with low terrain roughness and high wind exposure.

This research played an important role in the revision of Portuguese regulations for the air infiltration requirements in residential buildings [27], [31]. It enabled a minimum infiltration rate requirement of 0.4 ACH for existing buildings and the calculation of an alternative value to the non-default value for the mean local velocity of wind in the calculation of air infiltration. These changes in the official infiltration rate calculation tool followed some critical aspects discussed in [32]. Recently, the authors of [33] performed a study on a single family house in Sweden revealing that it was possible to achieve acceptable IAQ values with 0.30 ACH against the 0.50 ACH requirements from the Swedish legislation. By lowering the ventilation rate in accordance to the number of the occupants of a dwelling, 43% energy savings were estimated.

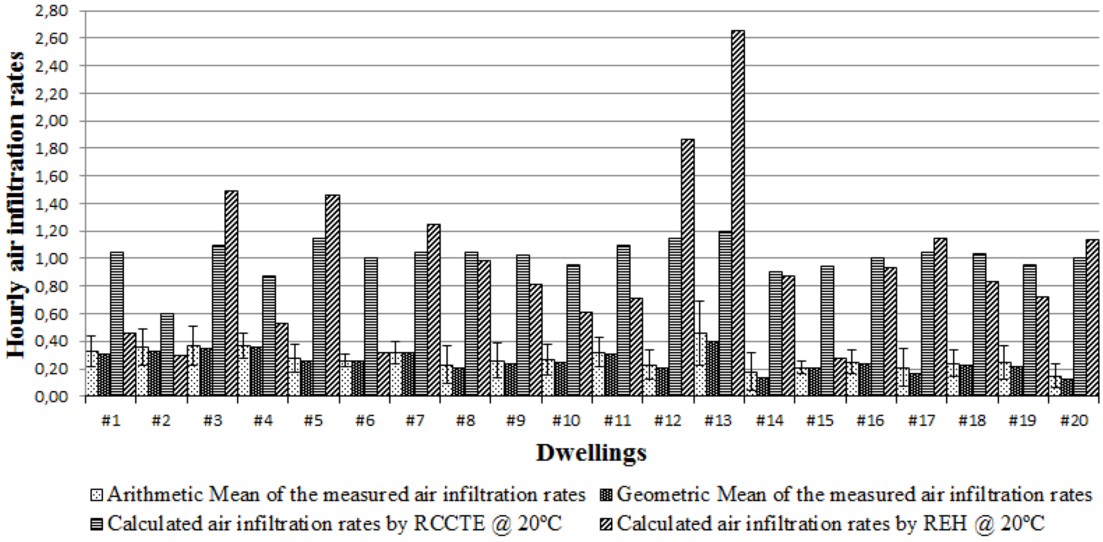

Figure 1 - Obtained mean infiltration rates and estimated infiltration rates in the assessment of 20 dwellings in Oporto, Portugal.

1.2 New tracer gas techniques for measuring time-varying air ventilation rates

The importance of being able to quantify infiltration rates in buildings is twofold: on one hand, air infiltration can represent an important component in a building's energy balance and there are now well established strategic policies that have resulted in regulatory pressure to reduce uncontrolled airflows through the building envelope; on the other hand, air infiltration has traditionally been relied upon to provide a minimum of building ventilation, particularly in the residential sector, the lack of which has been associated with health problems and lower productivity. As air infiltration is the primary way to ensure that there is a minimum of air renovation in most residential buildings, it is essential to understand the magnitude of these flow rates and to what extent there can be innovative solutions for controlling them, aiming at minimizing energy wastage while maintaining a healthy indoor environment.

Although the physical principles of natural ventilation (NV) are well understood, it has been generally recognized in the past that it is difficult, if not impossible, to obtain detailed information on the continuous time evolution of air exchange rates (AER) in buildings. Instead, established methods determine time-averaged ventilation rates by processing the concentration time series of a tracer gas over a period of time, usually several hours. This gives a useful indication of the magnitude of the AER over the assessment period but lacks the detail and precision required to quantify the dynamics of the phenomena involved.

To this end, novel tracer gas based approaches to measuring AER in buildings are being developed and tested against conventional tracer gas techniques. A technique for estimating the time evolution of AER, using metabolic CO_2 was presented in [34]. This technique relies, however, on the generation of CO_2 by the occupants, and it is not possible to apply it during extended periods of occupant absence, such as weekends and holidays. An alternative approach is to use a tracer that is already present in the outdoor atmosphere, which has a measurable cyclic variation. This method belongs to the class of tracer gas techniques but, unlike conventional methods that assume the background tracer concentration is constant, the proposed method recognizes that some tracers, such as CO_2, have daily quasi-periodic variations in the outdoor concentration (**Figure 2**).

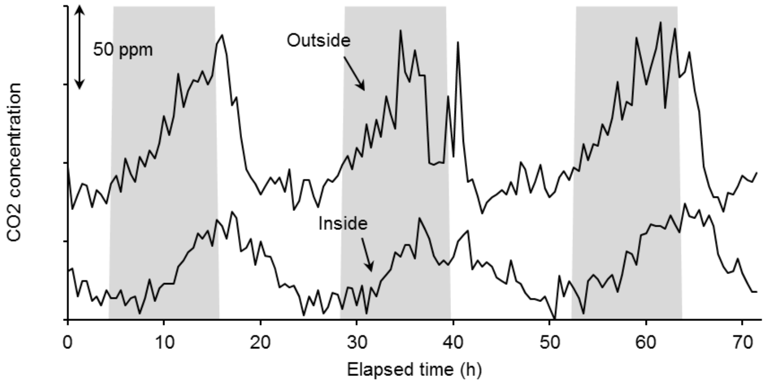

Figure 2 - Time series, recorded over 3 days, of exterior and interior CO2 concentrations: raw data shown with an artificial vertical offset for better visualization. Ticks on the vertical axis are 50 ppm apart and the shaded areas identify night periods, between 20:00 and 07:00.

These daily variations, which can be small but are still within the detection range of existing monitoring equipment, can be successfully used for estimating building ventilation rates without the need of a source of tracer inside the building. The new method has the advantages that no tracer gas injection is needed, and time resolved results are easily obtained. A general application of the determination of time varying air infiltration rates is presented in [35], which does not rely on the tracer gas concentration having a well-defined period. This has a greater potential for application with tracers that occur in urban settings, for instance those generated by traffic pollution, which have variations with a broader frequency spectrum.

1.3 Environmental noise

One aspect of IEQ that is known to have direct repercussions in people's health is environmental noise. Like other pollutants, its source can be inside the building but, more often, environmental noise has its origin outdoors, for instance due to road traffic and other types of transportation, construction works, music events, to name a few. This factor leads necessarily to occupants' discomfort [36]. The assessment of people's exposure to environmental noise is performed through the determination of long term acoustic descriptors. This determination is often done through sampling, using short term measurements. Having these measurements in mind, conclusions are drawn, and decisions are taken, that may have greater or lesser impact on the life of citizens, on economic activities and on the environment.

In [37], a generic methodology was developed which, when applied to a temporal noise pattern, allows for the optimization of the sampling parameters in order to help in its definition when designing a sampling strategy and thus control the precision level of the sample. An urban site with road noise predominance was studied over four years. The data collected during that period allowed to statistically define the sound profile.

The permanent monitoring system (**Figure 3**), based on a laptop computer with a data acquisition board, an external microphone and its respective pre-amplifier, and the data processing methodology is presented in refs. [42] and [43].

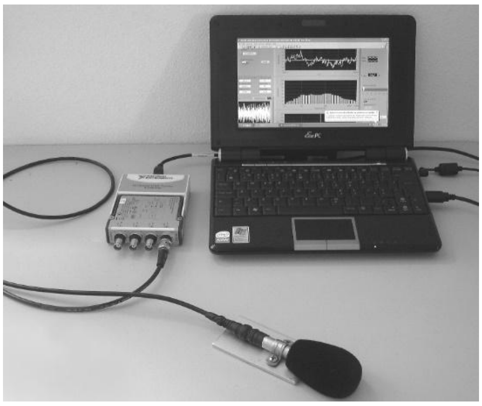

Figure 3 - Sound data-acquisition system – microphone, pre-amplifier, AD board and laptop.

To evaluate the influence of the sampling parameters on the precision of the noise descriptors, the collected data was subjected to a re-sampling process through the Bootstrap method. The bootstrap method [40] is a type of resampling method which can be easily used to estimate statistical properties of a complete population, of which only a sample is known. It has been successfully applied in [41] and [42] in estimating the uncertainty associated with environmental noise measurements. The advantage of the bootstrap method over the methods proposed in [43] is the lack of the requirement to assign a probability distribution to the input quantities in the measurement model. It relies on the assumption, however, that the sample is statistically representative of the complete population.

The algorithm selects measurement starting times randomly from the available time series with a uniform probability distribution. This is repeated a large number of times, in order to generate sequences of equivalent noise levels,

$L_{Aeq,\Delta T\,(N),i,}\ i = 1, \ldots, M$, from which the average levels, defined by

$$\bar{L}_{Aeq,T} = \frac{1}{M}\sum_{i=1}^{M} L_{Aeq,\Delta T\,(N),i} \qquad (1)$$

and the sample standard deviations, defined by

$$S(L_{Aeq,T}) = \sqrt{\frac{\sum_{i=1}^{M}(L_{Aeq,\Delta T\,(N),i} - L_{Aeq,T})}{M-1}} \qquad (2)$$

can be calculated.

In (3) the set of obtained results for the relationship between the uncertainty of the noise equivalent level and the sampling parameters (number (N) and duration (ΔT) of sampling episodes) allowed to obtain the following generalised expression that may be applied to the various reference periods (day, evening, night), where the coefficients c_1, α_1, α_2 and α_3 are characteristic of the site and must be determined experimentally [37] and [44]. Error! Reference source not found. shows an example set of coefficients determined for the site studied in [22].

$$s(L_{Aeq,T}) = c_1 \times \Delta T^{\alpha_1} \times N^{-[\alpha_2 + \alpha_3 \times \ln(\Delta T)]} \qquad (3)$$

Table 1 - Numerical coefficients determined for the site studied in [22]

Coef.	Day	Evening	Night
c_1	2.5224	2.2885	4.6034
α_1	-0.086	-0.181	-0.068
α_2	0.408	0.3695	0.4686
α_3	0.010	0.034	0.002

2. I2L: case-studies

2.1 EE and IEQ in residential historic buildings

In Portugal, residential buildings represent 77% of the built area and an estimated 16% of the total primary energy consumption, from which 43% rely on electricity based energy distribution. Although it is largely assumed that retrofitting the existing building stock towards the nearly zero energy target only lacks funding to occur, a deep assessment carried out in [45] demonstrates that misconceptions about ancient buildings still endure, and that enhanced knowledge is needed to harness a wider renovation potential: energy efficiency as a driver, not a goal by itself. Findings from the ongoing PhD thesis on "Upgrade Opportunities for Ancient Buildings (in City Centres)" [45]–[48] confirm that detailed studies using imaging techniques such as 3D tools and thermography; IEQ assessment; and building information model depictions, are viable if applied to the building scale and neighbourhood scale. Complemented, for example, with the use of neighbourhood sustainability assessment (NSA) tools that aim at integrating "the four pillars of sustainability namely, environmental, social, economic, and institutional dimensions" [49].

An ancient building dating back to the XVIth century located in Coimbra's UNESCO area was used as case study (**Figure 4**). The building's stacked masonry walls provide peripheral support to wooden floor levels and ceilings, protected by ceramic roof tiles on a wood structure. Wood doors and simple glazing sash windows with interior shutters exist, with high air infiltration due to lack of maintenance. Thick walls reducing towards the upper levels define growing internal areas: 13.7 m² in a semi-buried level with separate entrance, 15.3 m² on the intermediate level, and 20.6 m² on the top level. Currently, only 35.9 m² are inhabitable, as the lower level has severe humidity problems.

Figure 4 - Panorama view of the Montarroio case study in Coimbra, Portugal. The building is signalled by the rectangle.

The case study was documented using advanced tools for terrestrial laser scanning and digital photogrammetry, used to produce point clouds of the model and later tri-dimensional models [47]. Thermographic imaging was used to visualize the original thermal behaviour of the building: a set of range-calibrated thermographic images from exterior (top) and interior (bottom) of the top South facing window, adjacent to attached building, at different times of a winter day are documented in **Figure 5**.

Figure 5 - Terrestrial Laser Scan (left), Digital Photogrammetry (middle) and thermography (right)
[Darker colours represent colder surfaces, with low width walls and low inertia]

Using an indoor air quality (IAQ) and energy monitoring online system [50], environmental parameters such as CO_2, relative humidity and ambient temperature were measured in each level and outdoors. The CO_2 measurement effectively illustrated infiltration rates and human presence, while the temperature and humidity measurements depicted the influence of the vernacular materials inertia. These data were used to formulate a proposal that connects the known history of use and construction, with what is expected to guarantee the users comfort and safety. This proposal was carried out through the Energy Plus building simulation software.

Studies to evaluate the costs, both from an economic and an environmental perspective were also performed. The evaluation of five alternatives for the renovation of the Montarroio building, including demolition and reconstruction (**Appendix I**) was compiled in [48]. Here, the economic indicators Initial Investment Cost (IIC) and the 30 years Life Cycle Cost (LCC) were reported (**Table A.1**, **Appendix I**). The results demonstrated that higher IIC in efficient equipment reduces energy consumption (electricity and/or gas, as solar thermal and biomass are accounted as neutral in emissions in Portugal) and is, most of the time, favourable on the long term LCC. Nevertheless, the comparison between Option 0 ("Anyway Scenario") with Option 1 ("Business as Usual" regulation-inspired practices) casted doubts on building envelope options, and conclusions only emerge when tackling the Life Cycle Impact Assessment (LCIA) analysis.

Real data from a case study is important to become empathetic with building owners, and realize why apparently straightforward solutions fail to happen. Moreover, the LCIA evaluation of environmental impacts, expressed in parameters as Global Warming Potential (GWP) and Total Primary Energy (TPE), demonstrated that in the Mediterranean climate, deep renovation interventions, recommended or imposed by regulations, such as interior insulation with windows replacement (Option 1) have worst long term impact on environment**,** and owners pocket, than a lower price option – as the case study in its current state (Option 0). It was shown that in this climate, for ancient buildings, installing heat pumps for acclimatization (air-air) and DHW (air-water) is cost-effective, even considering their replacement every 15 years. These findings confirm proposals for a generalised use of heat pumps in a session of the European Association for Heat Pumps, but what would be the consequences of placing exterior units in each façade of the UNESCO historic centre?

75% emission reductions and increased energy security might also be achievable considering insulation only in the building envelope horizontal faces (ceiling and floor over the basement) and solar based DHW and heating with electric resistance heater backup. By connecting future and past, it is demonstrated that a market exists in between the individual needs for comfort and safety, and the collective goals of Energy Efficiency, Security and Climate Change Mitigation, today.

2.2 EE and IEQ in public schools

As people spend most of their time inside buildings, it is crucially important to provide adequate indoor air quality (IAQ) in addition to thermal comfort (TC), especially for office buildings and schools in which people are working, learning and studying, and where the level of personal control over their indoor environment can be very limited. IAQ and building ventilation are intimately related because ventilating indoor spaces with outdoor air supply is the most often used mechanism to decrease the concentrations of pollutants generated inside the building.

Within the 3Es project (*Escolas Energeticamente Eficientes* - Energy Efficient Schools) [51], it has been developed an integrated approach for energy performance and IEQ assessment in school buildings aiming at contributing to reduce the energy consumption in school buildings while providing good indoor environmental conditions to the occupants. This project was preceded of other studies on the field of TC and IAQ in schools [52] and followed the context of a major rehabilitation and refurbishment program of secondary school buildings that has been carried out in the last few years in Portugal [53]. From a database provided by the state-owned company Parque Escolar

E.P.E., energy consumption changes between the pre and post-intervention phases were characterized [54]. Based on the characterization and a set of criteria, a group of eight representative schools was chosen as case studies within the project. Aiming at achieving a functional benchmarking indicator, significant to situate each of the schools in a proper ranking, an extensive literature review on the theme was performed [10].

Energy and indoor climate quality post-occupancy audits, especially during the first occupancy phase of new and refurbished buildings, are important strategies to improve the energy use, since the indoor climate has a great impact on perceived human comfort and is related to the occupants' productivity [5]. From this perspective, besides energy auditing, it was proposed a methodology to assess IAQ and TC in Portuguese secondary classrooms (subjective and objective evaluation) [12]. Some of the typical data presentation achieved within this methodology was earlier presented in [55]. In terms of ventilation requirements and its contributions towards energy consumption in school buildings, several studies were also developed [56].

In terms of general conclusions, it was verified that students in secondary schools in Mediterranean climate under free running conditions accepted indoor air temperatures above 25ºC, and expressed thermal sensation votes for no change [55], [57], i.e. "feel comfortable under a wider range of temperature than those recommended by the norms" and "confirmed that thermal neutrality is not the preferred state". These results contrary nevertheless, the overheating concern recently exposed in the British classrooms [58], [59].

3. I2L: IEQ monitoring and web enabled practices

The main motivation behind the I2L platform [14] arises from the increasing necessity that researchers, educators and decision makers have for continuously available monitoring data on all aspects of building functioning. The concept of the I2L is equally grounded on an online web service for high availability of IEQ data, as well as in the physical instrumented spaces where the data is acquired, where both the indoor and outdoor environmental conditions can be monitored continuously in the long term and in a non-intrusive way, as the occupants go about their daily routine. The main objective of the Indoor Live Lab was to enable researchers to access continuously monitored indoor environmental quality data and indicators of energy efficiency. Several educational and research areas can benefit from this new facility as follows:

- Training in the assessment and auditing of IEQ: TC, IAQ, Acoustic Comfort, and Lighting Comfort;
- Development of new techniques for continuous measurement of ventilation rates in buildings;
- Proof of concept and validation of energy efficiency plans;
- Development and testing of indoor climate control strategies;

- Training in the calibration and uncertainty assessment of building simulation models;
- Technology demonstration of building energy metering solutions;
- Development and demonstration of new technologies for energy efficient hybrid ventilation.

The first installation is being developed and tested at an existing 6 person office, in the Department of Mechanical Engineering (DEM), at the University of Coimbra (UC), located at the street level in the southwest building DEM-UC. **Figure 6** shows an aerial view of the complex, retrieved from Google Maps. The lower images show views of the office interior and exterior. The location of the new weather station, online since November 2013, is also shown at the top left inset [60].

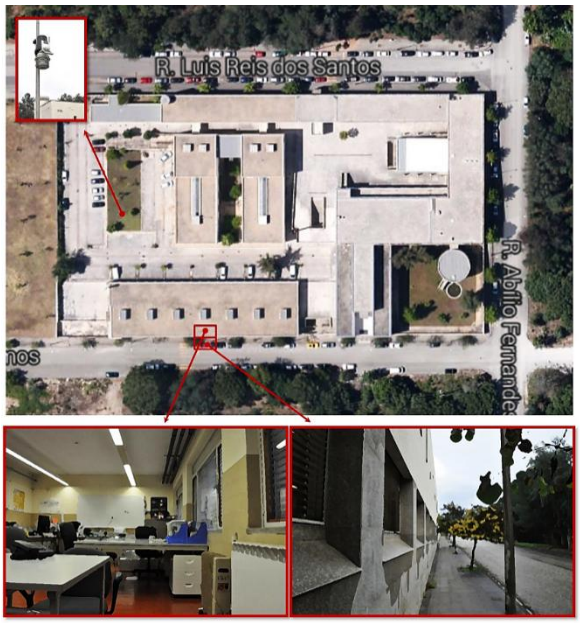

Figure 6 - Aerial view of the Mechanical Engineering Department of the University of Coimbra, retrieved from Google Maps, showing the 6 person office where the Indoor Live Lab is being developed (see text for detailed description).

The I2L installation relies on various types of instruments and sensors to measure and monitor energy consumption and IEQ descriptors, such as thermal comfort, indoor air quality, lighting and noise level. **Figure 7** shows a set of instruments and sensors already installed.

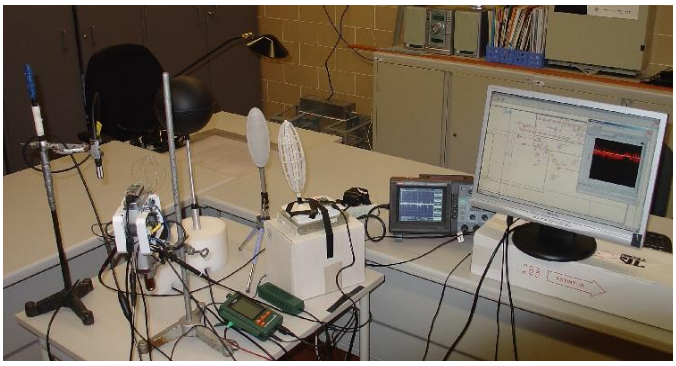

Figure 7 – Development of the instrumentation and data acquisition system used in the Indoor Live Lab.

Initial development of the thermal environment monitoring system is undergoing. A Bruel & Kjaer Thermal Comfort Meter Type 1212 was installed with its analogue outputs connected to a National Instruments (NI) USB-6008 data acquisition board. Data is acquired and logged continuously at a rate of one sample per minute by means of a software application developed in NI's LabVIEW application development platform.

Moreover, **Figure 8** shows an example of daily monitoring of the indoor climate. The graphs show the history of the last 24h for each quantity (other time periods are possible, e.g. weekly, monthly or yearly) and the numerical display shows the current value, which is updated every minute.

For TC, the Predicted Mean Vote thermal comfort index is used [61] [62] – showed at the top. Fanger's PMV model combines four environmental variables (air temperature, mean radiant temperature, air velocity and humidity) and two personal parameters (activity level and clothing thermal insulation) into an index which has been universally adopted in TC studies.

In practice, other indexes are also used that can be measured directly, such as the Operative Temperature, the Effective Temperature and the Equivalent Temperature. The Equivalent Temperature, shown in the second plot of **Figure 8**, is the air temperature that would be measured in an imaginary room with the mean radiant temperature equal to the air temperature and zero air velocity, where a person would experience the same heat losses as in the real room he/she is in. In addition, Fanger's Draught Model [8] predicts the percentage of occupants dissatisfied with local draught, from the three physical variables air temperature, mean air velocity, and turbulence intensity. These quantities will be monitored using a Swema Air300 and a SWA03 low velocity probe to calculate the Draught Rate thermal comfort index, and this part of the monitoring system is currently undergoing implementation. Also undergoing implementation is the replacement of the existing hydronic heaters manual controls with computer controlled servo-valves, for local automatic control of the heating system.

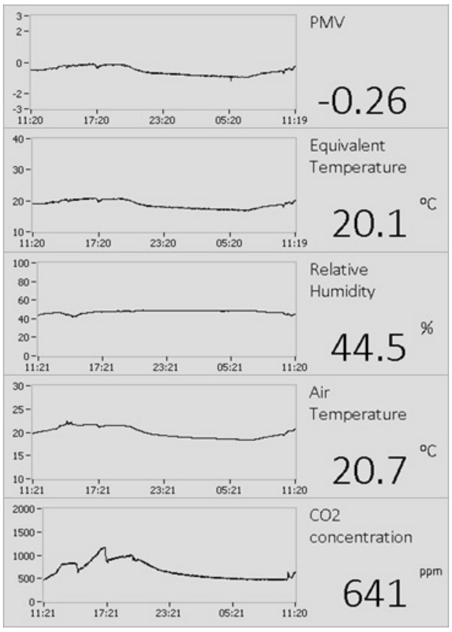

Figure 8 - IEQ indicators monitored in the Indoor Live Lab. From top to bottom: PMV and Equivalent Temperature (acquired from a Bruel & Kjaer 1212 Thermal Comfort Analyzer); Relative Humidity, Air Temperature and CO_2 concentration (acquired from an Extech SD800 CO_2 monitor).

Similarly, to monitor the IAQ, the concentration of CO_2 is being measured as an indicator of the balance between the ventilation rate and the generation rate of occupant-related pollutants. As previously stated, ventilation is the key issue for providing suitable IAQ as it is the process of replacing stale indoor air by fresh outdoor air. Ventilation in buildings can be done either by mechanical means or by NV. Recent studies have shown research activities in developing new control strategies to employ natural cooling and ventilation. For instance, Homod *et al.* [9] developed control strategies, which can predict when mechanical ventilation is required in order to maintain acceptable IAQ. Besides predictive control strategies, demand-controlled ventilation (DCV) strategies, which is used in many research such as [63]–[67], has a very significant effect on improving EE of a ventilation system. Moreover, it was mentioned by reference [68] that utilizing hybrid ventilation integrated with suitable control strategies, to adjust between active and passive ventilation, results in notable energy saving while delivers acceptable IAQ. However, there is still an obvious gap in the existing literature about employing intelligent window-based control strategies not only for increasing the share of NV but also integrating mechanical ventilation to compensate drawbacks of NV.

Within this context, a smart window system that allows the use of hybrid ventilation was installed in the I2L to employ the advantages and exclude the drawbacks from both natural and mechanical ventilation. In addition to TC and IAQ, lighting and sound quality in buildings can also influence occupants' satisfaction. In order to continuously measure these indices of IEQ, a lux meter as well as a sound level meter is installed in the I2L. The lux meter enables the users to adjust between natural and artificial lighting, which can causes mitigating the energy consumption from artificial lighting systems.

3.1 The smart window project

In the Smart Window project, several ventilation control strategies are being developed and tested using Smart Window in order to find out the best strategies that can provide an appropriate indoor climate with lower energy consumption. The control strategies, which are based on indoor and outdoor environmental parameters, such as concentration of CO_2, indoor and outdoor temperature difference, wind speed and its orientation, are defined in a way to use natural ventilation (NV) as long as possible (if suitable), otherwise, putting the mechanical system on circuit to provide the required space ventilation.

A number of control strategies were identified as potentially suitable, based on indoor environment parameters and outdoor weather as input data [30]. In particular, the indoor concentration of CO_2 is used to see whether ventilation is required or not. Temperature difference between indoor and outdoor (ΔT), wind speed (WS) and its direction (D) are used to detect the availability of NV. In the control strategies, the availability of buoyancy-driven NV is evaluated according to (4) [69], whereas (5) [70] evaluates the availability of wind-driven natural ventilation.

$$Q = CA\sqrt{2gH\frac{Ti - To}{Ti}} \quad (4)$$

where Q represents the ventilation airflow rate (m^3/s), C is the discharge coefficient for opening (typically 0.62), A indicates the cross section area of opening (m^2), g is the gravitational acceleration (m/s^2), H represents the height from midpoint of lower opening to midpoint of upper opening (m), T_i is the average indoor temperature (K) and T_o is the outdoor temperature (K).

$$Q = \frac{\mathrm{KAV}}{3600} \quad (5)$$

where Q represents the ventilation airflow rate (m^3/s), V indicates the outdoor WS (m/s), A indicates the cross section area of opening (m^2) and K is coefficient of effectiveness. This coefficient varies with the angle between D and the facade opening. For instance, if the angle at which wind hits the building is 45º, then the coefficient is estimated to be around 0.4, whereas, if wind hits the building perpendicularly, the coefficient is about 0.8.

According to all the aforementioned parameters, various rule-based (if *condition*, then *action*) control strategies were reported in the literature, in which indoor and outdoor environmental parameters are the conditions and different operations of window and fan are the actions.

The control strategies start with simple CO_2-based demand controlled ventilation strategies in the beginning and, going forward, reach more advanced control strategies, considering all the parameters and more advanced operations of window and fan. **Table 2** presents characteristics of some of the developed controls from simple to advanced strategies.

As shown, different input parameters and different operations of window and fan, define the control strategy either simple or advanced. Moreover, **Figure 9** demonstrates a simple control strategy in a flowchart.

Table 2 – The characteristics of control strategies.

Rule-based control	Mechanical ventilation operation	Natural ventilation operation	Input parameters
Simple	On/Off	Open/Close (O/C)	CO_2
.	Leveling speed	Leveling O/C	CO_2
.	Modulating speed	Modulating O/C	CO_2
.	On/Off	O/C	CO2+ ΔT+D
.	Leveling speed	Leveling O/C	CO2+ ΔT+D
Advanced	Modulating speed	Modulating O/C	CO2+ ΔT+D

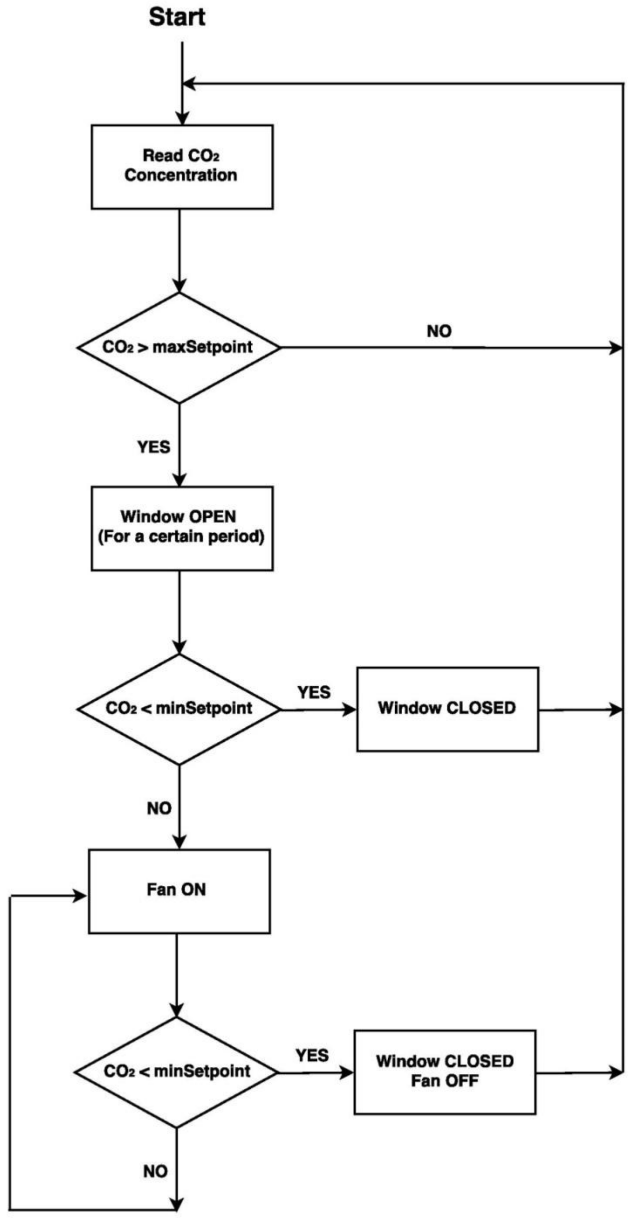

Figure 9 - Simple CO2-based control strategy.

The Smart Window includes a mechanical ventilator as well as a control system. **Figure 10** shows the first prototype already installed at the I2L. Furthermore, other prototypes using different types of blowers (tangential, centrifugal and axial) will be developed in order to test the air flow rates, the energy consumption, the noise made by each type and so on. During this project, an extensive literature review about energy-efficient ventilation methods is carried out.

Figure 10 - Prototype of the mechanical ventilation subsystem of the Smart Window hybrid ventilation system.

3.2 Further developments

In addition to controllable hybrid ventilation, a CO_2 monitoring equipment has been installed, which also measures the air Relative Humidity (RH) and Temperature (bottom 3 plots of **Figure 8**). The use of CO_2 as a tracer gas has gained popularity within the building engineering community because its concentration can be easily detected by infrared absorption spectroscopy.

CO_2 is also considered relatively inert and safe; it is cheap and readily available. The fact that building occupants exhale CO_2 makes it especially attractive as a tracer gas since only a sensor and a datalogger are needed to obtain the data needed to estimate the ventilation Air Exchange Rate (AER) in any given zone of the building. This is possible because the dynamics of the tracer gas concentration within a zone are well modelled by a first order mass balance equation, where the associated time constant is the reciprocal of the AER. When the occupants enter a room, they act approximately like a constant emission source, and the CO_2 concentration will grow like an inverted exponential approaching a steady-state value, as time passes. This is typically the response of a first order system to a step-up input, where the asymptotic steady-state value is proportional to the CO_2 generation rate. Similarly, when the occupants leave the room, the concentration will decay exponentially, just like the response of a first order system to a step-down input. New methodologies for continuous monitoring of AERs based on automated analysis of time series of tracer gas concentrations have recently been proposed [15]-[17] and are currently under development, testing and validation. The I2L is an important installation to test and validate these new methodologies in real operating conditions.

Furthermore, an infrared occupancy counter is being developed to be installed at the entrance. This is capable to record all entering and leaving, therefore it accurately shows occupancy level of the I2L at each moment. **Figure 11** shows the infrared occupancy counter set. This will enable the adjustment of the ventilation rate based on real occupancy level, which will cause preventing energy wasting.

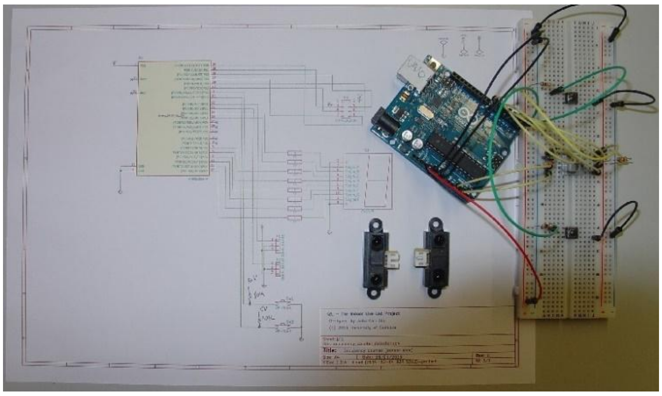

Figure 11 - Development of infrared occupancy counter

Besides continuously monitoring of IEQ elements, energy consumption is going to be continuously monitored in the I2L. An energy monitor prototype developed by WSBP [50] will be used to separately record energy consumption from different consumers such as lighting, ventilation, computers and so on. Moreover, flow meters will be installed on radiators hot water supply pipes integrated with enthalpy meters in order to measure heating energy consumption.

Monitoring energy consumption also allows the I2L users to test and compare energy consumption throughout their research and development carrier improvements – as stated in [71], *“Visualizing energy consumption is (...) an important way to motivate end-users to conserve energy”*. For instance, in smart window, the energy consumption from each control strategy can be recorded in order to find out the best suited strategy, which not only maintains acceptable indoor climate but also has the least energy use. Furthermore, it enables the users to find out an optimal strategy for heating, ventilation and lighting that can satisfy occupants and lower the energy consumption at the same time.

4. Conclusions and future research

The indoor environment is an important element in the quality of life of people. To make their buildings places where people feel good and perform well, building designers and building managers must balance the selection of strategies that promote energy efficiency and energy conservation with those that address the needs of the occupants and promote well-being.

Among other areas of activity, ADAI's research group on Energy, Environment and Comfort is active in several lines of research that have in common the duality of Energy Efficiency in Buildings and Indoor Environmental Quality. In this paper, the authors presented a summary of recent advances and ongoing work over the last 3 years. Results from the continued research in this field are reported to stakeholders and policy makers, both at a national and at an international level, and novel developments are regularly presented at international conferences and published in scientific journals.

Moreover, the motivation and objectives behind developing the Indoor Live Lab is discussed. The current state of development of the I2L, located in Mechanical Engineering Department (DEM) at University of Coimbra, is presented and discussed. The I2L enables the researchers to access continuously monitored data of IEQ and energy use, which can be used for a variety of scientific purposes. Additionally, the proposed development of the I2L is briefly presented.

The authors believe that many educational and research areas can benefit from this online platform. One of the strategies to reach a wider group of professionals who will benefit from this web enabled platform is the e-learning course on Indoor Environmental Comfort in Buildings of the University of Coimbra.

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APPENDIX I

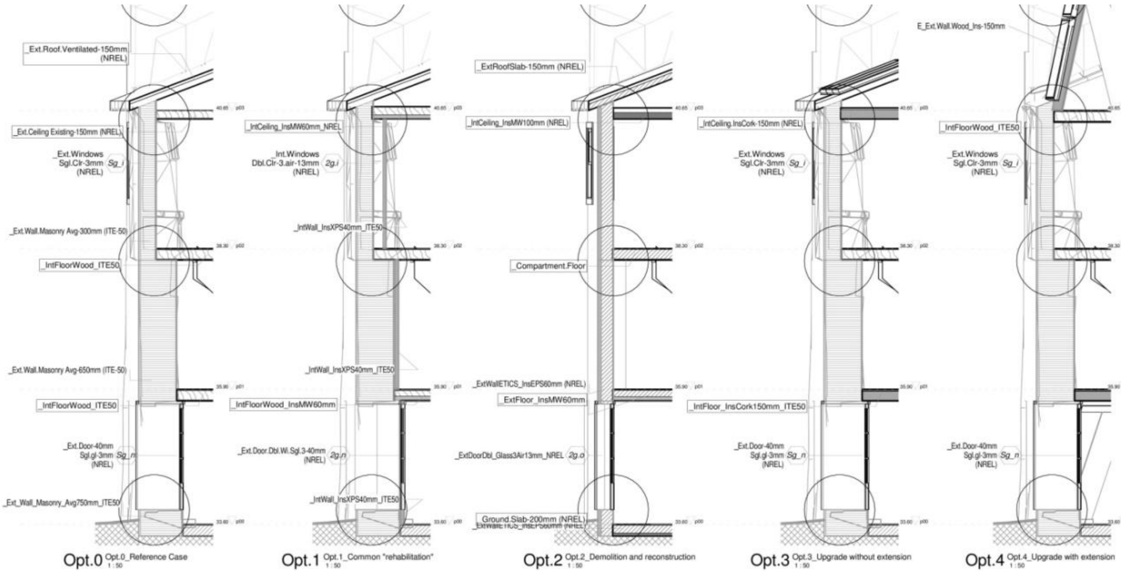

Figure A.1 - Montarroio Case Study intervention options scheme of studied options [21].

A summary comparing the five alternatives [energy efficiency (EE.) related renovation options for Montarroio (EE.Ren.Options) describing their non-energy efficiency related costs (Non-EE.costs), necessary to render the building inhabitable, and Initial Investment Costs for the building envelope (IIC_EE.Envel.) and EE. equipment (IIC_EE.Equip)] is presented in **Table A.1.**

Table A.1 – Renovation options: Initial investment (IIC) and lifecycle costs (LCC) per option and equipment

EE.Ren.Options:	**Opt.0**		**Opt.1**		**Opt.2**		**Opt.3**		**Opt.4**	
Equipment type:	_erh:	_hp:	_erh:	_hp:	_erh:	_hp:	_st-bio:	_st-erh:	_st-bio:	_st-erh:
Useful area	*36 m^2*	*36 m^2*	*31 m^2*	*31 m^2*	*63 m^2*	*63 m^2*	*36 m^2*	*36 m^2*	*46 m^2*	*46 m^2*
Non-EE.costs (€/y)	7 801	7 801	7 801	7 801	45 039	45 039	7 801	7 801	12 545	12 545
IIC_EE.Envel. (€/y)			6 906	6 906	4 957	4 957	1 188	1 188	2 733	2 733
IIC_EE.Equip (€/y)		2 120		2 120	1 874	3 719	4 840	2 975	5 490	3 475
%EE.OverCost/m^2	**0%**	**27%**	**119%**	**150%**	**280%**	**293%**	**77%**	**53%**	**108%**	**88%**
Energy costs (€/y)	1 546	423	811	218	160	44	36	92	32	82
Yearly LCC (€/y)	2 321	1 642	2 192	2 042	5 724	5 735	1 924	1 591	2 686	2 314
EE. Payback (y)	**no ROI**	**2y**	**9y**	**7y**	**5y**	**6y**	**4y**	**3y**	**5y**	**4y**
50% EE incentive?	no fund	1 060	3 453	4 513	3 415	4 338	3 014	2 082	4 112	3 104

*Note: Option 0 (Reference Case); Option 1 (common rehabilitation): Business as usual neighbourhood practices where interior insulation under plasterboard is placed to hide existing pathologies, with serious indoor air quality risks; Option 2 (Demolition and Reconstruction); Option 3 (Upgrade without extension): Detailed assessment to optimize the inherent building characteristics to achieve efficacy with users. Solar thermal heating and DHW require primary energy only for backup; Option 4 (Upgrade with extension): The previous strategy (Opt.3**)** with added structural seismic reinforcement made financially viable with an area extension (IEA A50): safer users / investment, and space for a small family.*