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# 01

# Assessing occupant comfort in historic churches when using localised heating systems

*Robin Talbot, Arman Hashemi, David Greenfield, and Marco Picco*

# Assessing occupant comfort in historic churches when using localised heating systems

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## Abstract

Historic churches often struggle to meet modern expectations of comfort, despite installation of relatively modern heating systems. With a focus on climate change and the emissions associated with fossil fuelled space heating, guidance to churches has been to heat the occupants rather than the building fabric. Seeking to quantify the effect that local and radiant heating systems have upon occupants in a historic church, this study uses a software model to predict comfort, expressed as predicted mean vote (PMV), for several different heating systems and scenarios. The PMV predictions from the model have also been calculated manually using an Excel PMV calculator as verification of the software output. Using a mean radiant temperature (MRT) tool, radiant systems are simulated, with the results utilised in the manual calculations to demonstrate an increase in comfort when using local heating options. In several instances PMV could be increased to between -0.5 and 0.5. This increase allows lower background temperatures to be realised within the church, opening up the potential to use alternative heating systems such as heat pumps. Such choices are aligned with UK Government ambitions for decarbonising heating. Further work related to activity and clothing levels of occupants will enhance understanding of the benefit of local and radiant heating options.

## Introduction

The European Union Directive on energy performance in buildings, adopted in 2002, strengthened the focus on the environmental impact of buildings. In the UK this complemented the Standard Assessment Procedure (SAP) method already in place for domestic dwellings and prompted the development of Simplified Building Energy Model (SBEM) for non-domestic and larger dwellings [1]. However, historic churches have remained exempt from mandatory energy performance assessment, due to difficulty improving energy efficiency with regard to the historic building fabric and construction techniques. Many European churches were designed without space heating, creating an environment where the building and artefacts were well preserved but made people occupying the space uncomfortable [2, 3]. Despite retrofit of modern heating systems, churches often provide poor local comfort levels for occupants. This is partly due to large volumes of air needing heated and their usage patterns limit the amount of energy absorbed by the building fabric during events [4, 5].

With the widespread installation of central heating in homes across the developed world, individuals routinely expect to find optimal thermal comfort widespread in public buildings. Thermal comfort is a subjective measure based on individual sensation and evaluated using several criteria: temperature, thermal radiation, humidity, activity, clothing, and air speed [6-8]. Ethnicity, health, body type, fitness and acclimatisation all further contribute to the complex nature of thermal comfort. Personal adaptations such as clothing, duration of stay and activity can overcome temperatures outside individual comfort ranges [9]. Those occupying a space while being sedentary or undertaking stationary light activity are most sensitive to local discomfort. When higher levels of activity are undertaken sensitivity is decreased and the risk of thermal discomfort is lowered [10]. Occupants typically expect temperatures in the range of 18-22˚C [8]. Measurement of comfort is typically expressed using predicted mean vote (PMV). The seven-point scale of PMV are: +3 Hot, +2 Warm, +1 Slightly warm, 0 Neutral, -1 Slightly cool, -2 Cool, -3 Cold [10].

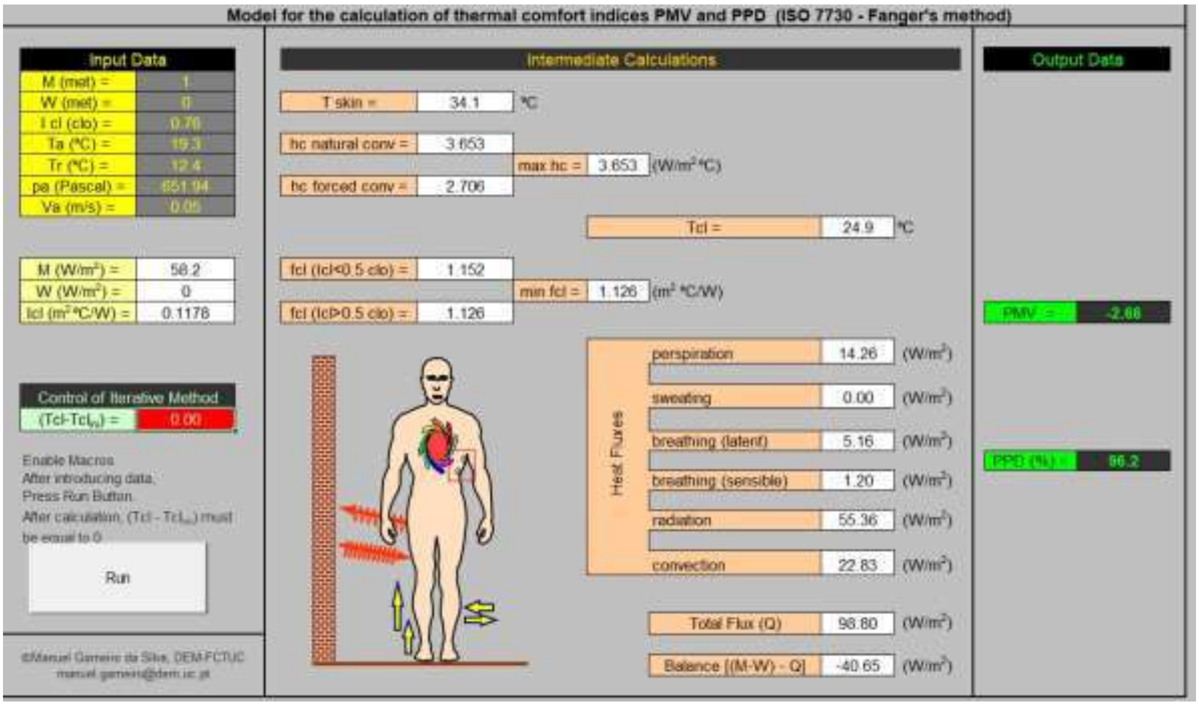
The Church of England, in recognition of the environmental impact of their activities, has committed to net-zero by 2030 [11]. The previous target was net-zero by 2045, which already required substantial change in the way churches and occupants are heated [12]. This shift of focus to heating occupants and not the building fabric may also benefit the conservation of building fabric and important artefacts. Localised heating and radiant systems seek to deliver heat to the occupant and hold potential to reduce emissions and the cost burden associated with traditional fossil fuelled central heating systems [13]. However, radiant systems are also known to fall short of adequate comfort in cold churches [14]. Evidence shows a combination of background low grade heat with radiant systems may achieve more acceptable comfort levels [15]. There are studies which focus on radiant and traditional space heating technologies in conjunction with building/artefact preservation. However, few assess the technical, environmental feasibility and comfort aspects together. Past research mainly focuses on replacing central heating systems with radiant or localised heating solutions, which do not always attain high comfort levels [16, 17].

## Aim

This paper investigates radiant and local heating systems in a software model of a historic church and seeks to quantify the potential increase in local comfort associated with their use.

## Methods

A model of St Mary de Haura, Shoreham-by-Sea, UK was created using Design Builder software, a graphical interface for EnergyPlus. All simulations were undertaken using this software to assess energy consumption, emissions and comfort. A gas fired hot water boiler and radiator system was set to provide either 14ºC or 20ºC background heat for the church model. The heating schedule was for operation four times a day, representing two hour blocks of operation when the church is usually occupied. Energy consumption from each local/radiant system was calculated from equipment ratings and in response to two occupation levels min and max. Calculations were undertaken at minimum and maximum occupation, meaning that only half the radiant system was energised for minimum occupancy levels. A fictitious energy load was added into the main zone of the church as additional energy considered in the simulation. For low temperature systems such as radiant panels and heated cushions this additional energy represented a small amount. For high temperature systems such as radiant emitters placed high on the wall there was significant energy input to the occupied space. A semi-automated PMV Excel calculator from da Silva et al was used to derive PMV from the simulation results [18]. Metabolic activity, clothing value, air temperature, radiant temperature, water vapour pressure and air speed were all necessary input data for the calculator (see top left of figure 1). While PMV is also generated as part of the Design Builder software simulation it was important to verify the results independently of the software. The calculated values were found to closely match the software output.


Model for the calculation of thermal comfort indices PMV and PPD (ISO 7730 - Fanger's method)

Input Data
M (met) = 1
W (met) = 0
I cl (clo) = 0.76
Ta (°C) = 19.3
Tr (°C) = 12.4
pa (Pascal) = 651.94
Va (m/s) = 0.05

M ($W/m^2$) = 58.2
W ($W/m^2$) = 0
Icl ($m^2$ °C/W) = 0.1178

Control of Iterative Method
($Tcl-Tcl_n$) = 0.00

Enable Macros
After introducing data,
Press Run Button
After calculation, ($Tcl - Tcl_{n}$) must be equal to 0

Intermediate Calculations
T skin = 34.1 °C
hc natural conv = 3.653
max hc = 3.653 ($W/m^2$ °C)
hc forced conv = 2.706
Tcl = 24.9 °C
fcl (Icl<0.5 clo) = 1.152
min fcl = 1.126 ($m^2$ °C/W)
fcl (Icl>0.5 clo) = 1.126

Heat Fluxes
perspiration 14.26 ($W/m^2$)
sweating 0.00 ($W/m^2$)
breathing (latent) 5.16 ($W/m^2$)
breathing (sensible) 1.20 ($W/m^2$)
radiation 55.36 ($W/m^2$)
convection 22.83 ($W/m^2$)
Total Flux (Q) 98.80 ($W/m^2$)
Balance [(M-W) - Q] -40.65 ($W/m^2$)

Output Data
PMV = -2.88
PPD (%) = 96.2

*Figure 1 PMV calculator from [18]*

A method was developed to understand the effect radiant systems would have on local occupant comfort. An online mean radiant temperature (MRT) tool developed by The Center for the Built Environment was used to generate localised temperature data for use in the calculation of PMV [19]. A box could be dimensioned on

the MRT calculator with a radiant surface placed on one or more surfaces. The occupant: seated or standing, radiant surface temperature, air temperature and presence of walls were all options within the simulation controls. Running the simulation resulted in a coloured temperature map within the box. A 2m x 2m box was created in the MRT calculator representing low temperature systems located near the occupant. While a large box was made with exact dimensions of the main zone of the church and radiant sources mounted high up on the walls to replicate high temperature radiant panels.
Temperatures for the systems adjacent to the occupant were taken approximately 35-40cm distance for those seated in front of a radiant panel. Figure 2 shows the set up for a radiant panel operating with a surface temperature of approx. 50°C. These new radiant temperatures were then used in the Excel PMV calculator as a substitute for those generated in the Design Builder simulations. PMV for January 4th, June 4th and December 3rd at 10am and 5pm were calculated. However, only the results for January 4th are presented here, at activitylevel of 1met and 0.76clo (clothing value).

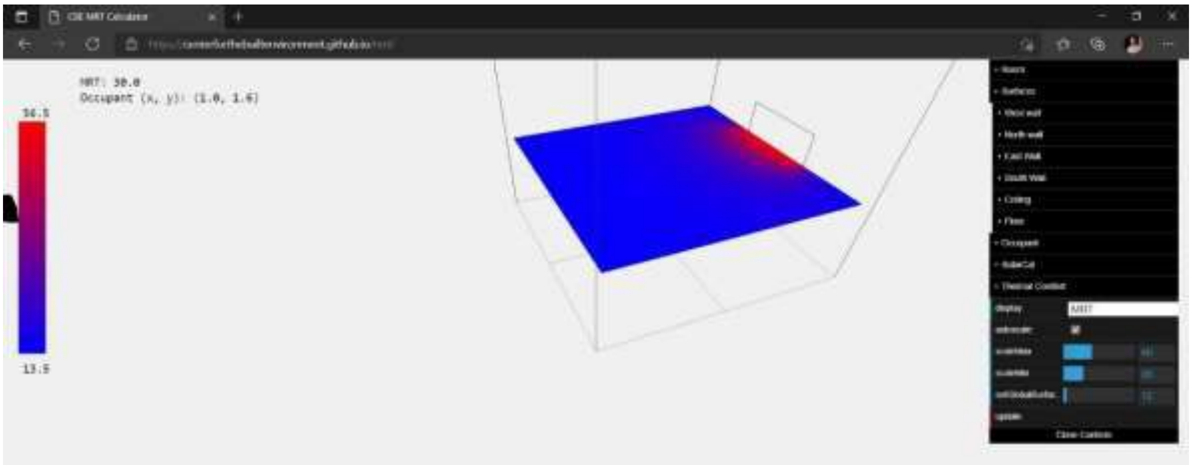


Figure 2: Mean Radiant temperature simulation tool from the Center for the Built Environment.

## Results

The adjusted PMV calculations, taking into account the effect of the adjacent radiant heater in the MRT tool, allowed an improved PMV figure for occupant comfort. In some cases (see figure 3) the PMV could be adjusted close to zero PMV, where the majority of occupants would experience neutral or stable comfort. Using a background hot water radiator heating system set to 20°C naturally achieved better comfort in all scenarios. However, heated cushions and pew mounted radiant panels could improve PMV to -0.5 even with the 14°C heating set point. High temperature radiant panels mounted 6m high on the walls were less able to provide improved comfort at 14°C background temperature. PMV calculated from data captured from the actual church that was modelled is shown on the left in figure 3. These preliminary results are promising, however further work is required on the effect of radiant asymmetry associated with close proximity to cold walls and pillars commonly found in historic churches.

When the same method of adjusted PMV is applied to the environmental data captured from the church in January 2020, the improved comfort for each system can be plotted (figure 4). The comfort attained in St Mary de Haura on 4th January was between -3 to -4 PMV. Adjusting the figures to account for a local or radiant system are shown as bars in figure 4. As some of the systems use small amounts of energy the difference between 10am and 5pm calculations are not easily discernible. Also, the church did not achieve 20°C on the day modelled. At best and depending on the location of the sensor in the church the figures represent 18°C on the 4th January. With a localised heating system active in the church a PMV of -0.2 could be attained basedupon this calculation method.

## Discussion and conclusions

The outcomes of this study are favourable towards the use of local heating to increase comfort for occupants in historic churches. Several different heating options have been explored in this study, leading to a large number of manual calculations being undertaken to establish current PMV in line with Design Builder outputs. There is sufficient evidence in existing research that historic churches frequently experience poor comfort levels, with the simulations undertaken in Design Builder verifying this to be the case. Using the data derived from the MRT tool to adjust simulation PMV reveals that comfort can be improved using several different local heating systems. Churches with expansive open seating areas, plus adjacent unoccupied areas, may require background heating. These may be predominantly urban churches which enjoy more regular usage throughout the week, benefitting the occupants through maintaining the building fabric at a stable low temperature. However, the modest increase in PMV through the use of wall mounted high temperature radiant devices in a 14°C room suggest such systems will still result in poor occupant comfort. This is consistent with evidence from churches using these systems. If undersized they may not reach the comfort levels required and a higherbackground heat would be required, cancelling out the benefit of the reduced power demand associated withradiant systems.

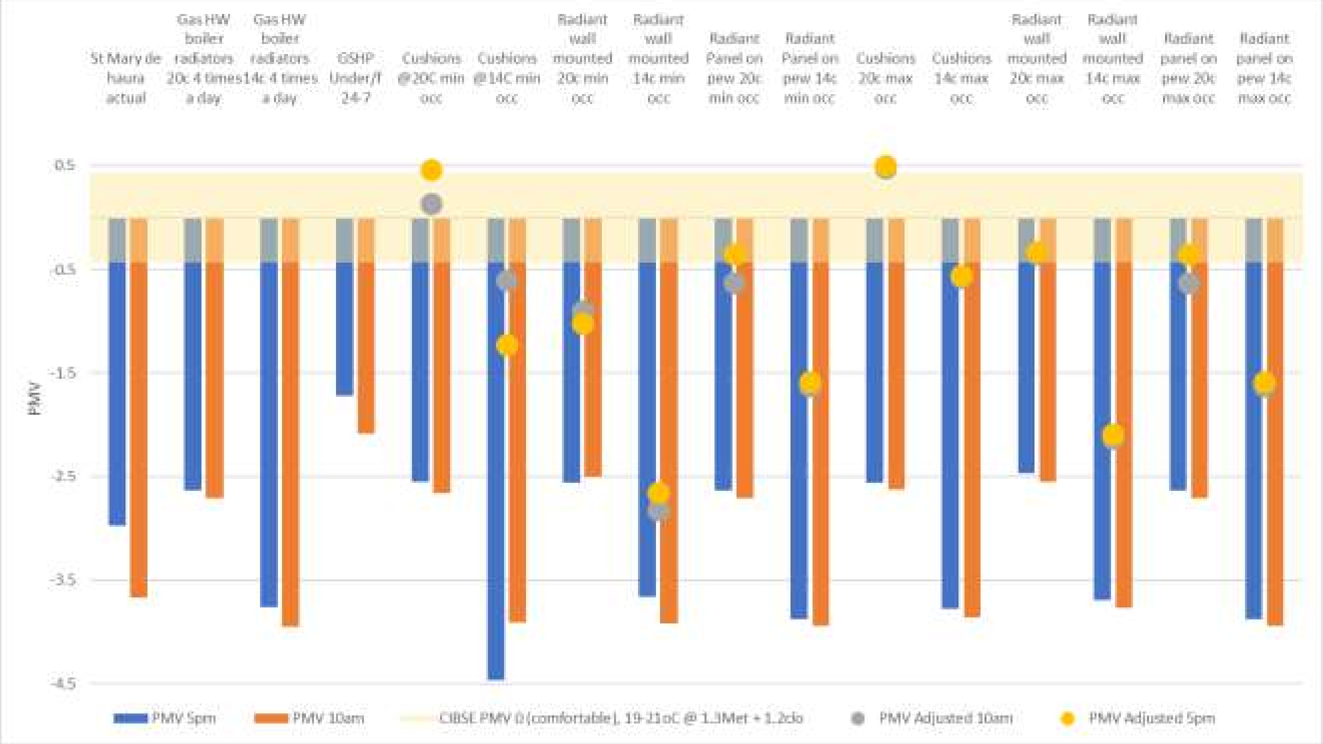


*Figure 3: PMV adjusted for radiant systems 1met 0.76 clo January 4th at varying occupation levels (occ)*

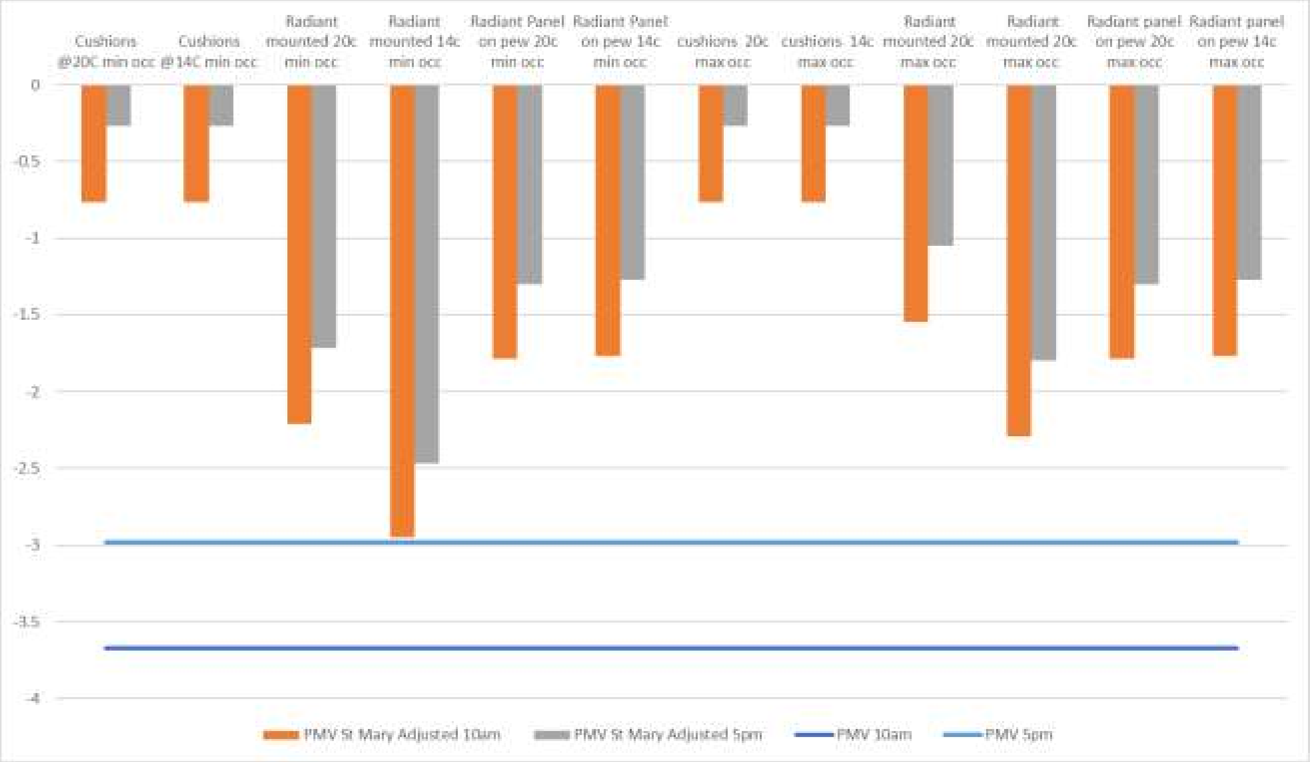


*Figure 4: St Mary de Haura 1met @0.76clo Jan 5th Radiant adjusted PMV on January 4th 2020*

There is clear direction from the Church of England that the future of church heating could be electric, rather than fossil fuel based, and churches should seek to heat people not the building. Furthermore, electricity is widely available, even in very rural settings. Parishes are encouraged to buy renewable energy and seek to generate their own where possible. One radiant technology not represented here are gas powered radiant heaters. These do feature in many churches as gas is considerably cheaper as a source of thermal energy. However, this technology was discounted from further analysis in an earlier component of this overall project to assess heating systems for historic churches. Although the PMV calculations are undertaken using background heat sourced from a gas-powered boiler, the data for a ground source heat pump (GSHP) with underfloor heating has been provided in figure 3. GSHP and underfloor heating proves to achieve better comfort before the addition of localised radiant systems, although it is accepted that underfloor heating is not suited to all churches partly due to invasive installation and associated costs. With the UK Government keen to transform the way buildings are heated, technologies like heat pumps, ideal for low temperature heat input over sustained periods of time, appear to be useful in the context of church heating [20].

This study is yet to look at the comfort attained at different activity and clothing levels. The CIBSE benchmark for neutral comfort is shown in figure 3. It should be noted that this was calculated at slightly higher activity and clothing values, with a temperature between 19-21ºC. It is important to realise that a radiant system providing local comfort at 14ºC background temperature may still result in occupant comfort. As churches look to expand the number of uses for the building, potentially becoming available for community use, being able to host varied activities at suitable room temperatures is an important consideration. Activities like social dancing or exercise classes would benefit from lower room temperatures. At present many churches have heating systems based upon hydronic radiators which are either on or off, severely limiting control of temperature and comfort levels. The introduction of a sustained low room temperature with localised heating may improve local comfort without compromising sustainability. Further work on the future of the UK energy mix could also inform choices in relation to fuel source and appropriate technologies. This study has demonstrated that using local and radiant systems has improved calculated PMV at certain clothing and activity levels. Further work encompassing the effect of radiant asymmetry is possible and planned using the methods outlined in this paper.

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## 02

# Investigating the validity of PMV for predicting thermal comfort in university classrooms - a case study

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# Investigating the validity of PMV for predicting thermal comfort in university classrooms - a case study

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## Abstract

Since students are spending an increasing amount of time in classrooms, the need for correctly evaluating thermal comfort is getting more and more important, as it can influence their wellbeing and affect energy consumption. In this work, the validity of PMV for predicting thermal comfort in university classrooms was assessed using the School of Engineering of the University of Pisa as a case study. The classrooms presented different characteristics, in terms of buildings' envelope, room volume, maximum occupancy, etc. The environmental parameters were assessed, and clothing insulation and metabolic rate were evaluated for the calculation of Fanger's PMV and PPD indices. Then, the Thermal Sensation Vote (TSV) was assessed through the use of questionnaires and compared to PMV. It resulted that the difference between the predicted and observed thermal sensation is statistically significant and that the error between these two variables increases for higher air and mean radiant temperatures. The missing inclusion of the adaptive processes in PMV calculation may be the cause of the higher tolerance of university students to the thermal environment.

## Introduction

In recent times, students spend a good part of the day in schools, they can be particularly sensitive to an unfavourable indoor environmental quality (IEQ) [1]. Considering thermal comfort as a fundamental aspect of IEQ, it is necessary to correctly evaluate it to provide thermal comfort and ensure the best learning conditions for the students [2]. There are several aspects that should be considered. For example, the educational stage is an essential issue that should be considered when investigating thermal comfort in educational buildings.

Several indices have been developed for evaluating thermal comfort, but Fanger's rational (or heat balance) and the adaptive models are still the most used [3]. Most studies in educational buildings were carried out using the rational model singularly, or together with the adaptive model. The rational model can be usually applied to air-conditioned spaces where occupants are in steady-state conditions with limited possibility to adapt. However, often these conditions do not occur in educational buildings, and this can lead to an overestimation or underestimation of the thermal sensation.

This incorrect assessment of the thermal environment can be reflected both in people's discomfort and in an increase in energy consumption. To overcome this issue, environmental monitoring was often associated with subjective measurements assessing the thermal response of the student through the use of questionnaires [4]. This allows comparing the response obtained from people in classrooms with the predictive models that were usually developed for office workers.

The aim of the work is to evaluate the applicability of Fanger's PMV through the use of a case study. In this direction, university classrooms were chosen. At this educational stage, several adaptive processes may occur, as students are freer to interact with their indoor environments and on personal variables.

## Methods

For the evaluation of thermal comfort, university classrooms from the School of Engineering of the University of Pisa were chosen. The measurements were carried out during winter 2018 and 2019. The monitoring location was chosen in a representative position of the classroom, close to students' seats, in order to assess the actual conditions of the students. The monitoring duration varied according to the duration of the classroom. During the campaign, the heating system was switched on. The classrooms selected for the case study were characterized by different envelopes, volumes, and maximum occupancy, as shown in Figure 1.

The monitoring campaign consisted of objective and subjective measurements. The objective measurements recorded the values of air temperature ($T_a$), relative humidity (RH), mean radiant temperature ($T_r$), and air velocity ($V_a$) with a microclimate datalogger whose characteristics are reported in Table 1. The metabolic rate (M) and clothing insulation (Icl) were also estimated during the field study. Moreover, subjective measurements included the assessment of the perception of the thermal environment using questionnaires.

In particular, the Thermal Sensation Vote expressed on a 7-points scale (from -3 cold to +3 warm) was evaluated for the comparison of the Predicted Mean Vote.

*Figure 1: Example of the classrooms selected as a case study.*

*Table 1: Technical specifications microclimate datalogger* [5]

| **General characteristics** | | |
|---|---|---|
| Working temperatures | -5 ÷ 50°C | |
| Working relative humidity | 0 ÷ 90%, no condensation | |
| Protection degree | IP65 | |
| **Globe thermometer temperature (TP3275 probe)** | | |
| Measuring range | -10 ÷ 100 °C | |
| Resolution | 0.1 °C | |
| Accuracy | 1/3 DIN | |
| **Air velocity (AP3203 probe):** | | |
| Measuring range | 0.1 ÷ 5 m/s | |
| Resolution | 0.01 m/s | |
| Accuracy | ± 0.2 m/s | |
| **Relative humidity and air temperature (HP3217R probe)** | | |
| Measuring range | 0 ÷ 100% RH, | -40 ÷ 100 °C |
| Resolution | 0.1 % RH, | 0.1 °C |
| Accuracy | ± 1.5 ÷ 2 % RH, | 1/3 DIN |

## Results and Discussion

Regarding the environmental and individual parameters, the mean values for each day of measurements are reported in Table 2. The air temperature ranged between 20.9°C and 26.7°C, the relative humidity was between 31% and 73%, the mean radiant temperature was between 21.1°C and 27.0°C, and the air velocity was between 0.00 m/s and 0.24 m/s. The individual parameters were estimated 1.2 met for the metabolic rate and between the 0.7 clo and 1 clo for the clothing insulation. From the six parameters, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) were calculated. The PMV was between -0.3 and 1.1, while the PPD was between 5% and 33%.

From the questionnaire, the TSV was calculated and compared to the PMV (Table 2). The Percentage of Dissatisfied (PD) was calculated from questionnaires considering dissatisfied who voted 3 (discomfort) or 4 (much discomfort) on the 4-points evaluative scale. The TSV ranged between -0.8 and 1.1, while the PD was between 0% and 18.7%. It can be noticed that people tend to be more tolerant with regard to the thermal environment than the prediction actually is. To assess if the difference between PMV and TSV was significant, a t-student test was applied. It resulted that the difference between the sample mean PMV and the TSV was statistically significant. Furthermore, the correlation between PMV and TSV was analysed, which showed a low correlation (r=0.31). In general, it can be noticed that the subjective response was attested more on thermal neutrality, while PMV tended to overestimate the thermal sensation of the students.

*Table 2: Objective and subjective measurements carried out during the measurement campaign.*

| ID | Class | Ta (C) | RH (%) | Va (m/s) | Tr (C) | Icl (clo) | M (met) | PMV | PPD (%) | TSV | PD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | A23 | 26.7 | 56 | 0.11 | 27.1 | 1 | 1.2 | 1.1 | 33 | -0.1 | 10.5 |
| 2 | SI5 | 24.6 | 42 | 0.07 | 24.6 | 1 | 1.2 | 0.5 | 11.6 | -0.3 | 5.1 |
| 3 | F02 | 25.3 | 51 | 0.08 | 25.1 | 1 | 1.2 | 0.7 | 16.7 | 0.2 | 2.5 |
| 4 | A23 | 24.2 | 51 | 0.07 | 24.5 | 1 | 1.2 | 0.5 | 12.4 | -0.1 | 0 |
| 5 | SI5 | 25.2 | 57 | 0.04 | 25.2 | 1 | 1.2 | 0.8 | 20.5 | 0 | 2.7 |
| 6 | F02 | 22.9 | 57 | 0.1 | 23.1 | 1 | 1.2 | 0.2 | 6.6 | -0.4 | 0 |
| 7 | A28 | 21.5 | 42 | 0.08 | 21.3 | 1 | 1.2 | -0.1 | 5.5 | -0.6 | 6.4 |
| 8 | C31 | 21.9 | 58 | 0.06 | 21.6 | 1 | 1.2 | 0.1 | 5.4 | -0.1 | 0 |
| 9 | F01 | 21.9 | 60 | 0.24 | 22.1 | 1 | 1.2 | -0.1 | 5.6 | 1 | 0 |
| 10 | C31 | 22.2 | 43 | 0.11 | 21.8 | 1 | 1.2 | 0 | 5.9 | 0.1 | 9.3 |
| 11 | A23 | 22.9 | 73 | 0.06 | 22.6 | 1 | 1.2 | 0.4 | 9.2 | -0.1 | 3.2 |
| 12 | SI5 | 23.3 | 47 | 0 | 23.3 | 1 | 1.2 | 0.4 | 8.8 | -0.2 | 0 |
| 13 | F01 | 20.9 | 66 | 0.02 | 21.1 | 1 | 1.2 | 0 | 5 | -0.6 | 12.5 |
| 14 | F02 | 22.1 | 62 | 0 | 22 | 1 | 1.2 | 0.2 | 6 | -0.2 | 3.8 |
| 15 | A28 | 23.1 | 32 | 0.02 | 22.8 | 1 | 1.2 | 0.2 | 6.1 | -0.3 | 0 |
| 16 | A23 | 24.3 | 64 | 0.01 | 24 | 1 | 1.2 | 0.4 | 8.4 | 0.4 | 3.5 |
| 17 | SI5 | 24.5 | 54 | 0 | 24.6 | 0.7 | 1.2 | 0.4 | 9.4 | 0 | 6.2 |
| 18 | F02 | 24 | 56 | 0 | 23.9 | 0.7 | 1.2 | 0.3 | 7.3 | 0.6 | 6.4 |
| 19 | A23 | 24.1 | 70 | 0.02 | 23.9 | 0.8 | 1.2 | 0.5 | 11.8 | 0.5 | 15.1 |
| 20 | SI5 | 24.7 | 31 | 0 | 24.5 | 1 | 1.2 | 0.4 | 9.4 | 0.1 | 8.5 |
| 21 | F02 | 22.7 | 39 | 0 | 22.4 | 1 | 1.2 | 0 | 5.7 | -0.1 | 6.9 |
| 22 | A23 | 22.9 | 62 | 0 | 22.8 | 0.8 | 1.2 | 0.2 | 6.1 | -0.1 | 8 |
| 23 | SI5 | 21.3 | 37 | 0 | 21.1 | 1 | 1.2 | -0.3 | 8 | -0.8 | 18.7 |
| 24 | F02 | 22 | 45 | 0 | 21.8 | 0.8 | 1.2 | -0.1 | 5.6 | -0.1 | 0 |
| 25 | A23 | 21.6 | 67 | 0 | 21.5 | 0.8 | 1.2 | -0.1 | 5.1 | 0.1 | 5.5 |
| 26 | C31 | 21.8 | 65 | 0 | 21.7 | 0.8 | 1.2 | 0 | 5 | 0.5 | 0 |
| 27 | SI5 | 26.5 | 45 | 0 | 26.1 | 1 | 1.2 | 0.9 | 13.9 | 1.1 | 9 |

Then, the error between the PMV and TSV was calculated at different air temperatures (Figure 2a), mean radiant temperature (Figure 2b), relative humidity (Figure 2c), and air velocity (Figure 2d). It can be noticed that the error increases with the increase of air and mean radiant temperatures, while it does not seem to depend on different relative humidity and air velocity. In particular, for high air and mean radiant temperatures the PMV tends to overestimate the thermal sensation of the students. The error is instead homogeneous for RH ranging between 30% and 70% and for air velocities between 0 m/s and 0.3 m/s.

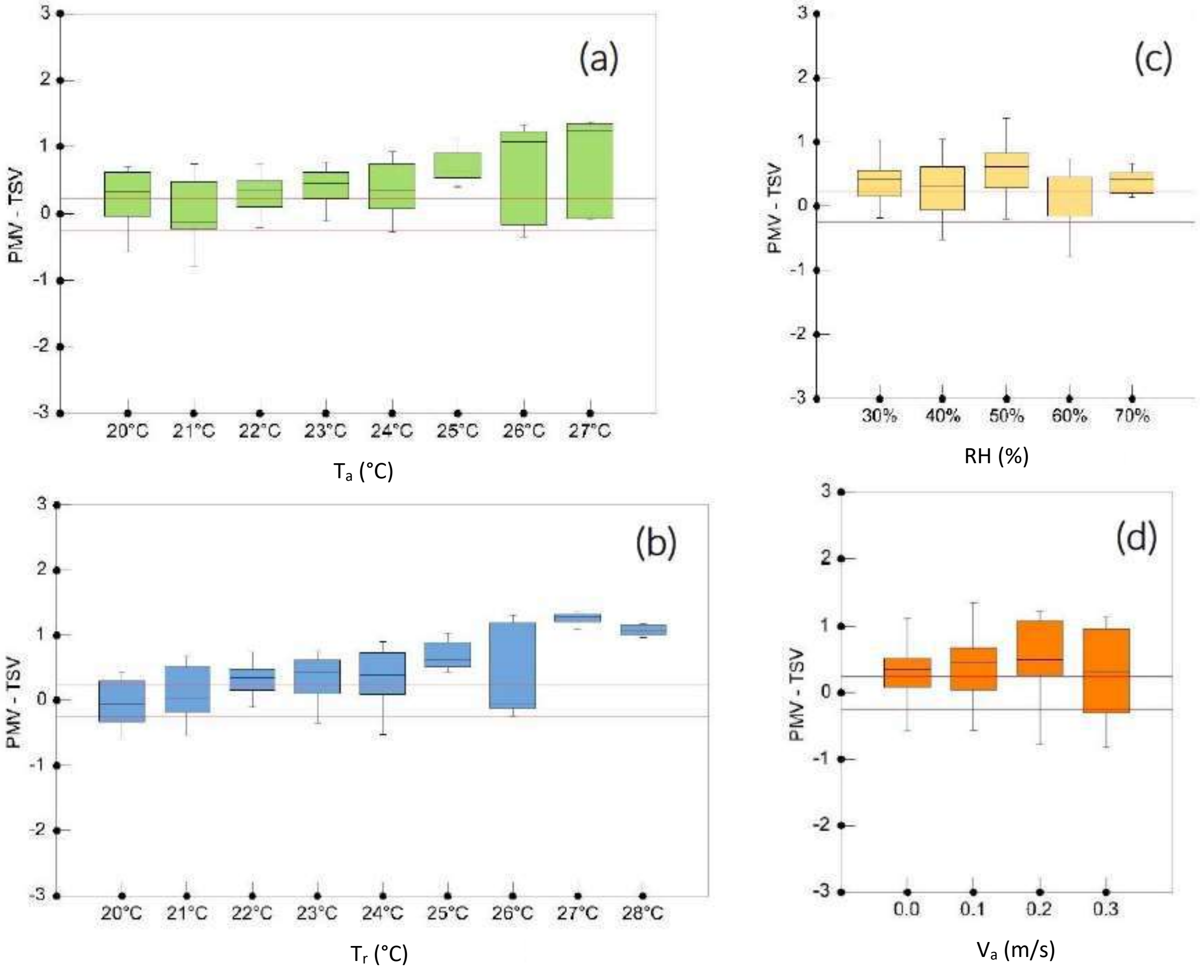

*Figure 2: Error between PMV and TSV against air temperature (a), relative humidity (b), mean radiant temperature (c), and air velocity (d).*

## Conclusion

The analysis showed significant differences between PMV and TSV, with the tendency of PMV to overestimate the thermal sensation of the students especially for higher air and mean radiant temperatures. The error could be associated with inaccuracy with the single variables but can also depend on the combination of contributing variables, both for the four environmental parameters and the two individual parameters Furthermore this error may be related to students' possibility to adapt to the thermal environment, as it was shown that the TSV was more towards thermal neutrality if compared to PMV. This may be related to the fact that the rational model accounts only for the heat balance between the human body and the environment but not for thermal adaptation, which may influence students’ habituations and expectations. This fact highlights the need for a combined model considering both the heat balance between the human body and the environment and adaptive processes.

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# 03

# Study of the variables in masonry rising damp: comparison between laboratory test and dynamic simulation

*Erika Guolo, Fabio Peron*

# Study of the variables in masonry rising damp: comparison between laboratory test and dynamic simulation

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## Abstract

Moisture control is a widespread problem around the world, with the aim of improving the healthiness of indoor spaces and building energy performance. In Venice, the phenomenon of rising damp and moisture is clear because many buildings are constructed directly on the water and the city is constantly subject to floods.

The objective of this research is the analysis of the typical behavior of Venetian masonry wall affected by rising damp and evaluates how this phenomenon works, correlated to intrinsic (properties of construction materials) and external (climatic conditions) parameters. Thanks to the comparison between laboratory tests and dynamic simulations it is possible to arrive at a higher understanding of the hygrothermal behavior of the masonry wall. By comparing the wall laboratory test monitored with non-destructive method and the simulated model via software, it is possible to see a similar trend in rising damp. On the other hand, it is possible to observe differences in the simulated models, due to variables entered.

## Introduction

The water inside the masonry determines a high-risk factor, both for the building and for the human organism, with dampness and molds that can cause allergies, symptoms and respiratory tract infections or asthma symptoms in sensitized people. Many studies have shown that the presence of microbes or fungal agents deriving from these phenomena have led to an increase of 30-50% of cases with respiratory diseases [1]. Therefore, the control of the moisture content is relevant for the determination of the sanitary conditions of the environment, strictly related to human health and comfort indoor, the durability of the building and its materials and its energy saving [2].

The factors that favor the entry of water into the structure are both intrinsic and linked to the surrounding environment. The former depends on the properties of the material (porosity and permeability), technological solutions of opaque envelope and physico-chemical-electromagnetic forces that regulate liquid movement in the pores of the wall. The characteristics of the environment that influence the moisture content are intended use and the level of crowding, ventilation, exposure and positioning, proximity to other buildings and the climate.

## Methods

With the aim of investigating the hygrothermal behavior in simulation, the software used is WUFI 2D by Fraunhofer Institute of Building Physics [3], in which heat and mass transfer is used to find heat and moisture distributions within a building structure, based on the characteristics of the materials and indoor/outdoor climatic conditions. The analysis is carried out on two wythes masonry, with and without plaster, in different climatic conditions: starting from the base case with controlled conditions in laboratory (temperature and relative humidity), the external variables are increased step by step to the real case masonry wall in Venetian environment. For the simulation of the conditions of the Venice lagoon, a layer under the masonry was considered with a high quantity of free saturation water (Figure 1). The simulation software requires a one-year weather file [4]. The indoor laboratory conditions are based on standard EN 13788 [3]. For Venetian conditions the “test reference year” [4] is used (Figure 2). The characteristics of the materials considered are shown in Table 1.

*Table 1: Characteristics of the masonry components ($\rho$, bulk density, φ porosity, c specific heat, $\lambda$, thermal conductivity, $\mu$ diffusion factor).*

| Material | $\rho$ [kg/m$^3$] | φ [%] | c [J/kgK] | $\lambda$ [W/mK] | μ [-] |
|---|---|---|---|---|---|
| New brick | 1700 | 37 | 850 | 0.345 | 9.5 |
| Historical brick | 1560 | 30 | 850 | 0.369 | 9.5 |
| Lime premixed mortar | 1800 | 20 | 850 | 0.920 | 15 |
| Lime historical mortar | 1750 | 20 | 850 | 1.000 | 13 |
| Marmorino plaster | 1650 | 32 | 850 | 0.800 | 0.14 |

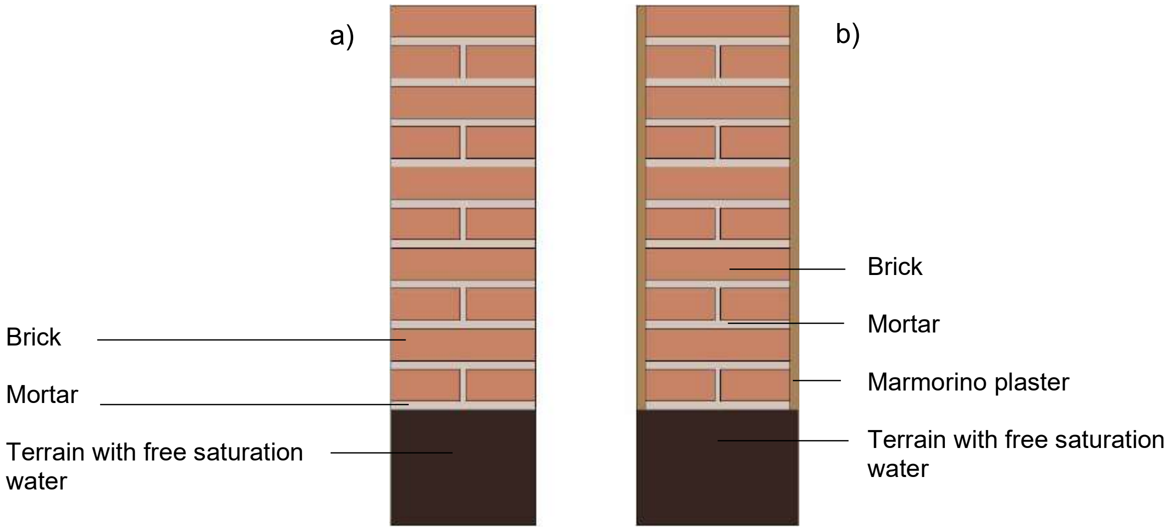

*Figure 1: Masonry wall simulated in WUFI 2D software: a) without plaster, b) with Marmorino plaster.*

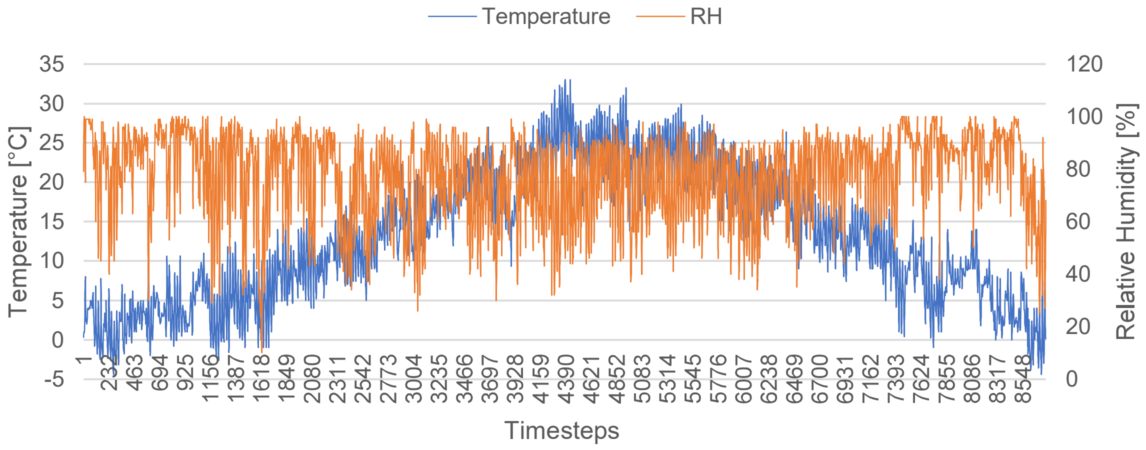

*Figure 2: Venice TRY – source "Energy Plus"* [4].

In addition to the simulation described above, there are also laboratory tests with the aim to simulating the rising damp on the masonry wall, using the materials (new brick and lime premixed mortar) described in Table 1. In this case, the masonry walls are in direct contact with a water layer to simulate Venice typical conditions.

## Results

The outputs of the dynamic simulation and non-destructive measurements carried out on the masonry in the laboratory are presented in Figure 3. Figure a) shows the level of surface rising damp in the laboratory wall, which the data derive from the observation of surface evaporation by means of thermography; in figure b) we can see the WC in the simulated non-plastered wall (brick and lime premixed mortar). Even if the images are not comparable from the point of view of quantitative measurement, it is possible to notice the similar trend of rising damp, connected to the WC: a rapid increase in the first soaking phase and then a decrease with a stabilization phase.

In Table 2 the difference in WC, recorded both in [kg/m$^3$] and in [vol.%], in the first 7 days and after 1 year of imbibition appears different: in the first phase the content is very high and then decreases with the time, until it stabilizes. This factor is related to the wall structure and the characteristics of the materials; the WC decreases when the pores are completely saturated and that is the masonry reaches its state of equilibrium.

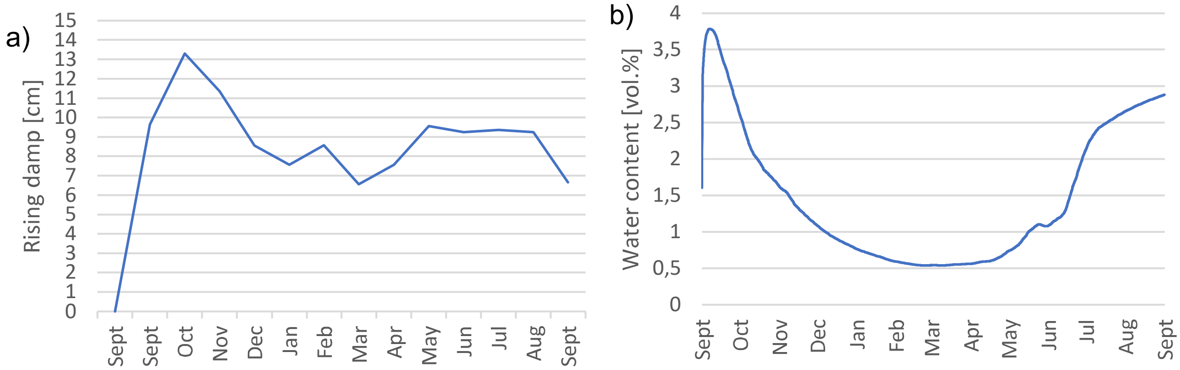

*Figure 3: a) Non-destructive methods analysis results (rising damp by thermography), b) Simulation outputs for the total structure of simple masonry – new brick + new premixed mortar.*

*Table 2: Water content (WC) for the different simulation with WUFI 2D, at 1 day (1d) and 1 year (1y).*

| **Boundary conditions** | **Simulation type** | **WC [kg/m³]** | | **WC [vol.%]** | |
|---|---|---|---|---|---|
| | | **7d** | **1y** | **1d** | **1y** |
| Laboratory conditions | New brick + lime premixed mortar | 37.82 | 28.80 | 3.78 | 2.88 |
| | Historical brick + lime historical mortar | 37.80 | 28.81 | 3.78 | 2.88 |
| | New brick + lime premixed mortar + Marmorino plaster | 38.06 | 7.95 | 3.81 | 0.80 |
| | Historical brick + lime historical mortar + Marmorino plaster | 38.05 | 5.71 | 3.80 | 0.57 |
| Venetian conditions | New brick + lime premixed mortar | 32.88 | 18.18 | 3.29 | 1.82 |
| | Historical brick + lime historical mortar | 32.83 | 18.03 | 3.28 | 1.80 |
| | New brick + lime premixed mortar + Marmorino plaster | 33.33 | 17.76 | 3.33 | 1.78 |
| | Historical brick + lime historical mortar + Marmorino plaster | 37.95 | 8.83 | 3.79 | 0.88 |

## Conclusions

It can be observed that the rising damp is very fast in the first 7-10 days of imbibition with direct contact with the groundwater, consequently there is a rapid increase in the WC through the masonry, and then gradually decrease until the stabilization phase. The difference in WC depends on the environmental context and the season analyzed: in the Venetian case a different WC can be observed, because it is influenced by the relative humidity of the air, precipitation, radiation, and air flows that influence the evaporation. Furthermore, the differences in WC in the masonry analyzed are also linked to the hygroscopicity of the materials, in fact, in the case of historical materials, the WC inside the structure is slightly lower, because it is characterized by a lower porosity in the brick and a lower vapor resistance factor in the mortar. Similar differences are recorded between masonry with and without plaster: the plastered masonry has a slightly higher WC in the first phase of imbibition, then released during the year. The same observations – capillary rise methods and speed of imbibition – were made in the laboratory tests.

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# 04

## Integrated seismic and energy building classification

*Martina Caruso, Rui Pinho, Federica Bianchi, Francesco Cavalieri, Maria Teresa Lemmo*

# Assessing occupant comfort in historic churches when usinglocalised heating systems

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## Abstract

The existing building stock is responsible for non-renewable resource depletion, energy and material consumption, and greenhouse gas (GHG) emissions. Life cycle analysis (LCA) procedures have thus been developed recently to quantify the environmental impact of construction and operational phases over the entire building's life cycle. Furthermore, the economic, environmental, and social consequences of recent natural disasters have encouraged the integration of hazard-induced impacts into standard LCA procedures for buildings. Buildings are indeed expected to provide population with safe living and working conditions, even when hit by different types of hazards during their service life, such as earthquakes. This study presents a life cycle framework for a new integrated classification system for buildings and the identification of renovation strategies that lead to an optimal balance between increase of energy efficiency and reduction of seismic vulnerability, considering building's life cycle economic and environmental impacts. Such a frameworkaccounts indeed for the contributions of several building's life cycle phases, including initial construction, operational energy consumption, earthquake-induced damage repair activities, potential retrofittinginterventions, and demolition. In this way, the resilience of buildings against both natural hazards and climatechange is addressed, while also improving the society awareness of the topic with the aim of prevention.

## Introduction

The consequences of recent hazardous natural events produced a growing concern on the impact of natural hazards on buildings environmental performance. Indeed, those events cause not only large economic and social losses, but also significant environmental impacts due to post-disaster rehabilitation activities, including debris removal and disposal, repair or replacement of structural and non-structural components, or, in worst cases, buildings demolition. Life cycle assessment (LCA) models for buildings have been developed to assess the environmental impact of construction/demolition and operational phases over the entirebuilding's life cycle. Only recently, in addition to standard life cycle stages, the effects of natural hazards and their induced retrofitting activities on buildings emerged as potentially significant contributions, especially in sites with high natural hazard demands. Earthquakes, for example, can produce extensive damage to buildings, if compared to other natural hazards.

As shown in Figure 1, most existing buildings in Europe have almost exhausted their initially intended service life, and require seismic strengthening intervention, given that their design and construction feature none or limited earthquake-resistance detailing. According to the report [1], 44% of the territory and 36% of the municipalities are subjected to high level of seismic hazard. It is also estimated that approximately 21.8 million people live in earthquake-prone municipalities and are thus exposed to a high level of seismic hazard. Given that, over the 50% of the Italian residential buildings (i.e., approximately 6.4 million) need urgent and major interventions to improve life protection against seismic action. At the same time, such buildings are highly energy-consuming, and rely on fossil fuels for heating, cooling, and other services, using old and wasteful technologies.

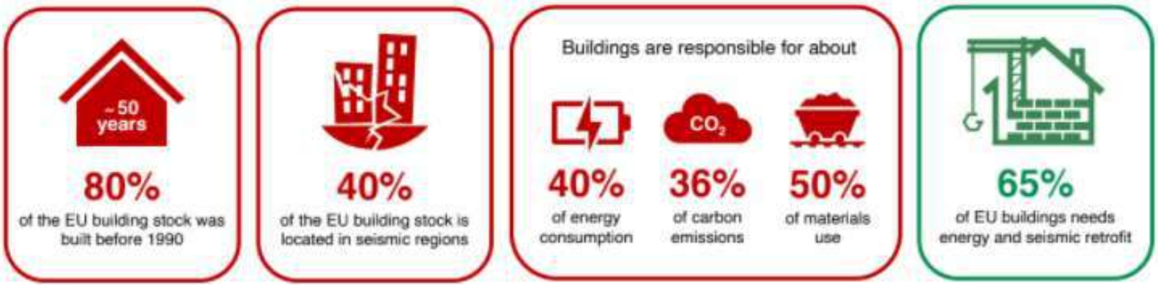


*Figure 1: The European building stock at a glance ([2-3]).*

It is also known that Europe is characterized by wide ranges of seismic areas and climatic zones, producinga high variability in terms of seismic demands and energy needs in buildings. The parameter that is typically used in seismic design of structures is the peak ground acceleration (PGA), whilst a measure of energy demands is in terms of heating degree days (HDD). In Italy, such parameters are used to define seismic and climatic zones, respectively, as shown in Figure 2. Their geographic distributions show that wide regions, suchas Central Italy, are subjected to high demands in terms of both energy needs for heating and seismic protection. At the same time, there are regions where one of the two parameters is clearly predominant, this being a potential approximate way to prefer a specific retrofitting intervention rather than any other. For instance, in some areas of Lombardy and Piedmont, PGA is almost negligible, whilst HDD is very high, thus an energy efficiency refurbishment may result in a higher reduction of life cycle economic and environmental impacts if compared to a sole seismic strengthening.

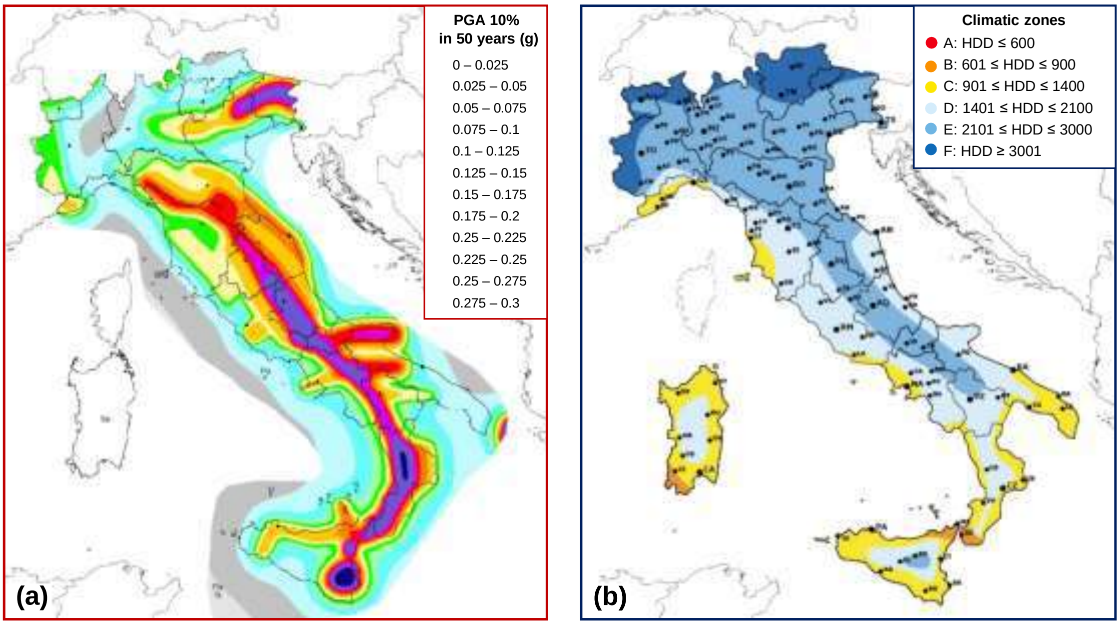


*Figure 2: Maps of Italy with spatial distributions of (a) design seismic acceleration, and (b) heating degreedays.*

Nevertheless, buildings renovation rate is still very low (approximately 1% per year), due to non-negligible costs, possible business inactivity (or downtime), potential need of inhabitants' relocation and insufficient hazard-awareness, and it currently mostly refers to energy efficiency refurbishment, since structural strengthening is more often operated only after strong seismic events (or in case of emergency). However, if a sole energy efficiency refurbishment is considered, the building would still be unsafe and vulnerable to seismic events, and it could experience from light to extensive damage, or even collapse, depending on the earthquake intensity, and the effectiveness and the monetary savings of the energy efficiency upgrade would be compromised (it would instead represent an additional loss, due to the brief life of the intervention system). If, instead, a sole structural retrofit is considered, the building will be safe and seismic-code compliant, but still very energy-consuming and carbon-dioxide emitting. Instead, sustainable renovation strategies should target both the mitigation of a building's structural vulnerability as well as the improvement of its energy efficiency, ensuring the highest savings in terms of both earthquake-induced damage repair and energy consumption.

For the reasons above, several European policies are pushing towards such a sustainable renovation of existing buildings. The European Green Deal [4], being one of the six European Commission priorities for the five-year term 2019–2024, is the new growth strategy to turn the European Union (EU) into a sustainable, resource-efficient, and competitive economy, aiming at a target reduction of greenhouse gas (GHG) emissions by 2030 to at least 55% compared to those in 1990, and at carbon-neutrality by 2050. The recently devised Next Generation EU recovery fund includes such a vision as one of its underlying layers, and thus aims to contribute to a decisive boosting of the sustainable modernisation of the European existing building stock, representing an unprecedented resource for the so-called Renovation Wave [5].

New approaches for such an ambitious transition towards a greener and sustainable building stock and to guarantee the best use of economic and environmental resources are thus needed, tackling for multifaced needs of buildings, such as the ones related to energy consumption, as well as safety against seismic hazard. Recent pioneering research projects have thus proposed integrated frameworks for the coupled energy and seismic renovation of buildings, sometimes based on life cycle approaches, also highlighting the need for adding environmental metric into standard procedures used to assess earthquake-induced impacts on buildings (indeed, in current practice only human and economic losses are considered). Some of the most recent research efforts can be found in [6-8]. The main goal of all the above efforts, including the present research, is thus the improvement of the resilience of buildings against natural hazards (e.g. earthquakes) and above all climate change.

## Methodology

With a view to provide a contribution to this important field, the main objective of this study is to propose a life cycle framework for a new integrated classification system for buildings and the identification of renovation strategies that target an integrated improvement of seismic and energy performances of buildings [9-10]. This paper indeed discusses a life cycle framework for existing buildings renovation that accounts for the contributions of several life cycle phases, including initial construction, potential seismic and energy retrofitting interventions, operational energy consumption and earthquake-induced damage repair activities (both pre- and post-retrofit), as well as demolition, in terms of both economic and environmental performance metrics. The contribution of damage repair and retrofitting activities due to potential earthquakes (with consequent downtime and possible need of occupants' relocation), which may occur during the operational life of the building, can be non-negligible, especially in regions with a high level of seismic hazard. In addition, different outcomes are expected for different geographic locations (i.e. different climatic and seismic conditions).

The proposed framework for the integrated assessment of buildings can serve multiple purposes. First, by considering all the life cycle stages listed above, it may be of interest to compare costs and environmental impacts associated with past, present and future constructions, as well as with different buildings and building typologies (e.g. reinforced concrete frames, masonry or steel structures, and so on): in other words, the framework allows for an integrated seismic and energy classification. Second, and most notably, by just considering post-retrofit building's life, the framework can be used to compare alternative retrofitting solutions and to identify the strategy that minimises running economic and environmental impacts over the remaining life of the given building, as well as the payback period (PB) of the retrofit investment and the average annual loss of life (AALL) due to earthquakes. The payback period of the retrofit investment and the average annual loss of life due to earthquakes (i.e. the number of earthquake-induced fatalities that are expected yearly on average in a given site) are thus suggested as additional decision-making tools for the identification of the most suitable retrofitting strategy for a given building. In other words, the framework can serve as a multi-criteria decision-making tool.

Figure 3 is an illustrative plot showing post-retrofit economic and environmental impacts for a hypothetical building, comparing the as-built configuration with three retrofitting options, including a purely structural intervention (referred to as 'Strct_Int'), a sole energy efficiency refurbishment (referred to as 'Enrg_Int'), and an integrated strategy (referred to as "Intgr_Int"). The hypothetical building is also assumed to be located in three different geographic locations, namely a highly seismic site with warm weather (referred to as 'Warm_HighEq'), a site with average seismic and climatic characteristics (referred to as 'Mild_AvgEq'), and a very cold site with a low level of seismic hazard (referred to as 'Cold_LowEq').

The optimal retrofitting option, considering post-retrofit annual costs and carbon emissions, would ideally be the closest to the axes origin, while also minimising the payback period and the average annual loss of life due to seismic hazard. That considered, the integrated solution appears to be the optimal retrofitting strategy for the given building in all sites. However, for instance, in the 'Mild_AvgEq' site considering the payback period alone, one could conclude that there is no significant difference between the integrated intervention and the sole energy efficiency refurbishment (in terms of life cycle costs and carbon emissions only) and that therefore it could be better to adopt the sole energy retrofitting option, thus avoiding longer working times and higher invasiveness of the intervention. However, if one also takes into account the average annual loss of life due to earthquakes, it is evident that the possibility of loss of life should not be ignored and that the sole energy efficiency refurbishment does not improve the as-built configuration in terms of life protection, whilst the integrated option confirms its optimality in those terms as well.

Lastly, Figure 4 hints at the possibility of using this plot of post-retrofit economic and environmental estimates as the basis for a new potential seismic vulnerability–energy efficiency integrated classification scheme for buildings retrofitting. It is noted that one or more class upgrades are possible only if an integrated reduction of costs and impacts is pursued (in other words, a reduction of costs or impacts alone would not always be sufficient for a class upgrade). Seismic strengthening and energy efficiency refurbishment techniques alone may produce a significant reduction of either running costs or emissions, whilst integrated options aimed at improving both seismic and energy performances may result in their contextual reduction. Such integrated classification system could clearly aid the process of identifying the optimal retrofitting strategy for a given building, most notably facilitating the definition of and the accessibility to potential financial incentives for buildings retrofitting at a national or even international level. However, a more extensive study will need to be carried out to define appropriate ranges of values for each one of the classes.

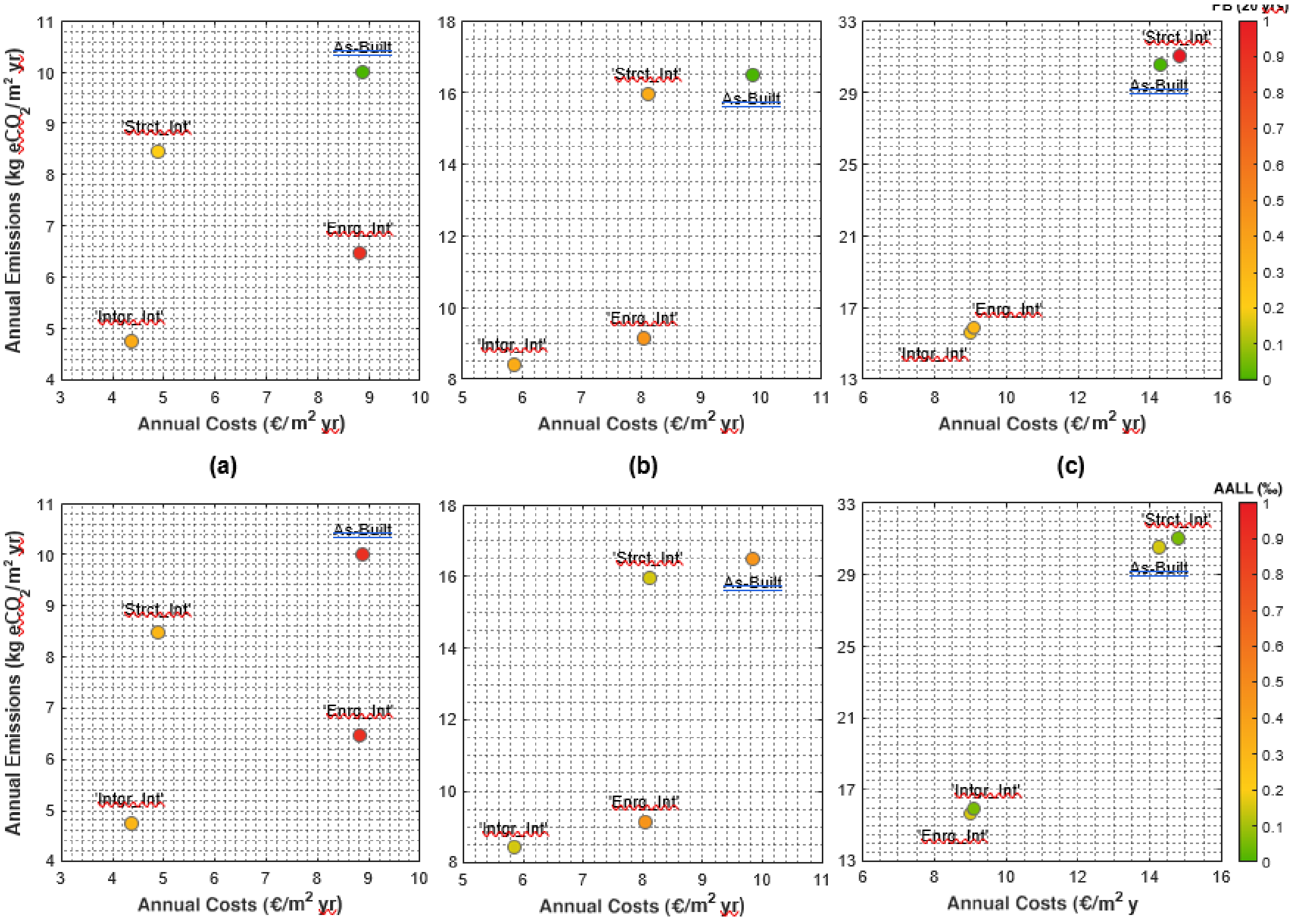


*Figure 3: Post-retrofit annual costs and emissions plots, including payback period (PB) and average annual loss of life (AALL) for each retrofitting option, in (a) 'Warm_HighEq' site, (b) 'Mild_AvgEq' site, (c) 'Cold_LowEq' site.*

## Conclusions

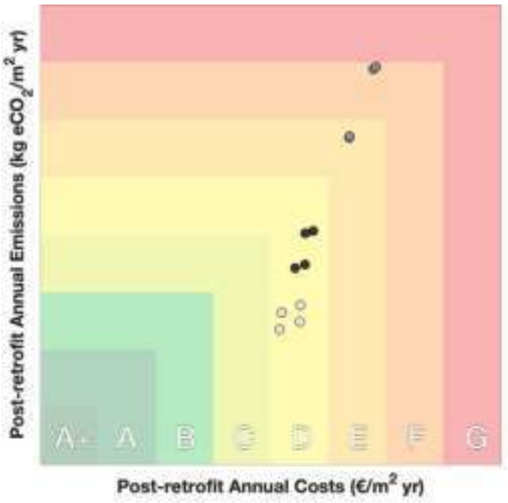
This study presents a life cycle framework for a new integrated classification system for buildings and the identification of renovation strategies that lead to an optimal balance between reduction of seismic vulnerability and increase of energy efficiency. It is shown that:

- the framework provides a viable and practical approach for buildings retrofitting and classification, including all the three main pillars of sustainability, namely economy, environment and society;
- within a sustainable perspective, not only the energy performance of a building but also its seismic performance are crucial in life cycle evaluations, due to the relevant consequences that strong earthquakes may have on the community, and that are not always quantifiable economically or

environmentally;

- the geographic location quantitatively affects the estimates of economic and environmental impacts over the building life cycle, according to its seismic hazard and climatic conditions, but also the effectiveness of different retrofitting options;
- integrated renovation strategies proved to be always convenient, especially in a long-term perspective.

The most ambitious goal of future research in this topic is to foster an unprecedented paradigm-shift for building engineers towards an interdisciplinary perspective in buildings assessment and retrofitting, including aspects related to seismic/structural engineering, energy efficiency, life cycle analysis, architecture, and economy, amongst others.



**Note**: The correspondence between cost/emission value ranges and the colour scale in this plot is purely demonstrative.

*Figure 4: Post-retrofit annual costs and emissions for all the illustrative application cases (related to the three locations), superimposed on a potential seismic vulnerability–energy efficiency integrated classification scheme.*

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# 05

## Cyber-Physical-Social System Conceptualization for Next Generation Building Energy Systems

*Cem Keskin, M. Pınar Mengüç*

# Cyber-Physical-Social System Conceptualization for Next GenerationBuilding Energy Systems

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## Abstract

Building energy systems (BES) are responsible for considerable share of global energy consumption and GHGemissions. They are also the major determinant of occupant experience within a built environment that is rely on both physiological and psychological satisfaction. The next generation BESs are expected to improve occupantcomfort while decreasing energy consumption and GHG emissions. As an example, HVAC systems are expectedto meet not only the thermal comfort but also the environmental control expectations that are highly personal. This is only possible with transdisciplinary methodologies that incorporate physical, technological and human dimensions of energy use in buildings. The cyber-physical-social system (CPSS) approach can bring together diverse realms to handle complex dynamics of indoor built environment. This study presents a brief overview oftechnological evolution of building energy systems and highlights the importance of human-in-the-loop systemapproaches. An integrated modeling approach that extends hybrid dynamical system modeling as to involve human dimension is presented. The approach can be used to deploy CPSS based conceptualizations for modellingand operation of BES.

## Introduction

Having a share of 30%, buildings are one of the major contributors of global energy consumption that is predictedto reach 15 Mtoe in 2020 [1]. Moreover, due to the widespread usage of fossil fuels, buildings are responsible of almost 3 Giga tones of CO2 emissions per year [2]. These numbers highlight the importance of energy efficiencyin buildings for minimizing global carbon footprint of modern daily life. Energy systems of the buildings are categorized based on their dependency on energy sources. The systems that don’t consume energy to perform (like shading systems, natural ventilation systems) are referred to as passive systems whereas the energydependent ones are referred to as active systems.

Driving major physical interactions of a building with its environment (heat transfer, airflow, among others), thepassive systems determine the minimum and maximum energy consumption of a building. Within these limits, high performance active systems keep building energy consumption close to the minimum possible values [3]. Moreover, the active systems are at the center of human interaction with building systems. Switching on/off the lights or adjusting the thermostat set values not only determines the energy consumption of the building, but also the occupant comfort within it [4]. Here, the term “experience” refers to the occupant’s overall satisfaction that is an outcome of physiological and psychological states influenced by interaction with BES [5]. These systems should be designed in a way that optimizes each of physical, technological and human factors. This paper presentsa brief review of technological transformation of BESs to highlight how these factors converge for the next generation system requirements. Moreover, the paper offers a conceptual framework and a modeling scheme forthe inherent integration of the factors.

## Building Energy Systems

The conventional building energy systems can be referred as cyber-physical systems due to the fact that they aremainly composed of physical and cyber components. Physical components are responsible for driving indoor environment towards desired conditions. A fan-coil for moving, heating and cooling the indoor air in a built environment can be considered as a typical example of it. During the second half of last century, physical components were basically electrical (like lighting) or electro-mechanical (like HVAC) systems that are controlled manually with basic measurements and several switch combinations. Since such a control scheme is very limited in terms of deploying optimum operation conditions and prone to human (operator) error, it was unable to deliver energy efficient operation of systems.

For the purpose of eliminating energy waste due to the improper operation of these systems, advanced control schemes have been deployed during the last thirty years. These systems were naturally more complicated due tocomplex cyber components. At early stages, microcontrollers or programmable logic controllers (PLC) were putin charge of controlling energy systems taking advantage of improved control approaches such as proportional
(P) or proportional-integral (PI) control[6]. Furthermore, more advance automation, integration and monitoringsystems have appeared to manage large number of end points. Consequently, energy systems of modern buildings have involved highly complex cyber infrastructure that require central and edge computation units as well as a dedicated communication networks [7]. As a result, indoor environments within modern buildings are manipulated by cyber-physical energy systems.

Since building energy systems are among the primary factors to characterize the indoor living environment, theyare subject to intense human interaction. As more intelligent and complex energy systems have been deployed during the last decades, the occupant perception and expectations regarding the performance and capabilities of these systems have evolved. In parallel with the advancements in other sectors (communication, transportation,among others), the occupants are looking for systems that can adopt their preferences and optimize energy consumption. Beside the sensors conventionally used for system control (like thermostats controlling HVAC), IoT-enabled sensor networks (involving indoor positioning systems, wearable sensors, luxmeters, among others)and mobile user interfaces are used for augmenting occupant experience and energy efficiency within built environments [8].

The improved interaction among occupants and building systems brings together the involvement of the humanelement during design and operation of building energy systems. In other words, cyber-physical system conceptualization is not enough to meet requirements for human-in-the-loop energy system design for buildings.At this point, the cyber-physical-social system (CPSS) conceptualization can provide broader perspectives to meetextended requirements. CPSS approach aims to unify considerations related to the human and machine intelligence [9]. Starting from the system design level and incorporating in the operation phase of building energysystems, it can outline a systematic approach to synthesize the distinct realms of cyber, physical, and social contexts. However, a standalone conceptualization is not enough to guide designers and operators. Next section of the paper discusses how hybrid dynamical modeling can be coupled with occupant behavioral modeling to beused for establishing a methodology for CPSS conceptualization.

## Hybrid Dynamical Modeling

The common modeling approach for building energy systems is to express relevant physical phenomena (primarily heat transfer and air flow) with difference or differential equations that are based on continuous-timedynamics. Then, equations are coupled with proper initial and boundary conditions that represent physical, geometrical, and environmental properties of a building. These equations can be used for energy performance simulations, control approaches, life-cycle analysis, thermo-economic analysis, among others. Nevertheless, building energy systems are controlled by cyber components that work with discrete-time dynamics. If-then- else conditions or finite state machines are two common ways of deploying it.

Hybrid dynamical modeling is an approach that mathematically synthesizes continuous and discrete time dynamics:

$$\dot{x} \in F(x), \quad x \in C$$

$$x^{+} \in G(x), \quad x \in D$$

In this notation, $\dot{x}$ refers to time derivative of $x$ when the time is continuous whereas $x^{+}$ refers to time derivativeof it when the time is discrete for the given dynamical system. Accordingly, $C$ is called the flow set and $D$ is calledthe jump set that describe the solution domains for continuous and discrete dynamics respectively. Similarly, $F$ is the flow map and $G$ is the jump map that are the functions representing the continuous and discrete evolutionof the given system respectively [10,11]. The interaction among these two realms is facilitated with mode switches and inputs (Figure 1) [12]. On the other hand, they interact with environment in accordance with their originalformulation. Discrete component accepts binary inputs and yields binary outputs whereas the continuous component accepts and yields real-valued ones.

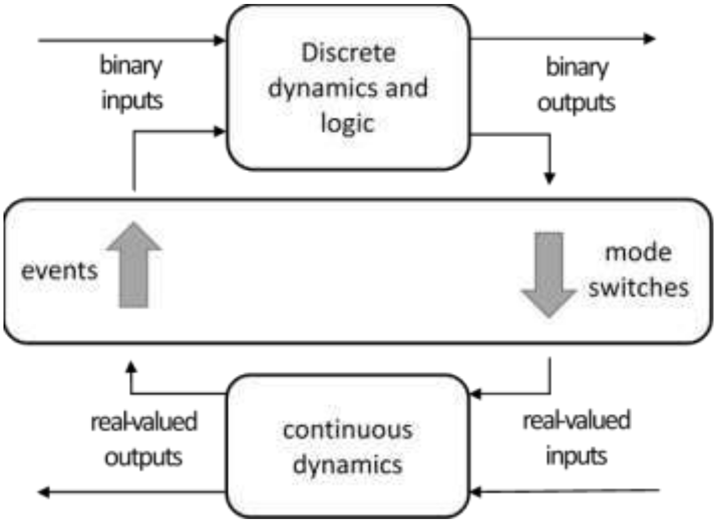

*Figure 1: Hybrid Dynamical Modeling (Adopted from [12])*

The hybrid dynamical modeling is a comprehensive approach for modeling and investigating cyber-physical systems. This approach can also provide a link to integrate occupant behavioral and CPS modeling. The integration can be realized with three interventions (Figure 2):

I. Time dependent definition of user control actions can be delivered as binary inputs of discrete component. Here, finite state machines can be used to represent various actions and options.
II. User preferences can be used as model constraints that trigger mode switches and events. Rule based(if-then-else) logic can govern the mode switches whereas occupant preferences (like set points of thermostats) can be defined as event rules.
III. As the drivers of occupant experience in built environment, time series measurement of environmental parameters can be used as inputs of continuous component.

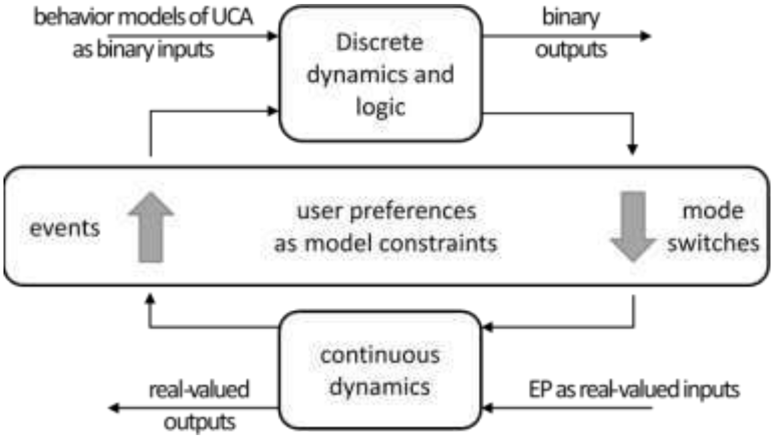

*Figure 2: Integratıng Hybrid Dynamical and Behavioral Modeling*

The schematic presented above extends hybrid dynamical modeling approach in a way that also represents occupant related factors. Accordingly, it can be used for modeling and control of building energy systems that can be conceptualized as CPSSs.

## Conclusion

BESs are among the major components of modern life and have a vital role in occupant experience, energy consumption and GHG emissions of buildings. Having intense human interaction, research and development activities for BESs are expected to improve both occupant experience and energy efficiency. Holistic approachesare required to bring together the distinct realms (physical, technological and social) of energy use in the built environment [13]. The CPSS approach can provide a framework to enable this by conceptually define the interdependence among them. A recent paper of authors shows how to apply the CPSS concept to design, development and operation of BESs taking advantage of hybrid dynamical modeling [11]. The current study discusses why and how behavior-driven human centric approaches can facilitate the design and development offuture BESs in line the with technical evolution and current trends of building technologies.

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# 06

## Potential benefits of passive solar design integration in buildings

*Giacomo Cillari, Alessandro Franco, Fabio Fantozzi*

# Potential benefits of passive solar design integration in building

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## Abstract

The issue of the energy demand in buildings is a relevant phenomenon to deal with. The construction sector can play a fundamental role in reducing energy waste and greenhouse gas emissions: more than 40% of the energy consumption and 36% of emissions come from buildings. The aim of the present work is to define the impact that passive solar energy integrated solutions can achieve in reducing the overall energy demand of the building. Through an extensive sensitivity analysis, the best solutions have been evidenced within different contexts in terms of climate condition and building use. The investigation of a case study determined a 16% of final energy saving.

## Introduction

The plan set by Europe aims to cut the net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels [1]. In this perspective come the incentives to nZEB and renewable energy systems integration [2]. The problem of energy demand is mainly worked out through energy conservation, e.g. building insulation, and system efficiency to reduce the energy demand. The integration of renewable systems allows to fill the energy gap with clean energy production. In this framework, construction sector can exploit available solar energy through the integration of passive solar solution within the building design. These solution merge energy conservation and renewable energy supply, with the plus of architectural integration. Configuration based on the proper design of solar collectors, namely windows, thermal masses and distribution systems, allow to passively exploit solar energy for heating, and cooling in some configurations. These solutions help, in a passive way, through the use of clean energy, reduce the initial energy demand of the building.

Common classification includes direct, indirect, and isolated passive solution, according to the mutual position of solar collector, thermal mass and building environment. Passive systems work on radiation, conduction as the main heat transfer phenomena, with natural circulation of warm air as distribution system. Regulation is usually relegated to shading systems, or vents, through manual or automatic systems, managed by probes and sensors. These solutions can provide heating and ventilation throughout the day and represent an energy reduction design feature to drastically reduce the energy demand considering that residential space heating is responsible for 86% of building energy demand [3].

The present work wants to determine the best solution over a range of performing parameters, according to climate, building use and exposure.

## Aim and Methods

The present paper, following a previous research [4] consists of a sensitivity analysis of the energy performance of various passive solar solution over different building configuration. The scope is to define the impact of different parameters on the final performance, and determine which kind of solution and set fits better in each configuration, according to heating and global energy performance. The analysis of a case study, moreover, allow to propose a methodology for the application of the guidelines, developed in the previous step, to a specific building.

Firstly, a thorough bibliography research has been carried out in order to define the most investigated kind of solution and select the parameters for the sensitivity analysis. To get a wide view of the different passive solar categories, 4 configurations have been investigated: direct gains (DG) and direct sunspaces (DS), Trombe walls (TW) and massive walls (MW), sunspaces (ST) and nano paintings (NP). The solutions have been selected as the most common for each category, the easiest in terms of architectural integration even in existing building, discarding complex solution like roof ponds or Barra-Costantini. From the scientific review, the main common parameters have been grossed up: Figure 1 shows the filtering process for the Trombe wall analysis. Table 1 summarise the parameter of the sensitivity analysis and the range of variation. The parameters have been selected as they are, among the shared influencing factor of all the solution, the most influencing ones: according to the review, the range of variation account for minimum and maximum values of the configuration commonly studied. Parameters take into account different exposure, window to wall ratio (WWR) and specific characteristics of glass and envelop material, for light and heavy structures [5].

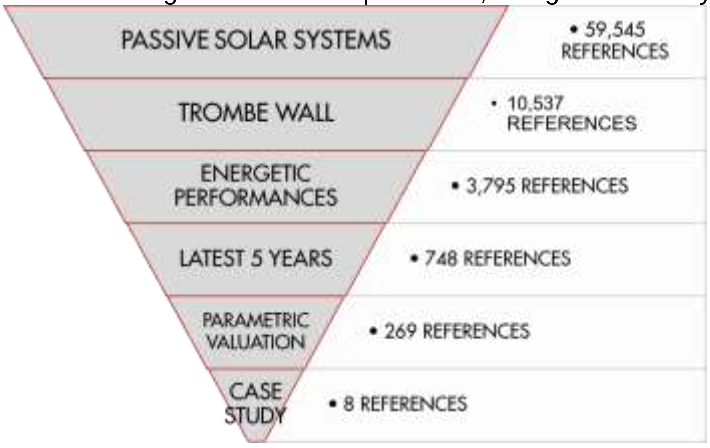


*Figure 1: Example of the filtering process for the scientific review of the selected passive solar solutions*

| **Latitude** | **South Italy** | | | **North Italy** | | |
|---|---|---|---|---|---|---|
| *Exposure* | E | S | W | E | S | W |
| *WWR* | 0.2 | | 0.6 | 0.2 | | 0.6 |
| *U-glass* [W/m²K] | 2.3 | | 0.8 | 1.0 | | 0.8 |
| *Heat capacity* [J/m²K] | 160,000 | | 800,000 | 160,000 | | 800,000 |
| *Reflexivity* | 0.1 | | 0.9 | 0.1 | | 0.9 |
| *Emissivity* | 0.1 | | 0.9 | 0.1 | | 0.9 |

*Table 1: Set of parameters for the sensitivity analysis*

From the permutations of each parameter a set of 336 simulations has been achieved following the tree diagram of Figure 2. Two building with two different Surface to Volume (S/V) ratio have been simulated in two different climate conditions representing south and north Italy weathers, for both residential houses and office buildings. In each passive configuration, permutation of the two values of each parameter have been analysed.

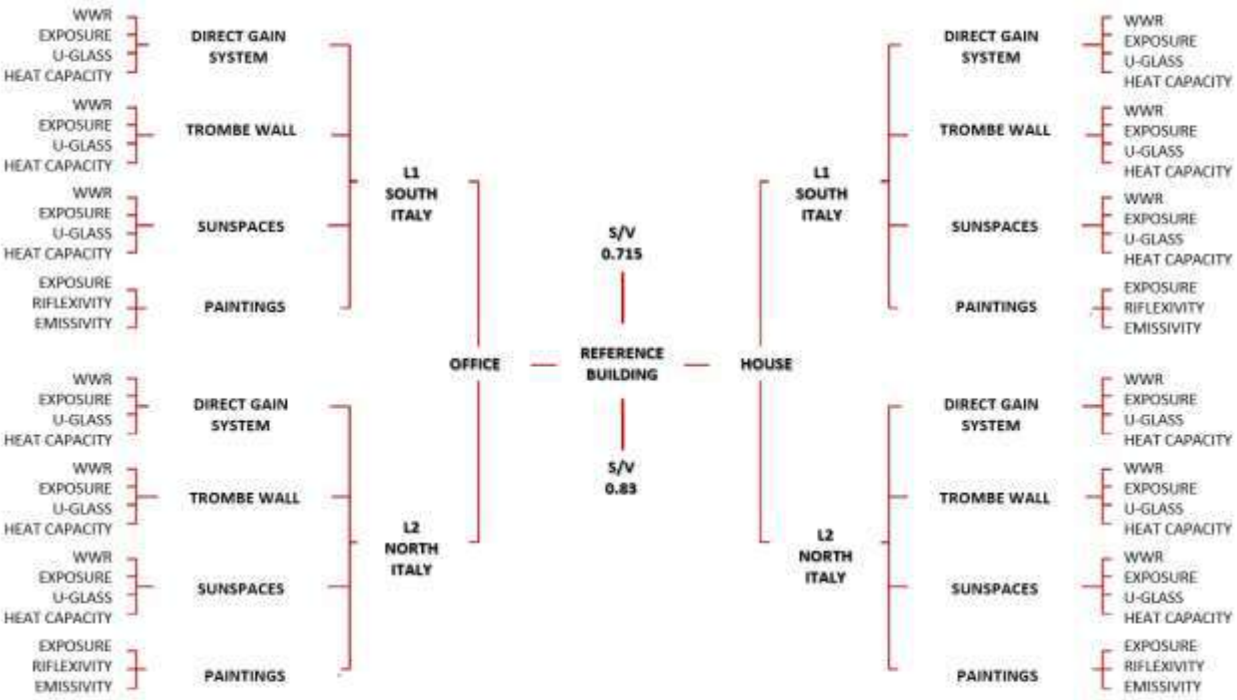


*Figure 2: Simulation list*

To manage all the results a specific alphanumeric code has been used to catalogue all the permutation: the meaning of the code is explained in Figure 3.

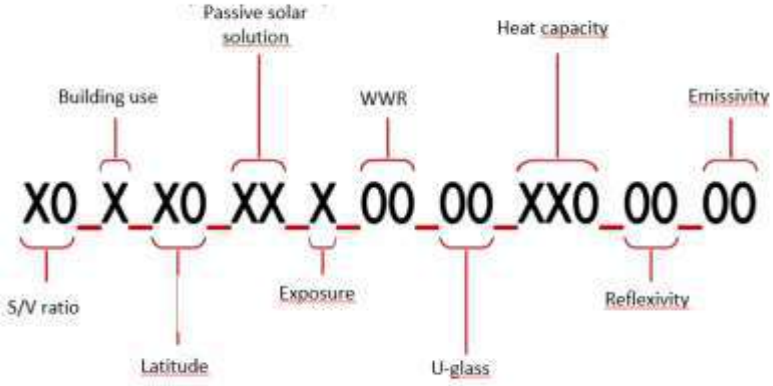


*Figure 3: Alphanumeric code legend*

At the end of the sensitivity analysis, a case study of a residential building (Figure 4) has been investigated in order to get results of energy performance on a design building and developed a methodology for the gradual application of the guidelines developed and achieved a proper architectural integration.

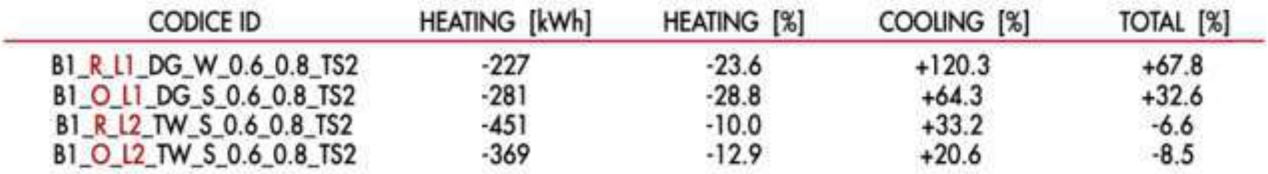
*Figure 4: Case study, cohousing project*

## Results and Discussion

### *Sensitivity analysis*

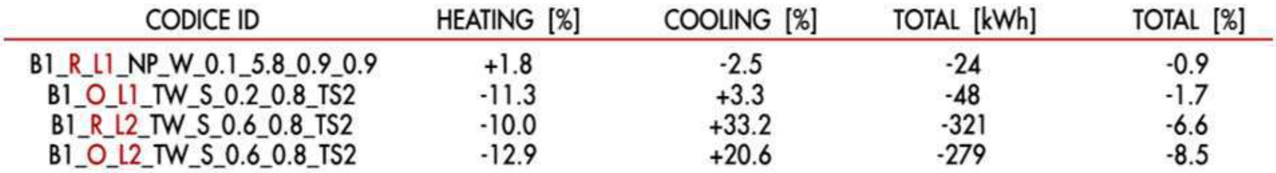
The results of the sensitivity analysis showed the variation of the energy performance of the passive solar solutions analysed. Regarding the direct gains, e.g., higher performance is achieved with low U-glass values in north Italy and high values in south Italy. Indirect gain systems like Trombe walls perform better in north Italy, and with a high WWR, as isolated gain systems, like sunspaces, that prefer low heat capacity thermal masses.

Following the sensitivity analysis, the best configurations have been collected to define guidelines based on either heating or global performance in the 4 main cases of residential and office building in the two spots, for the low S/V building (Figure 5 and Figure 6) and the high S/V one (Figure 7 and Figure 8).



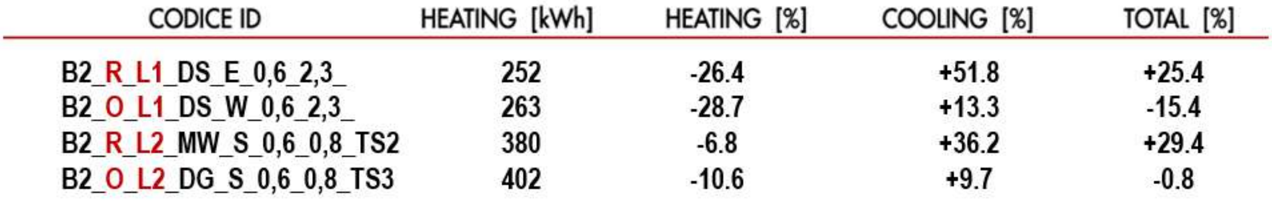
| CODICE ID | HEATING [kWh] | HEATING [%] | COOLING [%] | TOTAL [%] |
|---|---|---|---|---|
| B1_R_L1_DG_W_0.6_0.8_TS2 | -227 | -23.6 | +120.3 | +67.8 |
| B1_O_L1_DG_S_0.6_0.8_TS2 | -281 | -28.8 | +64.3 | +32.6 |
| B1_R_L2_TW_S_0.6_0.8_TS2 | -451 | -10.0 | +33.2 | -6.6 |
| B1_O_L2_TW_S_0.6_0.8_TS2 | -369 | -12.9 | +20.6 | -8.5 |

*Figure 5: best solutions for heating performance of building 1 S/V= 0.715*



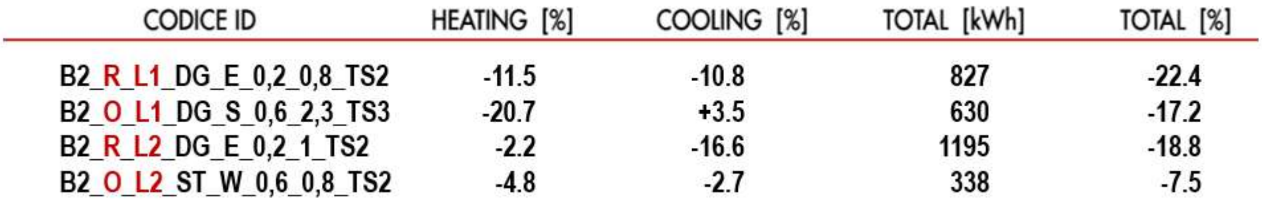
| CODICE ID | HEATING [%] | COOLING [%] | TOTAL [kWh] | TOTAL [%] |
|---|---|---|---|---|
| B1_R_L1_NP_W_0.1_5.8_0.9_0.9 | +1.8 | -2.5 | -24 | -0.9 |
| B1_O_L1_TW_S_0.2_0.8_TS2 | -11.3 | +3.3 | -48 | -1.7 |
| B1_R_L2_TW_S_0.6_0.8_TS2 | -10.0 | +33.2 | -321 | -6.6 |
| B1_O_L2_TW_S_0.6_0.8_TS2 | -12.9 | +20.6 | -279 | -8.5 |

*Figure 6: best solutions for global performance of building 1 S/V= 0.715*



| CODICE ID | HEATING [kWh] | HEATING [%] | COOLING [%] | TOTAL [%] |
|---|---|---|---|---|
| B2_R_L1_DS_E_0,6_2,3_ | 252 | -26.4 | +51.8 | +25.4 |
| B2_O_L1_DS_W_0,6_2,3_ | 263 | -28.7 | +13.3 | -15.4 |
| B2_R_L2_MW_S_0,6_0,8_TS2 | 380 | -6.8 | +36.2 | +29.4 |
| B2_O_L2_DG_S_0,6_0,8_TS3 | 402 | -10.6 | +9.7 | -0.8 |

*Figure 7: best solutions for heating performance of building 2 S/V= 0.83*



| CODICE ID | HEATING [%] | COOLING [%] | TOTAL [kWh] | TOTAL [%] |
|---|---|---|---|---|
| B2_R_L1_DG_E_0,2_0,8_TS2 | -11.5 | -10.8 | 827 | -22.4 |
| B2_O_L1_DG_S_0,6_2,3_TS3 | -20.7 | +3.5 | 630 | -17.2 |
| B2_R_L2_DG_E_0,2_1_TS2 | -2.2 | -16.6 | 1195 | -18.8 |
| B2_O_L2_ST_W_0,6_0,8_TS2 | -4.8 | -2.7 | 338 | -7.5 |

*Figure 8: best solutions for global performance of building 2 S/V=0.83*

Results highlight how direct gains o direct sunspaces are privileged in locality 1, south Italy, while locality 2, north Italy advantages of more massive solution as massive walls or Trombe walls. Offices prefers south bounded solutions, to get most from the higher solar radiation from the south, while residential solution suggest the integration in the east or west facades.

### *Case study*

The case study of the cohousing project allowed to verify the results achieved in the previous section and apply a methodology to integrate passive solution in the architectural design of the building. Figure 9 shows the cumulative step in the integration of passive solar solutions suggested. The process started with the guidelines in Figure 5, through the integration of direct gains in the west, firstly, and then in the east facades. A combination of the two configurations, moving the windows out from the north façades, allowed to achieve a better result in terms of heating and a reduction of the increase of global performance.

Then, to reduce the increase in cooling, the analysis moved on with the solution of Figure 6: the use of nano paintings and optimized shading systems to reduce the cooling load around 23%. Finally, looking at the specific conformation of the building, sunspaces have been installed in the open terraces: final result is minus 14% in the heating demand and 16.7% of energy saving globally. The cumulative application of passive solar solutions reached an energy saving share around 1/6 of the overall demand, with a proper architectural integration and low extra cost, as most of the windows have been simply displaced from the original position.

a b

*Figure 9: Energy performance resulting from the cumulative application of the suggested passive solar solutions (a) and render of the final building design (b)*

## Conclusion

Passive solar design can help reduce the original energy demand of the building, guaranteeing a proper architectural integration and passively exploiting available clean energy form the sun. These strategies have been ignored as saving measures in the last years, in favour of energy conservation and complex building systems promoted by the technical progress. The rising attention to sustainability can help passive solutions diffusion due to their potential in reducing the energy demand of the building. The aim of this work was to provide guidelines and criteria for the design of passive solar strategies, through the a wide, general simulation, and a methodological approach for the integration of this criteria in the building design by means of the case study.

Results showed that, based on the climatic conditions and building destination, up to 30% of the heating demand can be saved, with the share of the global energy demand for air conditioning up to 22%. The optimized case study reached a global energy saving around 17%, with a cumulative application of different solutions. Future perspective of this investigation will deal with the problem of integration in existing buildings and the development of multi criteria indexes to account for comfort.

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# 07

# Analysis of the influence of different buildings' envelopes and operation modes on local thermal comfort in university classrooms

*Roberto Rugani, Giulia Lamberti, Vito Tassielli, and Fabio Fantozzi*

# Analysis of the influence of different buildings' envelopes and operation modes on local thermal comfort in university classrooms

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## Abstract

This study aims at evaluating thermal microclimatic comfort in classrooms. Evaluation of school environments is crucial to improve the places where children spend most of their time and increase their capacity for learning. BES and CFD were coupled, using the outputs of the dynamic energy simulations in its most energy demanding timestep as input for the fluid dynamics analysis. This coupling allowed to study the environment no longer as a homogeneous space. The results showed that the environments substantially change punctually as a function of several parameters related to the use of the building, also depending on the climatic season. This paper provides a new methodology for the analysis of comfort assessment in non-homogeneous environments, with a creation of an individually-oriented comfort map.

## Introduction

The new progress in the field of construction and the stringent demands in the improvement of the existing building stock turned the attention not only to the reduction of energy consumption but also to the improvement of the environmental quality [1]. In particular, the demand for quality in the school environment are becoming more and more stringent. Classroom should be designed for providing student and teachers the best condition for learning and teaching [2].

Among other aspect that define Indoor Environmental Quality (IEQ), thermal comfort is particularly relevant as it influences the overall perception of the environment [3]. Global thermal comfort is defined by certain thermal conditions that modify the indoor environment to ensure occupants comfort, i.e. air temperature, mean radiant temperature, relative humidity, and air velocity of the ambience plus the clothing insulation and metabolic rate of the occupants [4].

The thermal comfort has so far been studied on environments considered all homogeneous, when instead substantial differences can be found within the same room as a function of many factors such as location and typology of the HVAC system, types of construction and so on [5].

Therefore, the objective of this work is to evaluate the thermal comfort within university classrooms, studying them as non-homogeneous environments and evaluating the differences between the different zones.

## Method

In this study, the space within a classroom was studied as a non-homogeneous environment, investigating the thermal comfort conditions within the space. Moreover, the impact of the building envelope and of the HVAC system typology was analyzed by means of different case studies.

Three different classrooms of the Engineering faculty of the University of Pisa were simulated, having three HVAC configurations. The buildings where these classes are located are widely different: the oldest was built in 1930 and has a traditional hydronic radiator system; the second was built in 2006 and is air-conditioned by an air to air heat pump with ceiling fan coil distribution; the latter is under construction and will be equipped with a VRF system with mechanical air exchange ventilation system.

Two simulation phases followed one another and were coupled to study the microclimate. An energy simulation campaign was performed using EnergyPlus tool [6]. The Building Energy Simulation (BES) was carried out using an airflow network to simulate internal air movements and aimed at assessing boundary conditions, i.e. mainly wall surface temperatures, for CFD analysis. The same three clasrooms of the previous methodology were studied using Autocad CFD, selecting boundary conditions as the EnergyPlus outputs in the summer and winter worst scenarios and in the summer and winter average scenario.

The aim was to obtain the local temperatures on an ideal manikin placed in the stalls to study the thermal comfort actually perceived by users. Therefore, it was possible to recreate homogeneous sub-zones within the room, creating a sort of thermal comfort map.

To determine thermal comfort, several models have been developed. Fanger's rational model [7] is still the most used, which determines the thermal comfort by means of the PMV (Predicted Mean Vote) index calculation. Its assessment is function of the 6 parameters that define a thermal condition: four environmental (air temperature, relative humidity, mean radiant temperature and air velocity) and two individuals (clothing insulation and metabolic rate). In this study, environmental values are computed using the BES-CFD coupling, the individual ones have been set with the standard values of students attending class in a university classroom.

## Results and discussion

The BES analysis allowed to obtain the values of the surface temperatures of the opaque and transparent closures of the investigated classrooms. A Typical Mean Year (TMY) weather file of Pisa has been used. The different stratigraphies, due to the different periods of construction of the buildings, showed substantial differences between the resulting values.

The CFD simulation allowed to study the distribution of the airflows inside the rooms, thus allowing to analyze the temperatures distribution, the effect of the different types of HVAC and the actual thermal comfort perceived by the students in the classrooms.

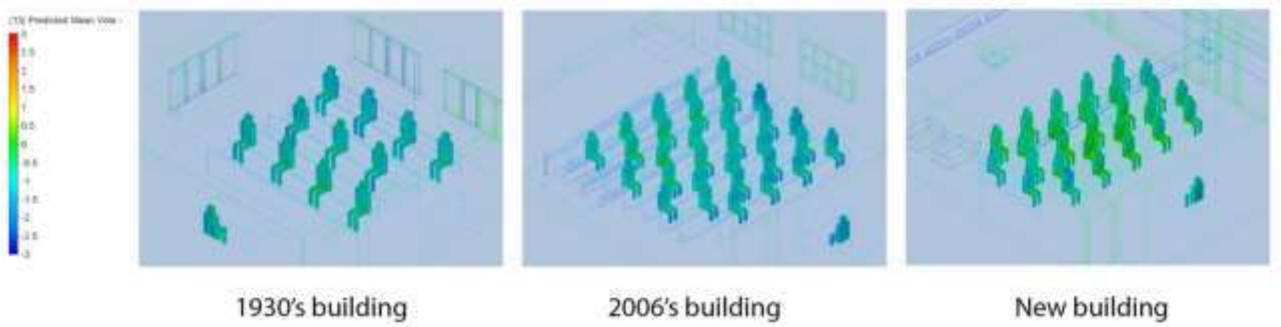
The results of the PMV values in the newly constructed building show a situation generally close to comfort even in the worst winter case, with values that are within comfort class C, as defined by ISO 7730. Moreover, the new HVAC system manages to create an almost uniform comfort condition in the room.

The 2006 building presents a more inhomogeneous situation, with the side areas of the room reaching substantial discomforts due to air distribution.

The classroom located in the historical building of the Faculty of Engineering presents some problems. The simulation was conducted keeping the windows open due to the absence of an air exchange system, creating discomfort situations near the openings, also due to high air velocities. On the other hand, opposite discomfort situations have been observed near the radiators.

In general, it was seen how zoning changes depending on the climatic season. The same zone that during winter presented high comfort values, in summer would presents a low microclimatic quality.

Figure 1 shows the distribution of the PMV values among classroom occupants in the winter worst scenario.



1930's building

2006's building

New building

*Figure 1: PMV values in the worst winter scenario in the three classrooms.*

## Conclusion

The International trend demand for high quality in school environment. This study aims to evaluate the thermal comfort within the internal environment of three different classrooms typology, considered the most representative and generalizing case studies of today's school classrooms.

The coupling of the BES and CFD analyses allowed for class zoning and the creation of individual-oriented guidelines. Classrooms can no longer be conceived as homogeneous environments, but need to be studied as non-homogeneous environments, and users need to be provided with the tools to address their preferences.

This new analysis methodology is not only useful to the user when choosing where to sit to attend a lecture but can also be used by designers in the school environment design phases.

Future research developments are focused on the infection perspective. This new methodology of non-homogeneous zones fits well with the analysis of the infection risk, very relevant in the current pandemic situation from COVID-19. All current infection risk models assume the study of a homogeneous zone, while it has been seen that the ventilation itself creates zones where air changes are greater and others where the air remains still for longer. In this way, the parameter of air Local Mean Age is considered a winning choice in the parameterization of the heterogeneous environment. Therefore, the goal will be to create an evaluation model of the classes creating non-homogeneous maps as a function of thermal comfort and risk of infection.

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# 08

# Future Development, Perspective and Obstacles of Ground Source Heat Pump Technology in the Building Sector: a Review

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# Future Development, Perspective and Obstacles of Ground Source Heat Pump Technology in the Building Sector: a Review

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## Abstract

In the European Union, 40% of the overall final energy consumption is attributable to the buildings sector. A reason for such data may be found considering that the great majority of the building stock is more than 40 years old. According to the European Commission, an interesting potential lies in the refurbishment of the building sector, and heat pump technology has been recognized as one of the most cost-effective solutions to tackle the environmental issue of this sector. Regarding heat pump technology, ground-source heat pumps (GSHPs) have been proven to be the most efficient solution on equal boundary conditions. Despite this, in most EU states' markets, GSHPs hold only a small market share with respect to air-source heat pumps. In this paper, the state of art and possible future developments of GSHP technology have been reviewed together with a focus on the potential of such technology, most of all on the refurbishment of existing buildings, and on the obstacles to its spread.

## Introduction

In the European Union, the building sector is responsible for 40% of the overall final energy consumption, considering both residential and commercial buildings [1]. An important portion of EU buildings energy consumption, from 60% to 80%, is attributed to space heating. Such data can find an explanation considering that 64% of the EU building stock is more than 40 years old [2]. For these reasons, a significant energy saving potential lies on buildings [3]. With the purpose to enhance buildings energy performance, the European Commission released directives such as EPBD [4] and EED [5]. Such directives also identified Heating, Ventilation, and Air Conditioning (HVAC) systems as the main solutions to increase renewable energy sharing and overall building energy efficiency, considering both the retrofit of existing buildings and the construction of new ones. In this context, electric heat pumps are among the most cost-effective solutions for decarbonising thermal energy, notably in buildings, and can be used in various environments, even in colder climates. Moreover, in the last few years, the heat pump market is facing a great expansion: in UE countries 1.6 million heat pumps were installed in 2020, 5% up with respect to 2019, despite shortages due to Covid-19 crisis, with Italy, France and Spain as leaders in this sector [6].

The great majority of installed heat pumps are air-source type, most of all in the Mediterranean countries, and the ground-source heat pumps market is pushed in cold climate countries [7]. In Italy, the first country for installed heat pumps, air-source heat pumps (ASHPs) involve 97% of the market while only 3% is occupied by GSHPs. Despite a significant expansion, heat pumps cover only a small market share in the overall heating generator market. A relevant reason is the practical infeasibility of a space-heating system retrofitting without replacing radiators, which represent over 90% of the existent domestic equipment in households [8]. In this perspective, ground-source heat pumps are able to keep high efficiency and performance also at high heat sink temperatures, making this technology an interesting solution for retrofitting buildings without replacing the existing heat terminals [9].

## Perspectives and barriers

Heat transition is crucial for achieving the EU climate targets. The European Commission has recognised in Energy Roadmap 2050 that electric heating can reach a share of 36-39% contribution to heat decarbonisation in 2050 [10] and heat pump technology seems to be the most appealing technology due to their higher efficiency and profitability [11]. Moreover, heating demand is expected to decrease, while cooling demand is forecasted to increase [12] and one of the main strengths of heat pumps is their capability of generating both heating and cooling with the same device.

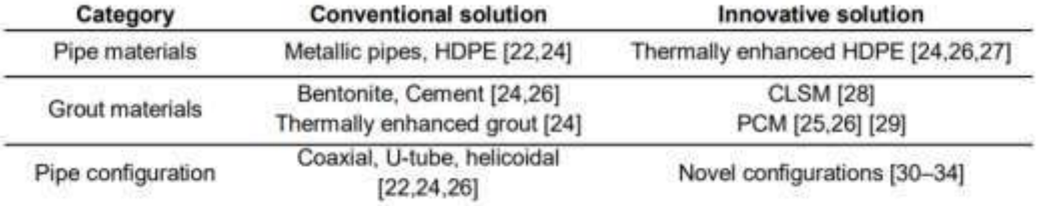
In retrofitting an existing building or in the construction of new ones, the choice of the heat generator is mainly driven by investment costs and operating costs [16], which are related to system efficiency and energy carriers price. Martinopoulos et. al. [13] shows that heat pumps, and in particular ground-source heat pumps, present the lowest operating costs among the proposed heat generators. Heat pumps, in general, have higher investment costs with respect to gas boiler or oil boiler, in particular ground-source heat pumps. Another aspect to consider when choosing the generator is its implementation. The system includes the building and its boundary conditions and heating terminals. Since heat pump efficiency and capacity depend on temperature difference between the cold source and the heat sink, ASHPs, whose cold source is ambient air, could be disadvantaged in cold climate countries or in case of coupling with high temperature terminals such as radiators, which are common in existing buildings. Instead, GSHPs efficiency and capacity rely on ground temperature, and consequently on a more stable cold source with a temperature level higher than ambient in winter and lower in summer, achieving higher efficiency (up to 20%) than ASHP at the same boundary conditions [13,14]. Being almost independent on ambient air temperature, GSHPs have their greatest market share in the European Nordic region. It is worth to underline the possibility to couple GSHPs with high temperature heating terminals without a drastically reduction on efficiency. This makes GSHPs technology a feasible solution for retrofitting existing building involving only the heat generator and therefore making easier and cheaper the refurbishment [9]. The main barriers that actually slow down the spread of GSHP technology are investment and installation costs [15]. The installation cost of a GSHP system depends on the system type to be installed, the collectors type and dimensioning, the heating and cooling load of the building, the soil characteristics, the system functions (heating, cooling, DHW) and the GSHP [16]. For vertical closed-loop GSHPs, half of the investment cost is due to drilling the borehole [17]. In order to make GSHP technology more competitive on the market, several research project, among which GEOCOND [18], Cheap-GSHP [19] and GEO4CIVHIC [9], were financed by UE working on the cost-effectiveness of both installation and operation and on stakeholder awareness.

## State of the art and technological developments

Nowadays, the high initial investment cost for the equipment installation represents the main barrier for a wider diffusion of GSHPs in residential applications. To date the payback time for the investment goes from 5 to 10 years [22]. Drilling and piping costs cover a major share in the total cost of the plant, between 20% and 60% [21,22]. Although this share is highly variable, it still covers a significant percentage of the total cost; it is thus of first importance to reduce the overall cost of the GSHP, to do so an all-around operation is necessary, including optimal use of materials and technologies (i), optimal design (ii) and optimal control of the system when operating (iii). In this paragraph a brief review on the state of the art of these three elements is provided.

**i. Components' materials:** according to the ASHRAE guidelines to geothermal energy [23] the thermal resistance of the ground heat exchanger (GHE), together with the thermal conductivity of the ground, must be considered as key variables when designing a GSHP; many studies have been dedicated to decrease the thermal resistance of the GHE, acting on its components, inside and outside the pipe: Badenes et al. [24] performed a sensitivity analysis to detect the parameters that have the highest impact on the overall performance of a GSHP system, *i.e.* thermal conductivity of the pipe and of the filling grout, together with the pipe configuration. For all these three aspects, new designs have been proposed to improve the GHE's performance; a summary of these proposals is reported in Table 1. In particular, since grout aim is to ensure the heat transfer between GHE and soil, the choice of its thermal conductivity and heat capacity is crucial for the efficiency of the GSHP. Grout's thermal conductivity has been proven to be proportional to the GHE effectiveness for all the possible configurations [25], and thus inversely related to the length of the GHE and its cost. Badenes *et al*. [24] suggest a target for grout's thermal conductivity between 2.5 W/m·K and 3 W/m·K., and reported that increasing the thermal conductivity of the pipe in combination with the one of the filling grout can lead to a reduction in the total length to be drilled up to 22%, for the same pipe configuration. The implementation of these technologies should contribute to make GSHPs a more widespread and accessible option for HVAC in residential buildings.

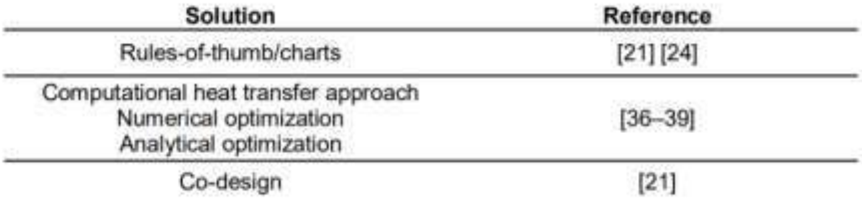
*Table 1: Summary of conventional and innovative solutions for GHEs*



| Category | Conventional solution | Innovative solution |
|---|---|---|
| Pipe materials | Metallic pipes, HDPE [22,24] | Thermally enhanced HDPE [24,26,27] |
| Grout materials | Bentonite, Cement [24,26]<br>Thermally enhanced grout [24] | CLSM [28]<br>PCM [25,26] [29] |
| Pipe configuration | Coaxial, U-tube, helicoidal [22,24,26] | Novel configurations [30–34] |

**ii. Optimal design:** the advantages of the use of the above technologies may be undone in absence of a design optimization procedure, a key step to guarantee high efficiency of the GSHP and avoid oversizing or downsizing of the system, and a consequent loose of the cost-effectiveness, in terms of both installation and operating costs [35]. To date several procedures are available to design and optimize GSHP configurations: a first distinction can be made between simplified models such as the ASHRAE approach [23], a rules-of-thumb method which does not require computer code, and detailed calculations based on precise theoretical models [36,37]. The challenge of optimal design lies in optimally determining the configuration of the plant and the heat transfer mechanisms involving boreholes and the transient response of the system. For this purpose, theoretical models have a higher chance to solve the optimal designing issue [38]. In the framework of the European project "Cheap-GSHPs" a design tool and a decision support system for the preliminary design were proposed, to be applied either with the ASHRAE simplified method or with a detailed Capacitance Resistance numerical Model [39]; aiming to make GSHP design a more expedite process, and to offer the public GSHP as an accessible technology, promoting its diffusion. A brief summary of the literature reviews this paragraph refers to is reported in Table 2:

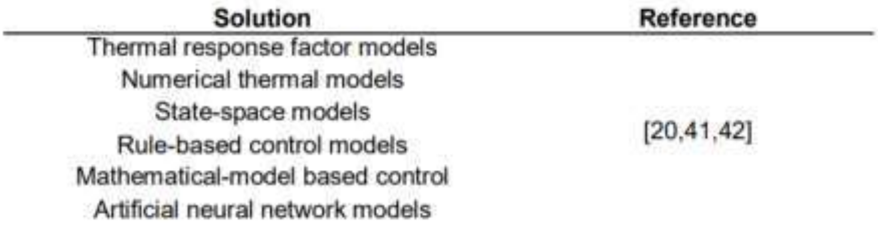
*Table 2: Classification of GHSP design approaches*



| Solution | Reference |
|---|---|
| Rules-of-thumb/charts | [21] [24] |
| Computational heat transfer approach<br>Numerical optimization<br>Analytical optimization | [36–39] |
| Co-design | [21] |

**iii. Optimal control:** usually, optimal design is followed by control optimization, *i.e.* optimising the operation time of the GSHP, considering the thermal inertia of the building. Since systems are typically sized basing on the peak load, control systems are necessary to optimise the use of the stored heat in the ground [40]. However, optimal control depends on the aim of the control itself, *i.e.* the objective of the optimization process, which could be either the GSHP efficiency, cost saving or maximizing comfort of the inhabitants. Moreover, the control method is strictly related to the approach used to model the heat transfer mechanisms in the GHE, which should properly consider both short- and long-term dynamic effects involving the soil, the boreholes and the thermal interaction between them; thus, some control models can be applied only to specific GSHP models. For this purpose, the choice of a co-design appears to be optimal, since it allows one to choose an integrated method for both optimal design and control at one time [21]. A brief summary of the main control models is reported in Table 3:

*Table.3 Classification of GHSP control approaches*



| Solution | Reference |
|---|---|
| Thermal response factor models<br>Numerical thermal models<br>State-space models<br>Rule-based control models<br>Mathematical-model based control<br>Artificial neural network models | [20,41,42] |

## Conclusion

In this paper, the state of the art and future developments on GSHP technology have been reviewed. A great potential emerges for GSHPs due to their high efficiency level. At the same time, such potential is still mostly unexpressed due to economic issues regarding drilling and installation costs. Other obstacles are the low awareness of the main stakeholder and the invasiveness of the drilling. In order to exploit GSHP potential, several EU research projects are ongoing with the aim to make this technology cheaper and more cost effective by working on more cost-effective heat pumps and more efficient borehole heat exchangers, with reduced length. Current research on borehole heat exchangers focuses mainly on more compact and easier to install heat exchangers, more efficient materials - such as thermally enhanced filling grout and thermally enhanced HDPE for tubes - and more compact drilling machines to reduce the invasiveness of installation. A great attention has to be paid also to proper design and proper control of the GSHP plant, in order to guarantee low operational costs and limit investment cost.

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