Comfort and economic criteria for selecting the optimal passive measures for the energy renovation of residential buildings in Catalonia

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ABSTRACT

This paper presents a detailed method to develop cost-optimal studies for the energy renovation of residential buildings. A realistic characterization of the building has been introduced, using measurement and survey data. The method allows improving the interaction between the occupancy and the building, and the characterization of the real state of the construction. In addition, the building simulation includes vernacular strategies of the Mediterranean regions, as for example the natural ventilation and the use of solar protection. The method presented takes part of an innovative approach: two-step optimization considering thermal comfort, energy and economic criteria. The passive optimization, the first part, is the focus of the paper and evaluates the passive measures from an economic and thermal comfort point of view. This method prioritizes the passive measures rather than the active ones, guaranteeing the thermal comfort of the users in all cases. The paper shows the results of a multi-family building built in the years 1990-2007 and located in two climates C2 and B3 (Barcelona and Tarragona). The method provides technical and economic information about a set of passive energy efficiency measures, with the objective to help to make decisions to the experts, politicians and users.

KEYWORDS

Thermal comfort; energy renovation; residential building; passive measures.

1. Introduction

Within the European regulatory framework and the agreement signed by Member States, the nations and regions have an essential role in decision-making to reach the 20/20/20 targets, applying the Energy Performance of Building Directive (EPBD, recast) [1] and the Energy Efficiency Directive [2]. As the existing residential sector is one with greater potential for energy savings, it is one which faces more barriers too. In Catalonia, the energy renovation rate is around 0.2% dwellings per year [3], which represents a low fraction of the building stock. The promotion of the energy renovation of buildings is needed, ensuring that available measures are cost-effective in a long term as well as, they improve the comfort of the users. In consequence, detailed studies are needed to consider all the aspects that have influence in the energy consumption of buildings: climate, building characteristics, user's characteristics and their behaviour, the performance of the energy systems and appliances, and their use.

In the last years, several studies were done in Spain and Catalonia with the objective to characterize the building stock and to evaluate their potential energy savings. Garrido et al. [4] made a detailed characterization of the residential building stock of Catalonia. They compare the current situation with two additional scenarios, national regulation and regional regulation, evaluating the energy savings and the economic impacts. In [5] the method applied is similar, with the difference that the scope of the study was at block of buildings level rather than a regional level. Manyes et al. [5] introduced a more accurate characterization of the systems and their use including concepts like fraction of energy demand supplied and energy poverty.

At national level, Cuchí and Sweatman [6] evaluated the residential building stock of Spain identifying the hot-spots for the energy renovation. They proposed an ambitious action plan for the deep renovation of the building sector, including political, regulatory and financial actions. The Ministry of Development of Spain [7] analysed the current building regulation to determine if it is possible to achieve the minimum energy performance requirement with cost-optimal solutions. The method used for the economic calculation is based on the global costs [8], which takes in consideration the energy costs, investment costs, replacement costs and maintenance costs over a long period (30 years).

Carlucci and Pagliano [9] optimized the building with the objective to maximize the thermal comfort of the users. They applied a method to design a new net zero energy building, analysing a set of passive measures

(insulation and windows performance). Their objective was to reduce the heating and cooling demand through the comfort improvement.

This paper presents a detailed method to develop cost-optimal studies for the energy renovation of residential buildings. A realistic characterization of the building has been introduced, using measurement and survey data to improve the interaction between the occupancy and the building, and the consideration of the real state of the construction. In addition, the building simulation includes vernacular strategies of the Mediterranean regions, as for example the natural ventilation and the use of solar protection. The thermal comfort has an important role in this study because it is one of the main criteria for the selection of the energy efficiency measures. Finally, the method introduced an innovative approach: two-step optimization considering comfort, energy and economic criteria. This optimization process prioritizes the passive measures rather than the active ones, guaranteeing the thermal comfort of the users in all measures. The method provides technical and economic information about a set of passive energy efficiency measures, with the objective to help to make decisions to the experts, politicians and users.

The paper is organized as follows; Section 2 makes an overview of the method introducing the context of the paper. Section 3 describes the method and the assumptions of the building simulation. Section 4 introduces the comfort models, and the criteria that have been used. Section 5 presents the optimization process and their results are analysed and discussed in the Section 6. Finally, the most important conclusions are outlined in the Section 7.

2. Passive optimization methodology

The present section describes a detailed process to optimize passive measures focusing on the thermal comfort and the initial investment cost. The passive optimization takes part of a complete method to develop cost-optimal studies for the energy renovation of buildings as in [10] was introduced. A brief description of the whole process is done before to detail the passive optimization basis.

The main objective of the method is providing the cost-optimal measures for the energy renovation of residential buildings, considering three main criteria: thermal comfort, primary energy use and global economic costs. The evaluation is done using dynamic building simulations, where the building and its interaction with the user is characterized in detail with TRNSYS [11]. The simulation evaluates the three main

criteria for the base case, i.e. the existing building, and for the building with different packages of energy efficiency measures (passive and active measures).

All the simulations are done in two-step optimization (Figure 1): passive and active optimization. In the first one (which is explained in detail in the present paper), the objective is to obtain optimal passive measures that provide a better thermal comfort without the use of mechanical systems and considering the required economic investment. In the second step, the active measures are applied and the primary energy consumption and the global costs have been compared to obtain the cost-optimal solution of each building typology. The economic evaluation follows the EN 15459 [8].

The multicriteria optimization is done with SDLPS [12], developed on the frame of InLab FIB (Polytechnic University of Catalonia, UPC). SDLPS is a general purpose simulation software infrastructure that makes possible to formally define the behaviour of a building and find optimal values for several building parameters and their associated impacts. The simulation model defined on SDLPS to represent the building behaviour is presented in [13]. SDLPS manages the main simulation process and TRNSYS is used as a calculus engine for the energy simulation in a co-simulation scenario.

2.1. Building stock characterization

A previous work is needed before to make the cost-optimal analysis: the building characterization. In that case, the study is focused on the region of Catalonia. An exhaustive research was done by the Catalan Housing Agency and Estudi Ramon Folch (AHC and ERF) in the framework of the MARIE project [14], in order to characterize the building stock from Catalonia defining the constructive features, the equipment and the users. Four main tasks were done for the characterization: analysis of the building regulations; review of the state of the art; analysis of statistical data; and detailed survey to complete and to validate the information collected. The main interest of the survey was to highlight aspects related to ownership of systems and appliances, together with information about the user behaviour.

After the stock characterization, the most representative building typologies were chosen, in order to carry out the cost-optimal study. The Figure 2 shows the distribution of the residential building stock in Catalonia and the selected building typologies with their corresponding climates. The climate classification follows the Spanish building code (“Código Técnico de la Edificación CTE”, [15]). The letter represents the winter severity (E is the coolest), and the number is the summer severity (3 is the warmest).

In the current paper, only the results from the building typology I are shown: block of apartments constructed during 1991-2007 in the climates B3 and C2 are presented. The representative cities of these climates are Tarragona and Barcelona.

3. Detailed building simulation

3.1. Building features

The building geometry (Figure 3) is introduced in the simulation by a multizone 3D model, using the plugin Trnsys3D for Google SketchUp [16]. Only two floors are included in the simulation, in order to simulate the building with more detail: the standard floor and the under roof floor. There are two dwellings per floor and each one is divided following two zonification criteria: night and day use, and orientation. The building model includes the external environment and their corresponding shadings.

The envelope materials are defined depending on the year of construction and according to the previous building characterization. The thermal characteristics of the envelope are described in the Table 1 and Table 2.

In addition, coldbridges are considered in façade, roof, windows and columns, using linear thermal transmittance from CE³X Handbook [17]. In TRNBuild, the thermal bridges are included using the parameters shown in the Table 3.

To finish the building characterization, a detailed model of infiltration is included [18]. The infiltration or air leakage is the unintentional introduction of outside air into a building, typically through cracks in the building envelope and through the border of doors and windows. The method considers the indoor conditions, the weather and the building conditions. In that sense, the method allows to improve the estimation of the air infiltration flow and adjust it to: a) the location of the buildings; b) the variation over the year and c) the real conditions of the building. The model of infiltration includes two effects: stack and wind effect. The indoor and outdoor temperatures and the height of the dwelling are needed for the stack effect calculation. Regarding to the wind effect, the wind velocity is used. In both cases, the tightness of the construction has to be characterized by n_{50} parameter and it has been obtained from experimental data [19, 20] ($n_{50}=7.5 \text{ h}^{-1}$ for

current building). The n_{50} represents the air changes per hour at 50 Pa and it is the result of the blower door test (common test to identify the air leakage of buildings).

3.2. Occupancy as a driver

In the simulation, the occupancy has been defined as the main driver of the use of the building (heating and cooling systems, natural ventilation, solar protections, and lighting). For that reason, one of the main objectives is to use realistic profiles of the occupants. This profile has to reproduce the variability of the real occupants and, at the same time, their behaviour has to be representative of the average occupant.

The occupancy characterization starts with the definition of the family type: how many people are in every household and their ages. This information has been obtained from the surveys done in the building characterization study [14]. The family type for the building typology I is made up of two adults and one child. The stochastic profile of each user is created from the Time Use Data survey of Spain (TUD) [21]. This survey allows knowing what the people are doing at each moment of the day. Then, applying a statistical analysis of the raw data it is possible to create an annual profile, assigning a state of each occupant: outside of home, passive at home, and active at home.

Table 4 shows which information is used in the different systems of building simulation: the occupancy, the number of occupants, or the state of each occupant.

3.2.1. Natural ventilation

The natural ventilation is considered as the main strategy to reduce the temperature during the warm season, following vernacular behaviour in Mediterranean zones. The strategy is based on the following assumption: the users use the natural ventilation for cooling the household. In the case that the natural ventilation is not enough and overheating occurs, then, the windows are closed and the cooling system is switched on. This assumption is consistent with the results obtained in the surveys of the building characterization study in [5] which shows that the cooling system is used only occasionally.

The implementation of the natural ventilation can be divided in two parts: renovation rates calculation and control of the natural ventilation. The renovation rate calculation depends on the building features and it can be: single side ventilation, cross ventilation and stack effect. The methods used are the Gids and Phaff [22] for the single side ventilation and the British Standard [23] from the cross ventilation. In some building typologies,

the effect of the courtyard has been included. The natural ventilation of the building typology I is single side ventilation with the courtyard effect, as Figure 4 shows.

The control of the natural ventilation depends on the following parameters: occupancy, operative temperature of the zone, courtyard temperature and outdoor temperature. Table 5 describes the control rules of the natural ventilation applied in the simulation model.

In general terms and if there is occupancy in the household, the natural ventilation is on when the operative temperature is between 24°C and 28°C. The Figure 5 shows that this range of temperature is comfortable for ASHRAE adaptive comfort model [24], especially, when the outdoor temperature is higher than 20°C (warm season). If the household does not have a cooling system, the control of the natural ventilation follows the same rules: the windows will remain closed until the outdoor temperature will be lower than the operative temperature, usually at night.

The building model has been configured with the option to simulate the building with natural ventilation and without natural ventilation. The objective of this configuration is to be able to distinguish the buildings that have the possibility to do natural ventilation or not due to its environment (the possibility of ventilation is not the same in a spacious village than in a compact city).

3.2.2. Solar protection

The solar protection is the second strategy used to prevent the increase of the temperature during the warm season. The idea is that when the operative temperature is lower than the comfort criteria, the solar radiation is used to heat the household. However, when the operative temperature is higher, it is needed to protect the household of the radiation to prevent the overheating. Two control strategies have been defined and they are described in Table 6: average use and optimal use of the solar protection. The main difference between the strategies is that in the optimal use the occupants have a preventive behaviour using the solar protection. It means that the users put the solar protection before to leave the household if the day will be hot, as vernacular strategy [25]. In the average use, the solar protection is only utilized when there is occupancy in the household.

3.2.3. Daylighting and artificial lighting

There is not concrete actuation regarding the use and the improvement of the daylighting. However, in order to define the use of the artificial lighting, the daylighting availability has been calculated to know when it is needed to switch on/off the lights. The artificial lighting is controlled by occupancy and daylighting.

Table 7 describes the control strategy for the artificial lighting. As a difference of the other controls presented in this work, this control takes into consideration the state of the occupants. In addition, the control has different rules depending on the hour of the day: night (from 24h to 7h) and day (from 7h to 24h).

The conversion of radiation to irradiance over the window is based on the simplified method proposed in French building regulation [26]. This is a simplified method than is useful for this application because details of daylight distribution and visual comfort are not needed.

3.2.4. Results

Figure 6 shows the results of the simulation visualizing how the occupancy is linked to the use of the building: heating and cooling system, natural ventilation, artificial lighting and solar protection. In the left column there are the results of a winter week, and on the right column there is a summer week results. The first row of graphs represents the state of the occupancy during the week: outside home, passive at home and active at home. In the second row there are the temperature profiles: outside temperature, indoor temperature and operative temperature. The third row shows the behaviour of the infiltration and the natural ventilation represented by the air renovation and its relation to the wind velocity. The fourth row of graphs represents the use of the solar protection related to the solar radiation over the windows. In the last row, the daylighting and the use of artificial lighting are shown.

Analysing the winter week of the Figure 6, it is possible to see, for example, how the temperature of 4th February is below the set point (20°C) because there are no occupants in the building and the heating system is off. The use of the solar protections (blinds) is done only at night as a thermal protection. Regarding to the air renovation, the only effect present during the winter week is the infiltration because the natural ventilation is not used.

During the summer week, the use of the natural ventilation and the solar protection has an important role in the building. The natural ventilation is active when there are occupants and the operative temperature greater than 24°C, as it could be depicted during the 17th July (right graphs of the Figure 6): at night the temperature is lower than 24°C and the natural ventilation is not used; in the morning the temperature is increasing and the

natural ventilation is active; at midday, there is no occupants in the household and the natural ventilation is off. In reference to the use of the solar protection, during the same day (17th July) it is also possible to observe that their use depends on the operative temperature, the occupancy and the solar radiation.

Finally, the use of the lighting is a result of several effects: the availability of daylighting, the occupancy, the number of occupants and the state of the occupants. For that reason there are not big differences between winter and summer despite the difference hours of daylighting.

3.3. Energy efficiency measures

In Table 8 a brief description of the passive measure evaluated in the optimization process is shown. The table includes the description of the measure, their additional benefits and their corresponding initial investment cost. The measures and their corresponding costs were defined in [14]. The investment costs include the material, their installation and the taxes (21% VAT). All the measures have been simulated both individually and in combination. The range of thickness and costs means that several configurations of each measure have been evaluated (e.g. 4, 6, 8, 10, 12 cm of thickness of EPS insulation are simulated). The current building has already insulation in the façade and in the roof, and the measures consist of including additional insulation to the building.

4. Comfort evaluation

The comfort evaluation is one of the main points of the method. The comfort models selected for the evaluation are Fanger [27] and ASHRAE adaptive model [24]. The Fanger model is used in the second step of the method, where the simulation takes in consideration mechanical systems for the heating and the cooling of the households. The ASHRAE adaptive model is used in the passive optimization because in that case, the simulations are done in free running mode (without mechanical systems). The selection of these models is based on the analysis done by Carlucci in [28, 29].

There are two classes of comfort index: short-term and long-term indices. The short-term index evaluates the comfort of a particular moment, and the long-term index evaluates the comfort along a period of time. The short-term indices of the Fanger model are Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). In the case of the ASHRAE adaptive model, the short-term index is the operative temperature (T_{op}). The comfort categories according to ASHRAE 55 are shown in the Table 9. These categories establish the comfort requirements depending on the use of the building.

The long-term index used in the study is the Long-term Percentage of Dissatisfied (LDP) developed by Carlucci [29]. LDP is a symmetric index that is able to evaluate the overheating and the overcooling of the building. The index can be applied to both comfort models: Fanger and ASHRAE adaptive model. The index is normalized over the total number of people inside the household, over all the zones and over all time corresponding to the calculation period (annual, warm or cold season)

$$LDP = \frac{\sum_{t=1}^T \sum_{z=1}^Z (p_{z,t} \cdot LD_{z,t} \cdot h_t)}{\sum_{t=1}^T \sum_{z=1}^Z (p_{z,t} \cdot h_t)} \quad (1)$$

where t is the counter of the time step of the calculation period, T is the calculation period, z is the counter for the zones of the household, Z is the total of zones of the household, $p_{z,t}$ is the zone occupation rate at certain time step, h_t is the duration of a calculation time step and $LD_{z,t}$ is the Likelihood of Dissatisfied inside a certain zone (z) at a certain time step (t). The LD depends on the comfort model and is a function of the short-term index, as in Table 10 is shown. The calculation of the Predicted Percentage of Dissatisfied (PPD) and ASHRAE Likelihood of Dissatisfied (ALD) is detailed in the Appendix.

An advantage of the LDP is that it can be calculated for different periods (annual, warm and cold season), allowing to detect the weakness of the building. This index describes the average comfort of the household over a period; however the extreme values are not represented with the LDP. Then, the index only reflects the problems of overheating or overcooling when this phenomenon is sufficiently representative of the period.

One of the main problems of the Mediterranean regions is the increase of the overheating hours due to an over-insulation of the building. In this context and with the objective to avoid overheating problems, the hours of overheating (OH) have been included for complementing the LDP index in the comfort evaluation. The criterion used says that the percentage of OH hours has to be lower than the 1% of the period calculation in order to have a comfortable building. This criteria is based on the design-overheating criteria proposed by the Chartered Institution of Buildings Services Engineers (CIBSE) [30], however, some adaptation has been done in the calculation of the index. The overheating is considered when the operative temperature of the zone is above the upper comfort temperature of the ASHRAE model, as in the equation (2) is represented.

$$P_{OH} = \frac{\sum_{t=1}^T p_t \cdot OH_t}{\sum_{t=1}^T p_t \cdot h_t} \left\{ \begin{array}{l} OH_t = 1 \Rightarrow T_{op} > T_{upper,ASH} \\ OH_t = 0 \Rightarrow T_{op} \leq T_{upper,ASH} \end{array} \right. \quad (2)$$

All the comfort calculations are included in the building simulation and therefore the comfort indices are outputs of the simulation.

4.1. Climate analysis

As explained above, the LDP index is calculated for different period of time: annual, warm and cold season. However, one of the uncertainty, as Carlucci analysed in [29], is how to define the calculation period. There are some definitions, as meteorological definition or Spanish building code (CTE) definition, where the season periods are independent of the local climate. It seems not reasonable that the winter period of the Pyrenees will be the same than the one in Barcelona. An unsuitable definition of the calculation period could have consequences in the comfort index: if the calculation period increases, the comfort index tends to improve.

The method used for identifying the calculation period is proposed by Carlucci [29] and is based on the relationship between outdoor conditions and the indoor comfort target. The objective of this approach is to define the cold period (or warm period) when the outdoor conditions start to be lower (or higher) than the comfort target. The metric used to represent the outdoor condition is the sol-air temperature [31], which is function of: dry-bulb air temperature, solar radiation incident on the building and the radiation exchange with the surroundings surfaces and the sky.

$$T_{sol-air} = T_o + \frac{\alpha \cdot I}{h_o} - \frac{\Delta q_i}{h_o} \quad (3)$$

where T_o is the dry-bulb air temperature, α is the solar absorptivity, I is the global solar irradiance on the surface, h_o is the heat transfer coefficient for radiation and convection and Δq_i is the correction due to long wave infrared radiation transferred between building surface and the sky. The first term of the equation (2) represents the effect of the solar radiation and assuming that the wall has a light coloured surface $\alpha/h_o=0.026(m^2C)/W$. The second term represents the convection and the radiation heat transfer and for vertical surfaces it could be assumed that is 0, as suggests [29, 31].

Following this approach and using the Fanger model as a comfort target, the season periods have been obtained for the climate B3 and C2 (Tarragona and Barcelona). Figure 7 shows the results obtained for both climates. The right graphs show the evolution of the outdoor temperature and the sol-air temperature over the year, represented by a 15-day average. The horizontal lines represent the comfortable temperature for the Fanger model (solid line for warm period and dot line for cold period). Then, when the sol-air temperature is higher than the cold comfort temperature, the cold season has finished (vertical dots line). The warm season starts when the sol-air temperature is higher than the warm comfort temperature (vertical solid line), and so on. The results of the calculation periods are represented on the left side of the Figure 7. In this scheme, there are three seasons: cold, warm and intermediate.

The intermediate season represents the period of the year where the sol-air temperature is in the comfort range. In that sense and in order to simplify the comfort evaluation, only two seasons have been considered and the intermediate season has been included as a cold season. These periods have been used only for the comfort evaluations, the use of the heating and cooling systems follows a free running mode (the systems are used when are needed without depending on the season).

5. Co-simulation process

This process is carried out with the co-simulation engine SDLPS and TRNSYS as a calculus engine, following the process described in Figure 8. SDLPS manages the main optimization and simulation processes: launching the building simulation with TRNSYS and collecting the outputs from the simulation. Since we want to obtain a complete characterization of the problem we use the Brute-Force approach. This approach consists on run the simulation with all the possible combinations. The factors are climate, natural ventilation, façade, roof, window and solar protection, implying about 6,000 simulations.

6. Results and discussion

The results of the passive analysis are described in the following section. The objective of the passive analysis is to obtain the optimal measures that provide the best thermal comfort with the lowest initial investment cost. For the evaluation, the building has been simulated without the use of the heating and cooling system (free running mode) and the comfort model used is the ASHRAE adaptive model. The purpose is to explore to what extend the passive measures are able to reduce the discomfort conditions without the use of the mechanical systems. Despite that the climates B3 and C2 are temperate, the heating demand is

more important than the cooling demand. In that sense, one of the objectives of the passive optimization is to evaluate in which cases the cooling system could be avoided: the summer discomfort and the hours of overheating are in the comfort ranges only with passive measures.

A general view of the results is done in the first part of this section, and then particular situations are evaluated (the effect of measures, the impact of the natural ventilation and the difference between climates).

6.1. Passive optimization: comfort .vs. investment

To develop the passive optimization, the building simulation has been run for the base case, to know the current situation, and for the different package of passive measures. The parameters evaluated are: LDP annual, LDP cold season, LDP warm season, OH hours and the initial investment cost. The climate of Barcelona and the simulations with natural ventilation are selected for the general analysis of the results.

All the graphs of the Figure 9 represent the results of the mean dwelling: each dot represents one simulation. The results of the mean dwelling are calculated as the weighted average between the results of the standard dwelling and the results of the under roof dwelling. In the graphs, the results are analysed using the different comfort parameters. The colours of the dots represent the optimal measure depending on the corresponding criteria (annual discomfort, warm season, cold season and hours of overheating)

The annual discomfort (top-left of the Figure 9) of the starting point is around the 33%. It means that, the occupants are in discomfort conditions during the 33% of the year. As the cost of the energy efficiency measures is increasing, the discomfort tends to decrease, reaching values near the comfort zone: 24% (the threshold of a comfortable building is 20%). However, the discomfort levels are quite different if the season indices are analysed (bottom of the figure). For the cold season, the current building has around 55% of discomfort, reaching a 40% with the best combination of measures. Nevertheless, the warm season discomfort index reflects comfortable conditions for all the simulations ($LDP < 9\%$). With this discomfort values during the cold season, it can be concluded that the heating demand can be reduced; however, the heating system is already needed to provide comfort condition to the users.

For a more detailed evaluation of the comfort during the warm season, it is needed to include the hours of overheating in the analysis (top-right graph). For the Barcelona's climate, the threshold of a household without overheating problems is 41 hours (1% of the warm season). The current building presents slight problems of overheating (45 hours). In that case, the effect of the different measures does not follow a linear behaviour

and depends on the measures the overheating is reduced or increased. There is a set of measures that allows reducing the hours of overheating behind the 1%. In those cases, the household has a comfortable condition during the warm season without the use of mechanical systems.

Comparing the optimal measures of the different criteria, there is a correlation between the annual and cold season criteria: the optimal measures of the annual period are consistent with the cold's ones. However, the optimal measures of the warm season and the overheating are not the same. In the case of the overheating in relation with the annual/cold season, the behaviour is, in most of the cases, the opposite: the optimal measures of the annual/cold season are the worst of the overheating analysis. Regarding to the cost of the measures, the annual and cold comfort are improved as the cost is increased, achieving maximum investment around 240€/m². However, this trend is not observed for the warm season, even the expensive measures provide more hours of overheating than the others.

6.1.1. Standard dwelling vs. under roof dwelling

Figure 10 shows the difference between the standard dwelling and the under roof dwelling. During the cold season, the under roof floor shows results slightly better than the standard floor. However, during the warm season, the situation is opposite, especially if the hours of overheating are analysed. This situation is due to the fact that the roof of the building already has insulation: during the cold season the under roof floor is protected from the cold and the solar radiation has a beneficial effect for this floor; Nevertheless, during the summer the insulation and the solar radiation play a negative role for the under roof floor, increasing the thermal discomfort and the hours of overheating in the under roof floor.

6.2. Effect of natural ventilation

The natural ventilation has been analysed with special attention. For that reason, the simulation has been done with two configurations: with natural ventilation and without natural ventilation. In this section the difference between the results are analysed, comparing their corresponding comfort indices.

Figure 11 compares the results of the two sets of simulations for the mean dwelling. The graphs of the top represent the annual discomfort and it is possible to observe that the simulations with natural ventilation are able to achieve better comfort conditions (24% in front of 25%). If focus the analyses on the hours of overheating (colour scale), the difference is more important between both configurations: the hours of overheating increase pronouncedly in the simulation without natural ventilation, having uncomfortable

conditions in all the cases (> 150 hours of overheating). On the contrary, in the simulation with natural ventilation there are some measures that reach comfortable conditions (<41 hours of overheating), as in the previous section has been shown.

The bottom graphs of the Figure 11 represent the relation between the cold season comfort and the warm season comfort. The difference between both sets of simulations is very evident. In the case of natural ventilation, the measures follow a linear behaviour: as the cold season comfort improves, the warm season comfort also is improved. However, in the simulations without natural simulation, there is a significant group of measures where the comfort index in the cold season is improved, but the warm season comfort gets worse. This pattern is also reflected with the hours of overheating.

To complete the comparison between the simulation with and without natural ventilation, the results of the standard floor and under roof floor are analysed. Figure 12 shows how the difference of the warm season index between floors is higher than the simulation with natural ventilation (Figure 10). Most of the measures present problems of overheating in both floors; however, in the standard floor the situation is slightly better.

6.3. Effect of measures

After the overview of the results, it is interesting to analyse the effect of the different measures. The results of the under roof floor are analysed because this floor has the worst behaviour during the warm season. All the graphs of the Figure 13 represent the results of all the simulations having difference colour scales, which represents the type of façade, roof, window or solar protection that is simulated in each case. The graphs want to show how affect the different measures to the discomfort during the cold season (y-axis) and the hours of overheating (x-axis). Analysing all the graphs together is possible to differentiate three groups: base case of windows (top), internal insulation in the roof (left) and external insulation of the roof (right).

Focusing on the effect on the types of façade, the increase of insulation provides always an improvement of the cold comfort, being the best option the external insulation with higher thickness (achieving a discomfort of 39% in combination with other measures). For the summer season, there are not clear patterns and the behaviour of the insulation depends on its combination with the other measures (from 29 to 64 hours of overheating).

The comfort during the summer season (hours of overheating) has a high repercussion depending on the type of roof insulation. The external insulation gives better results than the internal insulation, reducing the hours of

overheating in most of the cases (< 41 hour of overheating). For the cold season comfort, the behaviour of the different types of roof insulation is similar, being slightly better the external insulation (39% in front of 40%). Regarding to the thickness of the insulation, greater thickness provides better comfort during the cold season. However, the situation is opposite for the summer season.

The change of the windows has a direct improvement over the cold season comfort (from 44% to 39%); but, for the hours of overheating the effect is not significant. The difference between the aluminium with thermal break and the PVC framework are very small.

Finally, the effect of the solar protection has been reflected only in the overheating hours, giving better results the optimal use of the awnings.

6.4. Climate comparison

As in the Figure 7 is seen, the climate B3 is a bit hotter than the climate C2. The season periods of the discomfort index are different in both climates, being the warm season longer for the B3. The idea of this section is to analyse which is the effect of the different climates and also the definition of the season periods for the discomfort index calculations.

Figure 14 shows the comparison between the results of both climates, in term of annual and seasonal discomfort. If the analysis is focused on the top graphs, the results are coherent with the differences between climates: the annual discomfort is lower for the hottest climate (29% in front 33% in the base case) and the hours of overheating are higher also for the hottest one (57 in front of 45 hours of overheating in the base case).

On the contrary, the graphs of the cold season (bottom-left) represent the opposite behaviour: the climate C2 has lower discomfort than the B3 (55% and 58%). The reason of this situation is the difference between the lengths of the cold period. The period of the cold discomfort index in the B3 climate goes on during the 5 months and finish at the end of March. However, in the C2 climate the end of the cold season is at mid-May and its length is 6.5 months, which includes 1.5 months of intermediate season. Then, the comfort index tends to improve in the climate where the cold period is longer, as in the section 4.1 has been explained. Despite this situation, the results show how the difference between climates is lower for the expensive measures.

7. Conclusions

This paper presents a detailed method for the energy renovation of residential buildings. The paper is focused on the first step of the method, where the passive measures are evaluated from the thermal comfort and the investment cost point of view.

The method is based on detailed energy simulation of buildings developed with TRNSYS. The simulations are defined with a great detail, improving aspects of the building features, occupancy behaviour and passive strategies. The building characterization allows relating the simulation parameters with the real state of the building, making possible to include monitoring data in the constructive definition (thermal bridges and blower door tests). The occupancy has been conceived as the main element of the simulation: the occupancy is needed for the activation of the different elements of the simulation (heating and cooling system, natural ventilation, solar protections and lighting). For this purpose, realistic occupancy profiles have been developed: reproducing the variability of the real occupants and being representative of the average occupants.

Vernacular strategies from the Mediterranean climates have been included in the simulation as the main strategy to cool the household during the warm season. To that end, the control strategies of the natural ventilation and the use of solar protections have been defined with the objective to reproduce the real behaviour of the users.

The criteria to evaluate the energy efficiency measures are based on thermal comfort and economic parameters: annual discomfort, cold season discomfort, warm season discomfort, hours of overheating and initial investment cost. The objective of this evaluation is to reduce as much as possible the discomfort conditions with the minimum cost of passive measures. If the comfort is improved by passive measures, then the energy demand will be lower because the users are closer the comfort conditions (set-point).

In most of the cases, the better measures to improve the annual discomfort are the same than the better ones from the cold season discomfort. However, in some cases the situation could be opposite for the warm season. To analyse the warm season is appropriate to evaluate the warm season discomfort index and the hours of overheating because each one gives complementary information: general and extreme information of the warm period. The under roof floor reflects some overheating problems during the warm season, as a difference of the standard floor. One of the reasons for this behaviour is that the current building already has insulation, and then the roof could be over-insulated. Nevertheless, if the natural ventilation is not possible, both floors have significant problems of overheating (more than 150 hours of overheating). The comparison

between the simulation with and without natural ventilation show how an appropriate use and design of passive strategies could provide comfortable conditions without the need of mechanical systems.

Regarding to the effect of the different passive measures, in general all the measures produce an improvement in the cold season comfort (from 55% to 39%), being better the external insulation of the façade and the roof with the greatest thickness (12cm and 8cm respectively). The effect of the window change has a significant reduction of the discomfort during the cold season (from 44% to 39%), however the investment cost is high. Even though the cold season discomfort is improved and then the heating demand is reduced, the mechanical system is needed to provide comfortable conditions to the occupants.

In the warm season, the behaviour of the measures is not always positive. The internal roof insulation causes an increase of the hours of overheating, making more noticeable with the highest thickness of insulation (from 45 to 64 hours of overheating). Furthermore, the optimal use of the solar protection provides interesting improvements during the warm season, especially when there is no natural ventilation. The results have shown that the cooling system can be avoided, guaranteeing comfortable conditions during the warm period (the hours of overheating < 1% of the warm period) for some packages of measures when the building can use the natural ventilation.

Finally, in the climate comparison is possible to see that the definition of the season periods has a direct repercussion in the discomfort index. For that reason it is very important to analyse the results putting in mind all the hypothesis and boundary conditions. In addition, the results show how the same building located in different climates and environments could have a great variety of responses.

The detailed model allows adapting the simulation to real data, making possible to improve the building and the user definition. The results of the study reflect that the method proposed could be very useful for choosing the best passive energy efficiency measures depending on economic and thermal comfort parameters. The study provides technical and economic information to help making decisions of the users, experts and politicians, focusing on the energy efficiency passive measures.

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Appendix – Comfort index calculation

$$PPD = 100 - 95 \cdot e^{-0.03353PMV^4 - 0.2179PMV^2} \quad (A.1)$$

$$ALD = \frac{e^{0.008\Delta T_{op,ASH}^2 + 0.406\Delta T_{op,ASH} - 3.050}}{1 + e^{0.008\Delta T_{op,ASH}^2 + 0.406\Delta T_{op,ASH} - 3.050}} \quad (A.2)$$

where PMV is the Predicted Mean Vote [27], T_{op} is the operative temperature and the T_{ASH} is comfort temperature following the ASHARE adaptive comfort model [24].

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Figure caption

Figure 1 Overview of the two-step optimization process

Figure 2 Distribution of the residential building stock in Catalonia. Selection of the building typologies and their climate.

Figure 3 Building typology I: block of apartments 1990-2007

Figure 4 Natural ventilation of the building typology I: single side ventilation and courtyard effect

Figure 5 Adaptive comfort range following the ASHRAE 55 comfort model [24].

Figure 6 Results of the simulation for a winter (left) and summer (right) week.

Figure 7 Calculation period for the climates B3 (Tarragona) and C2 (Barcelona) based on the Fanger comfort model

Figure 8 Architecture of the co-simulation process.

Figure 9 Economic and comfort parameters of the simulation for Barcelona (C2) with natural ventilation. Top-left: Annual discomfort. Top-right: Hours of overheating. Bottom-left: Cold season discomfort. Bottom-right: Warm season discomfort.

Figure 10 Comparison between the standard floor and the under roof floor. Top-left: Cold season discomfort. Top-right: Warm season discomfort. Bottom: Hours of overheating.

Figure 11 Comparison of the simulation with natural ventilation (left) and without natural ventilation (right). Top graphs: Annual discomfort index; Bottom graphs: cold season comfort vs. warm season comfort. Colour scale: hours of overheating.

Figure 12 Comparison between the standard floor (right) and the under roof floor (left) in the simulation without natural ventilation.

Figure 13 Results of the simulation of the under roof floor in Barcelona (C2) with natural ventilation: comparison of the effect of the measures regarding to the cold season discomfort (y-axis) and the hours of overheating (x-axis), emphasising: type of façade (top left and right), type of roof (middle left and right), type of window (bottom-left) and type of solar protection (bottom-right).

Figure 14 Comparison between the results of the simulation in both climates (B3 and C2). Top-left: Annual discomfort. Top-right: Hours of overheating. Bottom-left: Cold season discomfort. Bottom-right: Warm season discomfort.

HIGHLIGHTS

- Optimal passive measures for energy renovation of residential buildings
- Comfort and economic parameters as criteria for choosing energy efficiency measures
- Building simulation including real state of the building and the user interaction
- Effect of passive strategies as natural ventilation and solar protections

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CLIMATE	Detached house	Block of apartments		
	1991-2007	<1950	1951-1980	1991-2007
	D	E	G	I
C2	x	x	x	x
B3	x		x	x
D3			x	
E1		x	x	

Climate zones from CTE 2013, current building code
C2: Barcelona B3: Tarragona D3: Lleida E1: Pre-Pyrenees

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B3

C2

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NATURAL VENTILATION

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Table 1 Thermal performance of the constructional elements

	U-value
	W/m ² K
Façade	0.625
Roof	0.546
Party wall	2.254
Internal wall	2.240
Floor framing	2.304
Sole plate	2.610

Table 2 Thermal performance of windows

		Window	
		Frame	Glazing
Composition		Aluminium without thermal break	Clear Double glazing 4/12/4
U-value	W/m ² K	5.7	2.83
g-value	-	-	0.755
Area frame/glazing	%	30	70

Table 3 Characteristics of the coldbridges

Coldbridge		I2	I3	I6	I9
Description		Pillar in a corner	Opening frame	Roof-wall junction	Cantilever-wall junction
Linear thermal conductivity Ψ	W/mK	0.22	0.32	0.65	0.85

Table 4 Use of the occupancy profile in the building simulation

	Profile information
Internal gains	Number of occupants and state
Natural ventilation	Occupancy
Solar protection	Occupancy
Artificial lighting	Occupancy, n° of occupants and state
Heating and cooling system	Occupancy

Table 5 Control strategy of the natural ventilation

General rules of control	Condition	Natural ventilation	Infiltration *	Cooling system
<i>First condition:</i>				
Occupancy	>0	YES	NO	YES
	0	NO	YES	NO
<i>If the occupancy is >0</i>				
Operative temperature (T_{op})	$T_{op} < 24^{\circ}\text{C}$	OFF	ON	OFF
	$24^{\circ}\text{C} < T_{op} < 28^{\circ}\text{C}$	ON	OFF	OFF
	$T_{op} > 28^{\circ}\text{C}$	OFF	ON	ON
<i>If the natural ventilation is OFF because $T_{op} > 28^{\circ}\text{C}$</i>				
Outdoor temperature (T_{out})	$T_{out} > T_{op}$	OFF	ON	ON
	$T_{out} < T_{op}$	ON	OFF	OFF
<i>If there is a courtyard in the household and the natural ventilation is ON</i>				
Courtyard temperature (T_c)	$T_c > T_{out}$	Courtyard effect ON	-	-
	$T_c < T_{out}$	Courtyard effect OFF	-	-

*More detail about the infiltration is described in section [¡Error! No se encuentra el origen de la referencia.](#)

Table 6 Control strategy of the solar protection.

General rules of control	Condition	Average use of solar protection	Optimal use of solar protection
Occupancy	>0	YES	YES
	0	NO	YES
Operative temperature (T_{op})	$T_{op}>25^{\circ}\text{C}$	YES	YES
	$T_{op}<25^{\circ}\text{C}$	NO	NO
Total solar radiation (R)	$R>140\text{ W/m}^2$	YES	YES
	$R<140\text{ W/m}^2$	NO	NO
Solar protection		Blind	Blind + awning

Table 7 Control strategy of the artificial lighting

General rules of control	Condition	Use of artificial lighting
Occupancy	>0	YES
	0	NO
Hour of the day	Day	YES
	Night	Only active occupancy
Irradiance (I)	I<150lux	YES
	I>200lux	NO
		YES if the occupancy is active and > 2

Table 8 Summary of the energy efficiency measures

Measure	Code	Description	Additional benefits	Initial investment costs (€/dw)
Façade insulation	F11-F15	External – EPS 4-12 cm	Reduce the thermal bridge.	8000 - 9900
	F16-F20	External – XPS 4-12 cm		8900 - 11400
	F21-F23	Air chamber – rock wool 3-10 cm		1900 - 2500
	F24-F26	Air chamber – EPS + graphite 3-10 cm		2300 - 4800
	F27-F28	Air chamber – cellulose 5-10 cm		1900 - 2200
	F29-F31	Internal – EPS 4-8 cm		3700 - 4100
	F32-F34	Internal – rock wool 4-8 cm		2700 - 2900
Roof insulation	C11-C13	Inverted – XPS 8-12 cm	-	5400 - 5800
	C14-C16	Internal – rock wool 4-8 cm		1600 - 1700
	C17-C19	Internal – EPS 4-8 cm		2100 - 2400
Window change	W11	4/16/4 Aluminium with thermal break	Reduce the air infiltration (n50=5)	8200
	W12	4/16/4 PVC		7400
Solar protection	S11	Awning	-	1200

Table 9 Definition of comfort categories according to ASHRAE 55

Category	Description	PMV	PPD	T _{op}
90%	High standard	+/- 0.5	<10	+/- 2.5
80%	Typical applications	+/- 0.85	<20	+/- 3.5

Table 10 Summary of the comfort model used in the evaluation

Comfort model	Use	Short-term index	Likelihood of Dissatisfied	Long-term index
Fanger	Mechanical heating and cooling system	PMV	$PPD=f(PMV)$	LDP_{PPD}
ASHRAE adaptive	Non-mechanical cooling system	T_{op}	$ALD=f(T_{op})$	LDP_{ALD}