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Analysis of phase change materials (PCM) for building wallboards based on the effect of environment

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ABSTRACT

One of the greatest global challenge and an indispensable requirement for sustainable development in the building sector is the reduction of greenhouse gas emissions and energy consumption. In this regards, it is necessary the development and promotion of efficient, affordable, and high impact technologies, systems, and practices. For this purpose, new technologies as phase change materials (PCM) is being studied to improve the energy efficiency and reduce energy usage in buildings.

This research aims to analyze the selection of PCM for building wallboards and roofs by comparison between multi-criteria decision methods (MCDM) and Building Energy Simulations (BES). For this purpose, a reference generic social dwelling designed in Ecuador to shelter four people in a space of 36 m^2 has been chosen to perform the study.

The MCDM COPRAS-G, TOPSIS and VIKOR are considered to accurately rank PCM alternatives, taking in consideration different material selection criteria. Moreover, BES are performed to: (a) further contrast the MCDM ranking of PCM and (b) numerically assess the thermal behavior and estimate the energy consumption with the incorporation of the PCMs.

The results found discrepancies between the MCDM and BES, demonstrating the importance that the environment variables play to appropriately assess the performance of PCM.

1. Introduction

The building sector was identified as one of the key sectors to achieve drastic greenhouse gas emission reductions. On the one hand, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the European Union (EU) [1]. While new buildings generally need less than three to five liters of heating oil per square meter per year, older buildings consumed about 25 l on average [2]. On the other hand, the U.S. Department of Energy (DOE) is advancing in building energy performance through the development and promotion of efficient, affordable, and high impact technologies, systems, and practices. The long-term goal of the building technologies office of the DOE is to reduce energy usage by 50%, compared to the 2010 baseline [3].

New technologies in buildings were introduced to improve the energy efficiency and reduce energy usage in buildings, such as thermal insulation materials applied in the building envelope or phase change materials (PCM) [4]. The use of PCM as storage medium for both cooling and heating applications appreciably reduces the energy demand of the building sector due to the high latent heat of the PCM at low temperature [5]. For this reason, the scientific community has been developing studies of PCMs building applications over the past decade [6–14]. Although, free cooling potential showed promising capabilities toward space cooling applications, it has not yet been widely commercialized and implemented in residential sectors [5].

PCM as building materials to improve the performance of heating, ventilation and air-conditioning (HVAC) systems has been implemented as an energy efficiency measure during the last decades. Rastogi et al. [15] developed a selection and performance assessment of PCM for HVAC in a room house. Turnpenny et al. [16] studied the reduction of air conditioning, using an innovative ventilation system using PCM. Parameshwaran et al. [17] presented a research about reducing air conditioning and improve energy efficiency in buildings using PCM latest generation variable volume. Sun et al. [18] conducted an economic and energy analysis in a building equipped with PCM wallboards.

The selection of the most appropriate PCM is a crucial component for the design and development of the building. Comparing candidate

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materials, ranking and choosing the best material, are one of the most important stages in the material selection process. To accomplish the selection, efforts need to be extended to identify those criteria that have a major influence in the engineering application to eliminate unsuitable alternatives and select the most appropriate choice using simple and logical methods [19,20]. The proper choice of PCM depends on factors such as their physical and thermochemical properties. In this regard, it has been demonstrated that the material selection process can be developed for a systematic and efficient approach as a multi-criteria decision-making (MCDM) problem [19,20].

In this direction, the application of material selection has been developed for PCM in energy storage. Fernandez et al. [7] conducted the selection of PCM materials for sensible thermal energy storage between 150 and 200 °C by the CES Selector software. Additionally, in 2013, Khare et al., [8] studied the selection of PCM materials to evaluate sensible heat storage between 500 and 750 °C by the software package - Granta Design's CES Selector.

In contrast, simulations which assess the thermal behavior of PCM in buildings provide essential information of the energy consumption and could improve the design process of the building. For this purpose, several numerical models have been developed to assess the thermal behavior of PCM. A review of the different models was performed by Al-Saadi et al. in [21]. According to this study, one of the most used and validated model is the finite difference algorithm. Most of the software that uses the finite difference algorithm has been validated to appropriately use the model. In this sense, the most advanced and well validated software that uses the finite difference algorithm is EnergyPlus which called the model as CondFD. Some of the studies mentioned in the review have pointed out that to accurately predict the behavior of PCM with EnergyPlus it is necessary to have an actual weather data [22] and take into account the sensitive behavior of a simulation due to parameters like air infiltration and internal thermal loads and occupancy schedules [23]. Furthermore, there are other studies that presented a good agreement between the simulated and measured data [24,25]. However, it has to be mentioned that before 2012 the EnergyPlus CondFD model gave some unreasonable results related with the heat flux and temperature distribution in horizontal placements as stated by Shrestha et al. [26]. For these reason, the EnergyPlus team developed several studies with the purpose of debugging the CondFD model based on experimental validation taking into account the ASHRAE 140 Standard [27,28]. After 2012, EnergyPlus released the version 7 of the software that currently includes the validated CondFD model. More recently, Lee et al. performed a verification of the CondFD model in version 8 against measured data [29]. The results demonstrated a maximum difference between the real and simulated results of less than 5%, which lead to the conclusion that the performance of PCM could be accurately predicted by the CondFD algorithm. More recent studies have highlighted the debilities of the CondFD model when assessing active systems such as a radiant floor [30]. The main concern when assessing these systems is that the model does not take into account the two-dimensional effect of heat conduction. However, for passive application of PCM, the CondFD model has been well validated as mention before. Even, a more recently study of Al Saadi el at., (Cita) [31] pointed out that although the CondFD model needs a revision on the associated simulation schemes for more accurate and less time consuming approaches, it shows a good agreement with EnergyPlus results for exterior and interior wall surfaces. Therefore, the CondFD model of EnergyPlus is one of the most advanced and accurate software tools to appropriately assess the passive application of PCM in buildings. In this sense, there are several studies that have assessed the thermal performance of PCM through BES. Tokuç et al. [32], performed an experimental and numerical investigation on the use of PCM in building roof in Istanbul. Other studies like the one performed by Castilho et al. [33] and Vautherot et al. [34], have performed BES in a school building and dwellings respectively, in order to assess the capabilities of PCM in reducing energy requirements. Finally, Rastogi et al. [15] compared the results of the MCDM method with the ones obtained with EnergyPlus concluding that MCDM method could be used to accurately select PCM to be applied in buildings.

Nevertheless, the aforementioned studies have ignored the effect of environmental conditions in the thermal performance of PCM whether they use MCDM methods or Building Energy Simulations (BES) as assessment tool. Given this considerations, this study aims to contrast the performance between MCDM and BES for the selection of PCM wallboards for buildings. In this study, three preference ranking-based MCDM were developed to choose the best PCM alternative. For these methods, a list of all the possible choices from the best to the worst suitable materials were obtained taking in consideration different material selection criteria. In addition, BES are performed to assess the thermal performance and estimate the energy savings of a social dwelling with the incorporation of the PCMs as wallboards. The simulation was performed in three different climatic macro-zones of Ecuador where accurate meteorological data were available. Finally, a comparison between the MCDM and simulation methods was performed to further contrast the ranking obtained in this study.

2. Materials and methods

2.1. Definition of the decision making problem for material selection

PCM utilize the latent heat of phase change to control temperatures within a specific range. The energy used to alter the phase of the material, given that the phase change temperature should be around the desired comfort room temperature and it should lead to a more stable and comfortable indoor climate [35]. For the material selection of PCM in buildings for HVAC, it is necessary to present the desired properties that should be required from PCM. The properties of the PCM are selected based on bibliography [6–15,35]

- High heat of fusion per unit volume and unit weight, and high specific heat. This is desirable to gain more effect from latent heat storage with a small as possible volume of PCMs.
- Phase change temperature suitably matched to the application. To gain the most out of PCMs, the phase change temperature must be in accordance with the climate, location in the building or the type of system where the PCM is used.
- Chemical stability and low corrosion rate.
- Harmless or nontoxic during fire or if the encapsulation is ruptured during regular use.
- Reproducible crystallization without degradation.
- Small volume change during solidification to avoid a collapse in the structure.
- High thermal conductivity to disperse heat through more rapidly, allowing the PCM to absorb or release heat at a higher rate.
- Use materials that are abundant and cheap is desired to provide a competitive advantage among manufacturers.

In order to meet all these requirements, the most important properties to consider are the heat of fusion (enthalpy difference) (Δh) and specific heat (C_p). High values are desired to keep the maximum quantity of energy and minimize the thickness of the walls. High thermal conductivity (k) to disperse heat through more rapidly. Low costs (C) are desired to provide a competitive advantage among manufacturers. The demanded melting temperature (T_m) allows the storage unit to operate in a desirable interval of working temperatures. Density (ρ) is important to reduce the thickness of the walls.

Given this consideration, nine alternatives of PCM are assessed in this study: GR25, RT25–RT30, n-Octadecane, $CaCl_2$–$6H_2O$, BioPCM-Q21, BioPCM-Q23, BioPCM-Q25, BioPCM-Q27, BioPCM-Q29. The properties of the alternatives with their quantitative data are given in Table 1.

Table 1
Material properties for the alternatives of PCM in buildings [6–14,25].

Material	Heat of fusion $[\frac{kJ}{kg}]$ (Δh)	Melting temp [°C] (T_m)	Specific heat capacity in solid state, $[\frac{kJ}{kg*K}]$ (Cp_s)	Specific heat capacity, $[\frac{kJ}{kg*K}]$ (Cp_l)	Thermal conductivity in solid state $[\frac{W}{mK}]$ (k_s)	Thermal conductivity in liquid state $[\frac{W}{mK}]$ (k_l)	Density in solid state $[\frac{kg}{m^3}]$ (ρ_s)
GR25 (1)	45,3	23,5	1,2	1,1	1,2	1	1310
RT25–RT30 (2)	232	26,6	1,41	1,8	0,19	0,18	785
***n*-Octadecane(3)**	243,5	27,7	2,14	2,66	0,19	0,148	865
$CaCl_2$–$6H_2O$ (4)	187	29,9	1,4	2,2	1,09	0,53	1710
BioPCM-Q21 (5)	225,6	21	2,73	0,83	0,21	0,19	235
BioPCM-Q23 (6)	245,5	23	1,822	0,65	0,21	0,19	235
BioPCM-Q25 (7)	236,9	25	1,813	1,031	0,21	0,19	235
BioPCM-Q27 (8)	251,3	27	1,77	0,99	0,21	0,19	235
BioPCM-Q29 (9)	260,7	29	2,22	0,271	0,21	0,19	235

2.2. Multi-criteria decision making methods

2.2.1. Criteria weighting

The criteria weights are calculated using AHP and Entropy methods combined. This methodology permits to take into account the subjective and objective weights of the criteria and to obtain more reasonable weight coefficients. The synthesis weight for the *jth* criteria is:

$$w_j = \frac{\alpha_j x \beta_j}{\sum_{j=1}^{n} \alpha_j x \beta_j} j = 1, \ldots, n \tag{1}$$

where α_j is the weight of *jth* criteria obtained via AHP method, and β_j is the weight of *jth* criteria obtained through Entropy method.

2.2.1.1. Analytic hierarchy process (AHP). The AHP method was developed by Saaty [19] in the 1970s and has been broadly investigated since then. The AHP provides a comprehensive and rational framework for structuring a problem, for representing and quantifying its elements, for relating those elements to overall goals, and evaluate the alternative solutions. In this research the AHP method issued to calculate the weights. AHP method steps can be seen in Appendix A a).

2.2.1.2. Entropy method. Entropy method indicates that a broad distribution represents more uncertainty than that of a sharply peaked one [36]. The Entropy method steps are shown in Appendix A b).

2.2.2. COPRAS-G method

COPRAS-G method [37] is a MCDM method that applies gray numbers to evaluate several alternatives of an engineering application. The gray numbers are a section of the gray theory to confront insufficient or incomplete information [37]. The COPRAS-G method uses a stepwise ranking and an evaluating procedure of the alternatives in terms of significance and utility degree. The procedure of applying COPRAS-G method is formulated in Appendix A c).

2.2.3. TOPSIS method

The TOPSIS method is a method to sort preferences by similarity to the ideal solution [38]. TOPSIS is a multiple criteria method to identify solutions from a finite set of alternatives. The basic principle is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. TOPSIS method steps can be seen in Appendix A d).

2.2.4. VIKOR method

VIKOR method solve problems of decision alternatives and criteria, assuming that compromise is acceptable for conflict resolution, the decision maker wants a solution that is the closest to the ideal, and the alternatives are evaluated according to all established criteria [7,8]. VIKOR ranks alternatives and determines the solution named compromise that is the closest to the ideal. VIKOR method is showed in Appendix A f).

2.2.5. Spearman's rank correlation coefficient

The Spearman's rank correlation coefficient measures the relation among nonlinear datasets. Its purpose is to quantify the strength of linear relationship between variables. If there are no repeated data values, a perfect Spearman correlation of + 1 or − 1 occurs when each of the variables is a perfect monotone function of the other [39]. The Spearman's rank correlation is computed by Eq. (2).

$$R_s = 1 - \frac{6 \sum d_i^2}{n(n^2-1)} \tag{2}$$

Where R_s is the Spearman's rank coefficient; d_i is the difference between ranks of each case and n is the Number of pairs of values.

2.3. Simulation methodology

Building energy simulations are performed to further contrast the obtained ranking with MCDM method and assess the thermal performance and the energy savings that PCM can achieve.

To perform the BES, EnergyPlus has been used as the calculation engine with the graphic user interface (GUI) – DesignBuilder. Regularly, the software uses the Transient Heat Conduction – CTF method to perform the simulations, which uses a single linear equation with constants coefficients to simplify the calculation of a multi-layered construction. However, this simplification is inappropriate when using PCM because it ignores the variation of the enthalpy with the temperature. Hence, Tindale [40] recommends using the Conduction Finite Difference (CondFD) algorithm that calculates the temperature-enthalpy function to fluctuate the specific heat capacity of the material in each iteration [33]. Moreover, a minimum of 12 time-steps per hour (30 in the present study) alongside the fully implicit first order difference scheme should be used for the numerical simulation. As mention in the literature review performed in the introduction, the CondFD model is one of the most advanced and validated algorithms to assess PCM in buildings.

On the other hand, since the simulation entirely depends on the definition of the temperature-enthalpy function, utter attention must be taken to properly define the enthalpy-temperature curve in DesignBuilder to accurately assess the performance of PCM [33] Therefore, Eq. (2) is used to calculate the points of the enthalpy-temperature curve for every PCM described in Table 1.

$$\Delta h = Cp^* \Delta T \tag{2}$$

Where Δh is the heat of fusion (enthalpy difference), (C_p) the specific heat for solid or liquid state and ΔT is the temperature difference. The properties used in Eq. (2) are melting temperature, heat of fusion and specific heat capacity (Table 1). For each material, the points of the enthalpy-temperature curve where obtained in three sections: (a) Solid

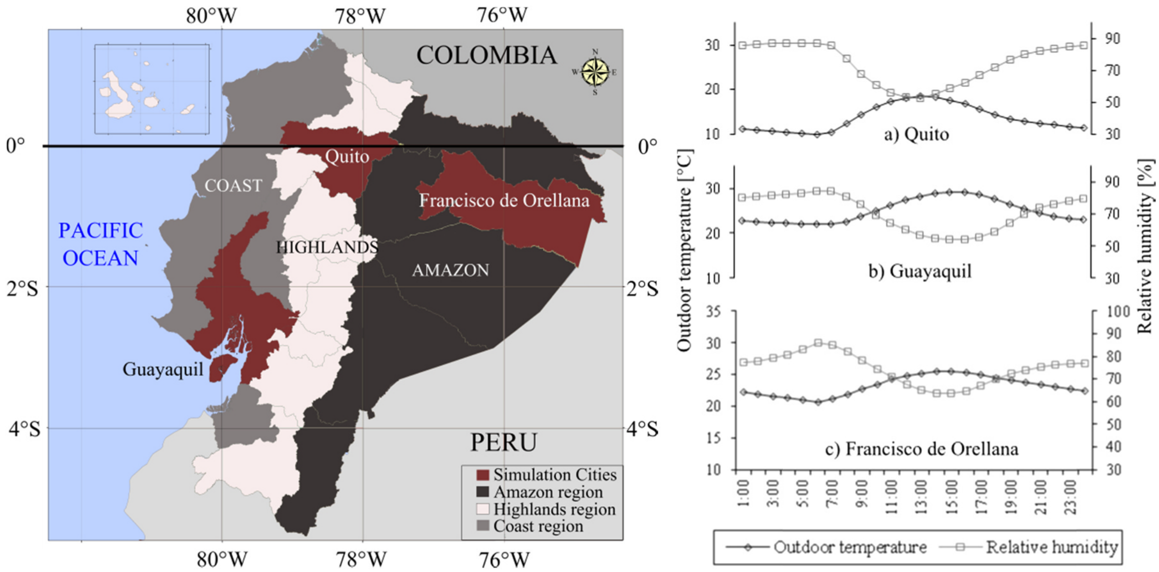


Fig. 1. Representative cities for each climatic macro-zone Coast, Highlands and Amazon of Ecuador. Quito for the Highland region with a cold and semi-humid weather, Guayaquil for the Coast region with a warm and humid weather and c) Francisco de Orellana for the Amazon region with a warm and very humid weather. On the right, distribution of the outdoor temperature and relative humidity in the different cities for a typical day.

state, where Eq. (1) is used to define the enthalpy at the melting temperature using the (C_p) at solid state and considering that enthalpy is zero when the temperature is zero. (b) Liquid state, where Eq. (1) is used to define the temperature at the heat of fusion when the material entirely becomes liquid. (c) During the phase change, a variation of 2 °C from the melting point to the heat of fusion temperature is assumed.

2.4. Simulation cases

The aim of the simulation is to numerically assess the thermal behavior and estimate the energy consumption of a social dwelling with the incorporation of PCM in wallboards and rooftops in three different climatic macro-zones of Ecuador of which there are accurate meteorological data. Ecuador has three macro-zones which are Coast, Highlands and Amazon regions as can be seen in Fig. 1. These macro-zones present different climatic conditions that are controlled by the height above sea level of each region. The Coast region has a rainy and a dry season, with mean temperatures that oscillates between 36 and 23 °C, respectively. The highland region has a rainy-cold and a dry season with mean daily temperatures between 13 and 18 °C respectively [41]. The amazon region presents rains throughout the year and its mean temperature is 25 °C.

The relative humidity in each region varies according to the topography, which generates several microclimates. Therefore, is not possible to standardize a relative humidity for each region. For this reason, three cities that represent each climatic macro-zone of Ecuador are chosen for this study. These cities are (a) Quito for the Highland region with a cold and semi-humid weather (Fig. 1-a), (b) Guayaquil for the Coast region with a warm and humid weather (Fig. 1-b), and (c) Francisco de Orellana for the Amazon region with a warm and very humid weather. (Fig. 1-c).

It has to be mentioned that in Ecuador, the hourly temperature oscillation is more representative than the daily or monthly oscillation. For instance, in Quito the hourly oscillation is around 9 °C whereas the daily and monthly temperature oscillation is 4 and 1.5 °C respectively. This behavior is similar in all the climatic zones of Ecuador. Therefore, the results described in this study will be considered as the mean value of the hourly data represented in one day as in Fig. 2. The minimum, maximum and mean temperatures, relative humidity and global radiation are presented in Appendix B

The reference building is a generic social dwelling designed by the

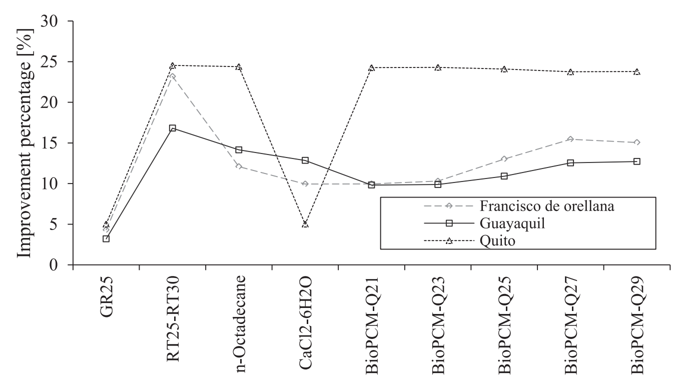


Fig. 2. Improvement percentage of the PCM materials for the cities of Quito, Francisco de Orellana y Guayaquil.

Ministry of Urban Development and Housing (MIDUVI) of Ecuador, which is given to the beneficiaries of the housing allowance. The social dwelling is designed to shelter four people in a space of 36 m^2 (Appendix C) which represents an occupancy density of 0.111 people/ m^2. For simulation purposes, this occupancy density is considered as continuous throughout the day and night generating an internal thermal gain of 4 W/m^2 including lighting and equipment [42] To simplify the calculation, a single zone is considered in the simulation.

On the other hand, despite the different climatic macro-zones of Ecuador, this dwelling has been built in every zone of the country, with the same construction materials (concrete for walls and metal sheet roofing). Depending on the region, the materials selection as well as the design has been performed neglecting the effects of the environment conditions. Referring to the materials, they do not prevent the building for radiation heat gains in the warmest regions. In addition, solar protection systems were not considered from the design perspective. In contrast, the material does not keep the internal heat gains during night which is important in the coldest regions. Consequently, as demonstrated by several researches, the conditions within the building are inappropriate to ensure healthy [43] and comfortable conditions inside the building [44] with the additional shortcoming of being energetically inefficient [45].

For this reason, the present study has the additional purpose of suggest an improvement to these buildings by using PCM on the wallboards (Appendix D). The envelope materials improvement is only considered for the walls and roof, because, those elements of the buildings present the highest thermal gains and losses during the day [46]. With these configurations, the thermal resistance for the envelope materials is presented in Appendix E.

Four different tests are performed in order to assess the thermal performance of the PCM through BES: (a) an operative temperature distribution on one year span, (b) a comparison between the outdoor and the indoor operative temperature, (c) an energy balance of the envelope materials and (d) a comparison between the inner and outer surfaces temperatures. These analyses are performed by comparing the reference case with the improved case.

In addition, to contrast the obtained ranking with the MCDM method, a comparison between the estimated energy savings achieved by the PCM in the different regions of Ecuador is calculated using Eq. (3) [47]. This equation compares the energy consumption between a reference case and the improved cases. Thus, an HVAC system is included in the simulations to obtain a result of the annual energy demand for every case. However, for the simulation to be comparable, a preliminary parametric simulation is conducted to determine the temperature and relative humidity set points that obtain zero discomfort hours for all regions (Table 2). This analysis demonstrated that heating, cooling as well as a dehumidification systems are needed in Quito to assure zero discomfort hours due to the temperature variation between day and night (i.e. approximately 9 °C). In contrast, in the warm and humid climate of Guayaquil and Francisco de Orellana, there is only need of cooling and dehumidification due to its elevated temperature and relative humidity during day and night. It is important to mention that the improvement percentage resulting from the heating and cooling demand simulation are an estimation of the relative behavior of each PCM.

$$Improvement\ percentage = 100 * \frac{Referece\ case\ consumption - Improved\ cases\ consumption}{Reference\ case\ consumption} \quad (3)$$

3. Results

3.1. Results MCDM

3.1.1. Criteria weighting

To obtain the criteria weighting, the comparison among properties has been performed for every alternative as showed in Table 1. The properties identification appears as (Δh), (T_m), (Cp_s), (Cp_l), (k_s), (k_l), and (ρ_s). The criteria weighting was firstly performed by the AHP method to obtain the subjective weights of different evaluation criteria. After the decision hierarchy for the problem was designed, the criteria was compared pairwise based on the experience of the authors. Appendix F shows the scale of relative importance used in the AHP method.

The comparison among criteria for balanced scales AHP method is shown in Appendix G. The most important criteria to generate the matrix was considered (Δh); moderate less important was considered (T_m), (Cp_s), (Cp_l), (k_s) and (k_l); extremely less important was taken (ρ_s). The value of the consistency index ($CI =$ 0,010) and the consistency ratio (CR=0,009), which are lower than the limit of 0.1, indicate that the results are consistent. Furthermore, the decision matrix generated for a PCM in buildings which take into account the importance of each criteria are illustrated in Appendix H. At the final step, the compromised weights of the criteria (w_j) were calculated using Eq. (1). In Appendix I, the weight coefficient of every criterion was determined based on the results of AHP and Entropy methods. On one hand, the most representative values were (Δh) 44%, (T_m) 19.1% and (Cp_s) 17.8%. On the other hand, 19.1% of the overall weight is distributed in (Cp_l), (k_s), (k_l), and (ρ_s).

Table 2
HVAC system set-points that ensure zero disconfort hours for the cities of Quito, Guayaquil and Francisco de Orellana.

	Heating [°C]	Cooling [°C]	Relative humidity [%]
Quito	20.5	26,0	35,0
Guayaquil	–	26,0	45,0
Francisco de Orellana	–	26,0	45,0

3.1.2. COPRAS-G method

The related decision matrix is first developed from the gray numbers applied in COPRAS-G as illustrated in Appendix J. The normalized matrix made of gray numbers for the COPRAS-G method is shown in Appendix K. Appendix L shows the priority values (Qi) and quantitative utility (Ui) values for the candidate alternatives of the PCM for buildings and the ranking of the alternative material of the method as 3–8-9-5-6–7-4-2-1. For this results n-Octadecane and BioPCM-Q27 obtained the first and second ranks respectively, in contrast GR25 resulted to be the worst choice.

3.1.3. TOPSIS method

The decision matrix given in Table 1 was normalized for the application of the TOPSIS method and this was multiplied by the obtained compromised weights. The weighted and normalized decision matrix V_{ij} for the material alternatives of a PCM for buildings are illustrated in Appendix M. The ideal and nadir ideal solutions are presented in Appendix N. The distances from the ideal (S_i^+) and nadir ideal solutions (S_i^-), the relative closeness to the ideal solution (C_i) and the ranking is shown in Appendix O. The rankings of the alternative materials are 3–8-5–7-2–6-9-4-1. For TOPSIS method, n-Octadecane and BioPCM-Q27 obtained the first and second ranks PCM in buildings. GR25 has the last rank and RT25-RT30 is the second to last rank.

3.1.4. VIKOR method

The values of E_i, F_i and P_i were calculated as shown in Appendix P. The material with the lowest P_i value was given the best rank. According to the ranking of alternatives by the VIKOR method presented in Appendix P, the ranking materials for a PCM for buildings is 9-3-8-4-2–7-6-5-1 which indicates that BioPCM-Q29 and n-Octadecane obtain the first and second ranks for the PCM for buildings. On the other hand, GR25 has the last rank and PCM-Q25 is the second last rank.

3.2. Simulation results

In order to understand the effect of the climate conditions in the thermal behavior of the PCM, four tests were performed for all PCM in the present study. The results showed that every material presented an improvement compared with the reference case. However, only the results of the RT25-RT30 PCM are presented in this paper as sample material due to its superior performance.

3.2.1. Indoor operative temperature distribution

The indoor operative temperature distribution test was performed to compare the indoor thermal behavior between the reference and the improved case. In Quito and Francisco de Orellana there is a scattered distribution of the operative temperatures with no significant differences between the reference and PCM case as shown in Appendix Q. Conversely, in Guayaquil the PCM material clearly maintains the majority of the hours below 30 °C while the reference case is always above this figure. This is related with the high solar radiation in Guayaquil where the metal roofing system is ineffective to protect the building from the solar heat gains.

3.2.2. Comparison between indoor and outdoor temperature

This test was performed to contrast the variation of outdoor and indoor temperature for the reference and PCM cases on an hourly basis. It is notable that the temperature fluctuation between day and night is elevated in Quito and Guayaquil (i.e. 7 °C). On the contrary, in Francisco de Orellana the temperature difference between day and night is only about 5 °C (Appendix R). This behavior is evident in the reference case where the indoor temperature follows the distribution of the outdoor temperature. Contrariwise, the PCM case maintains a uniform distribution during the day which in some cases acts as a detrimental side effect. In Guayaquil for instance, the PCM material maintains the indoor temperature around 28 °C whereas the reference case maintains it 1 °C less during the morning. During the afternoon when the outdoor temperature reaches its highest peak, the PCM material maintains the temperature 2 °C below the one obtained by the reference case.

3.2.3. Envelope energy balance

The envelope energy balance test shows the energy gains and losses of the envelope to comprehend the thermal performance of the PCM as wallboard compared with the reference case material. In Quito there is no difference between the energy balance of the PCM and the reference case. On the contrary, in Guayaquil and Francisco de Orellana the figures show that there are less energy losses from 1:00 to 11:00 with the PCM in the wall as demonstrated in Appendix S. Nevertheless, as discussed before this behavior is inappropriate for this kind of climate since more energy losses through the envelope are preferable to maintain a comfortable temperature within the building. Further, the PCM does not allow as much energy gains as the reference case during the afternoon which is desirable since this is the critical period of time.

3.2.4. Inner and outer surface temperatures

To utterly understand the effect of the climate conditions in the performance of the PCM materials, the energy balance test is complemented with the inner and outer surface temperatures of the reference and the PCM case (Appendix T)

Assessing the walls and roof in Quito, is immediately clear that the walls are a key element where the PCM can improve the thermal behavior of the envelope. During the night, the PCM maintains an inner surface temperature 2 °C higher than the outer surface which will lead to a better comfort sensation due to the radiant temperature of the wall. During the day, when the operative temperature could reach discomfort ranges, the PCM maintains the inner surface temperature lower temperature than the outer surface. However, the differences between the temperature of the inner surface with and without PCM are less than 1 °C.

On the contrary, in Guayaquil and Francisco de Orellana the inner and outer surface temperature differences between the reference and the PCM are more notable. The inner surface temperature using PCM is nearly constant during the day and night. Then again, this demonstrates a possible problem within the building since the thermal sensation of a warm wall could cause discomfort. During night, thermal losses throughout the envelope are preferable, so in the morning the inner surface generates a cool thermal sensation. Nonetheless, this effect is diminished because the inner surface temperature is higher than the outer surface. On the contrary, the PCM has a positive outcome during the day since the inner temperature is lower than the outer temperature.

4. Discussion

The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy [1,2]. Therefore, if targets for greenhouse gas emissions reduction are to be met, it is clear that decision-makers must tackle emissions from the building sector. In this regards PCM appears as one of the key element to reduce energy usage and greenhouse gas emissions in buildings.

This study developed MCDM methods and BES to assess the suitability of developing PCM for building wallboards in Ecuador. In doing so, it contributes towards the literature surrounding MCDM and BES studies with the novelty and added credibility of the use of expert validation. It is the first specific study to assess effect of the environment on the PCM selection. This approach can aid decision makers in moving towards to a regulation policy which improves the energy savings in Ecuadorian buildings between 10% and 25% as is given in Fig. 2. The method could also be applied more widely with appropriate adaptation, so could contribute for energy efficiency in buildings around the world.

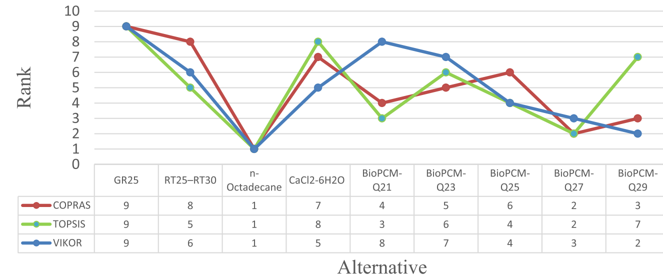


Fig. 3. Rank materials vs. alternative Material for a PCM in buildings. The value of 1 indicate the best material alternative, meanwhile 9 indicate the last rank alternative.

MCDM are an important tool to recognize and identify the best alternative in a bunch of several of them. These methods can adapt to different sort of environments and conditions that would affect the final result and that is why these approaches are applied in different areas of science, engineering and management [19,20]. The adoption of several MCDM and the correlation between the results shown as MCDM has a powerful tool for material selection [19,20].

In this case, we take advantage of MCDM in order to know the best alternative for the use of PCM in buildings. Fig. 3 shows the overall rank of each MCDM for the different material alternatives. According to the MCDM COPRAS-G, VIKOR, and TOPSIS, the best material alternative are n-Octadecane and BioPCM-Q29, because they have highest values of the most important properties for a PCM for buildings. They have a high heat of fusion (Δh) 44%, low melting temperature (T_m) 19,1% and high specific heat capacity in solid state (Cp_s) 17,8%. In addition, GR25 was presented on the last rank alternatives for this three MCDMs.

The Spearman's correlation coefficients for a PCM for buildings are presented in Table 3. This table represent the substantial agreement among MCDM methods. The magnitude of this parameter for a PCM exceeds 0,59 for the relation of COPRAS-G, TOPSIS and VIKOR. Moreover, the correlation has a value of 0,7 between TOPSIS and the other two methods.

In order to contrast the obtained ranking with the MCDM method, a BES was performed considering the social dwelling as conditioned. In addition, this analysis is used to establish the phase change material that obtained the highest energy savings in every climatic macro-zone of Ecuador. As shown in Figure 13, RT25-RT30 is the material that achieved the greatest energy savings compared with the reference case for Guayaquil and Francisco de Orellana. However, compared with the MCDM method, this material is ranked between 5 and 8.

On the other hand, all PCM resulted in good energy savings in Quito (around 25% of improvement), except for GR25 and $CaCl_2$–$6H_20$. The GR25 PCM has the lower improvement percentage in every climatic zone, which is directly related with the ranking obtained with the

Table 3
Spearman's correlation indexes.

	TOPSIS	COPRAS-G
VIKOR	0,700	0,592
COPRAS-G	0,700	–

MCDM method. On the contrary, the n-Octadecane which is ranked first in the MCDM method is not the best material according to the simulation results.

The discrepancies between the MCDM and the simulation method demonstrate the importance that the environment variables plays to appropriately assess the performance of PCM. In addition, these results are explained by the thermal behavior assessment previously made in this study. For example, in a warm and humid place, using PCM during night is rather detrimental because the dwelling cannot evacuate all the heat gained during the day, which generate a higher demand of refrigeration. These kinds of considerations are overlooked when evaluating PCM with the MCDM method, which generates the discrepancies in the results.

4.1. Literature comparison

The overriding consensus in the researches that uses MCDM method to select PCM performed by Fernandez et al. [7] and Khare et al. [8], is that PCM should have a high heat of fusion (Δh), an adequate melting temperature and high specific heat capacity in solid state (Cp_s) and liquid state (Cp_l). In either case, environmental or operational conditions have been overlooked.

Rastogi et al. [15] developed a selection of materials in PCM for HVAC using figures of merit to numerically identify the relative performance of participating candidates. Furthermore, they used TOPSIS method for the selection of a list of alternatives. The principal criteria for the material selection were the phase change temperature, density, heat of fusion, specific heat capacity and thermal conductivity. In addition, the top ranked PCMs were selected for a simulation study using open source software PCMs Express based on finite difference mathematical model and enthalpy method for simulation.

In case of Rastogi et al. [15] the simulation were executed for an unconditioned building in a span of a year (8670 h), as is in our study. To maintain the human comfort temperature (21–26 °C), a conventional system of brick masonry walls, concrete cement roof and ceiling compared with the PCM was used, whereas, in our study we assessed the performance of a conventional brick masonry for walls and a metal roofing sheet improved with PCM in three different climatic macro-zones of Ecuador. The thickness of each wallboard is considered to be 15 mm, while we considered a 10 cm brick with a 1 cm PCM for the wallboard and roof. The other boundary conditions being the night ventilation, window in outer wall (occupying 40% area of the total wall) and equivalent radiator output of 50 W/m^2. In our study, we consider natural ventilation in the unconditioned case and a HVAC and dehumidification systems for the conditioned case in every climatic macro-zone. Furthermore, 10% of window to wall ratio was used as the reference case and the internal gains value was considered as a typical dwelling (4 W/m^2).

Even though the results of Rastogi et al. [15] showed a good agreement between the MCDM and simulations methods, it did not take into account the effect of the environment to assess the performance of PCM. In fact, there is no clear information about the climate conditions surrounding the assessed building. However, taking into account that they only analyses the operative temperature of an air-conditioned building, the results are similar to the ones obtained in Quito in the present study. This means that the thermal performance is appropriate for the entire day in cold and semi-humid climates.

Nevertheless, as demonstrated in the present study, in warm climates, PCM could perform inappropriately during night. This fact demonstrates the discrepancies between both methods. Furthermore, it proves the importance of assessing the impact of the environmental variables in the evaluation of PCM.

Likewise, other studies have performed BES in order to assess the performance of PCM. Castilho et al. [33] evaluated PCM in a school building with large thermal gains due to computational equipment (i.e. 28 W/m^2). The PCM was incorporated in the roof and walls of the rooms as in our study. Moreover, they performed the assessment considering the rooms with and without HVAC systems. Although, they performed an hourly assessment of the indoor temperature performance, they neglected the effect of the surface temperature and the thermal gains and losses of the wallboards. In our study, these parameters are claimed to have an impact on the thermal perception of the occupants. On the other hand, Vautherot et al. [34] performed BES to assess the energy requirements and discomfort hours by using different PCM in a dwelling. They compare the energy requirements for the HVAC system with the discomfort hours associated with every PCM, whereas we compared the energy requirements achieving zero discomfort hours in order to the simulation to be comparable. Furthermore, they overpass the fact that the hourly variation of the indoor temperature affects the thermal comfort of the occupants. However, our simulation results are in some level of agreement with those obtained by them regarding the fact that the appropriate selection of HVAC system's set points affects the thermal performance of the PCM.

5. Conclusions and recommendations

In this paper the material selection problem for a PCM for buildings was solved utilizing a decision model. The model includes the COPRAS-G, OCRA, ARAS, VIKOR and TOPSIS methods. According to the results of COPRAS, VIKOR and TOPSIS methods, the best choices were n-Octadecane and BioPCM-Q29, because they have highest values of the most important criteria for a PCM for wallboards in buildings.

The BES were carried out to contrast the results of the MCDM method which led to the conclusion that a thermal assessment of the PCM is necessary to better understand the behavior of the materials during the operation with the effect of the environmental conditions as well as the indoor conditions. This fact is clearly demonstrated by the simulation results. Depending on the climate conditions, PCM has different thermal behavior that could be an improvement in some cases and disadvantageous in others. For this reason an extensive assessment of the climate condition should be made before actually apply this strategy in unconditioned buildings.

In addition, PCM present a good thermal behavior during day and night in cold places, especially at night, when the PCM maintain the indoor temperature on a constant comfortable temperature. Furthermore, the inner surface temperature provides a warm thermal sensation due to the radiant effect of the wall. On the other hand, the thermal performance during day and night is different in warm and humid places. During the day, the PCM prevents the heat evacuation of the building which in fact generates a warmer space compared with the reference building. Overnight, the PCM does not allow the inner surface to cool down, which generates a warmer wall than the reference case that could cause discomfort. Nevertheless, PCM present a good performance during afternoon keeping the indoor temperature below the outdoor temperature. For these reasons, in the case of unconditioned buildings, PCM are preferable to be installed in buildings located in cold places since it has a good performance throughout the entire day. For unconditioned buildings located in warm places, PCM has a better performance during afternoon. On the other hand, if social dwellings were designed to use HVAC systems, it is clear that PCM could represent an improvement in all climatic macro zones of Ecuador. In this sense, the RT25-RT30 PCM has the better performance among all assessed PCM in this study.

Furthermore, this methodology could also be used with appropriate adaptation to other places of the world and it could contribute for energy efficiency and greenhouse mitigation in buildings around the world.

Finally, in relation with the MCDM it is necessary to find an environmental variable that can fulfill a correlation with the BES model.

Acknowledgements

The authors of this research acknowledge to the Secretaría Nacional de Planificación y Desarrollo (SENPLADES) for financing the execution of the present research. This work was sponsored by the Prometeo project of the Secretaria de Educación Superior, Ciencia, Tecnología e Innovación (SENESCYT) held in the Republic of Ecuador. The information necessary to complete this work was given by the Ministerio de Electricidad y Energía Renovable (MEER) of Ecuador

Appendix A

See Fig. A1

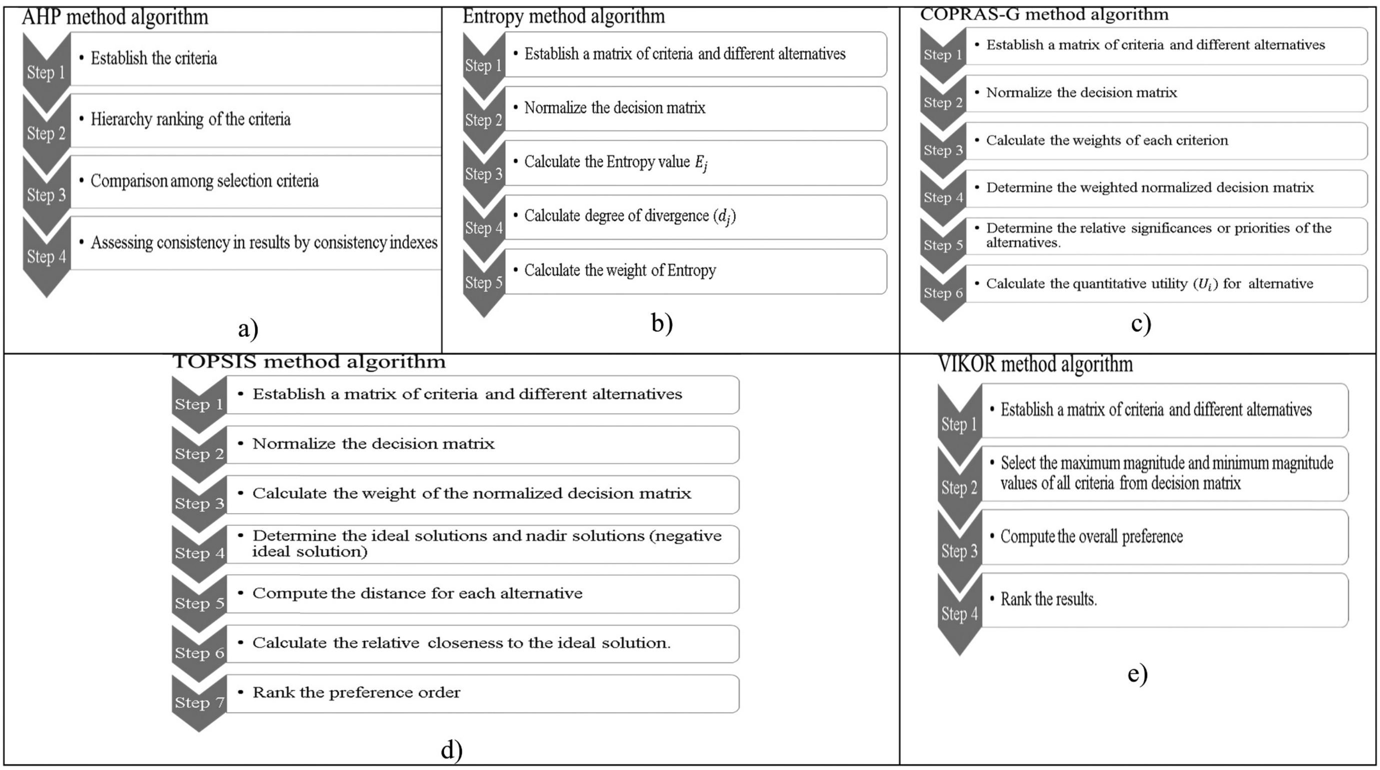


Fig. A1. Description of a) AHP method algorithm, b) Entropy method algorithm, c) COPRAS-G method algorithm, d) TOPSIS method algorithm, f) VIKOR method algorithm.

Appendix B

See Table B1

Table B1
Weather variables (temperature, relative humidity and radiation) for the simulation cities of highlands-Quito, Coast- Guayaquil and Amazon – Francisco de Orellana.

		Temperature [°C]	Relative humidity [%]	Radiation
Highland - Quito	Min	4	20.0	0.0
	Max	25.7	100.0	1066.0
	Mean	13.7	74.5	115.9
Coast - Guayaquil	Min	18.9	33.0	0.0
	Max	34.4	100.0	987.0
	Mean	25.0	71.1	75.6
Amazon – Francisco de Orellana	Min	16.6	42.0	0.0
	Max	30.9	100.0	914.0
	Mean	23.2	74.6	74.0

Appendix C

See Fig. C1

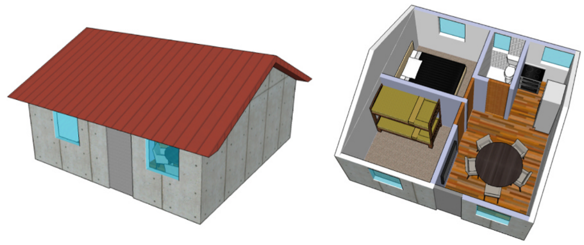


Fig. C1. Schema of the generic Ecuadorian social dwelling designed by MIDUVI of Ecuador, The social dwelling was designed to shelter four people in a space of 36 m^2. The dwelling has two bedrooms, one bathroom and a kitchen-dinning-living shared room.

Appendix D

See Fig. D1

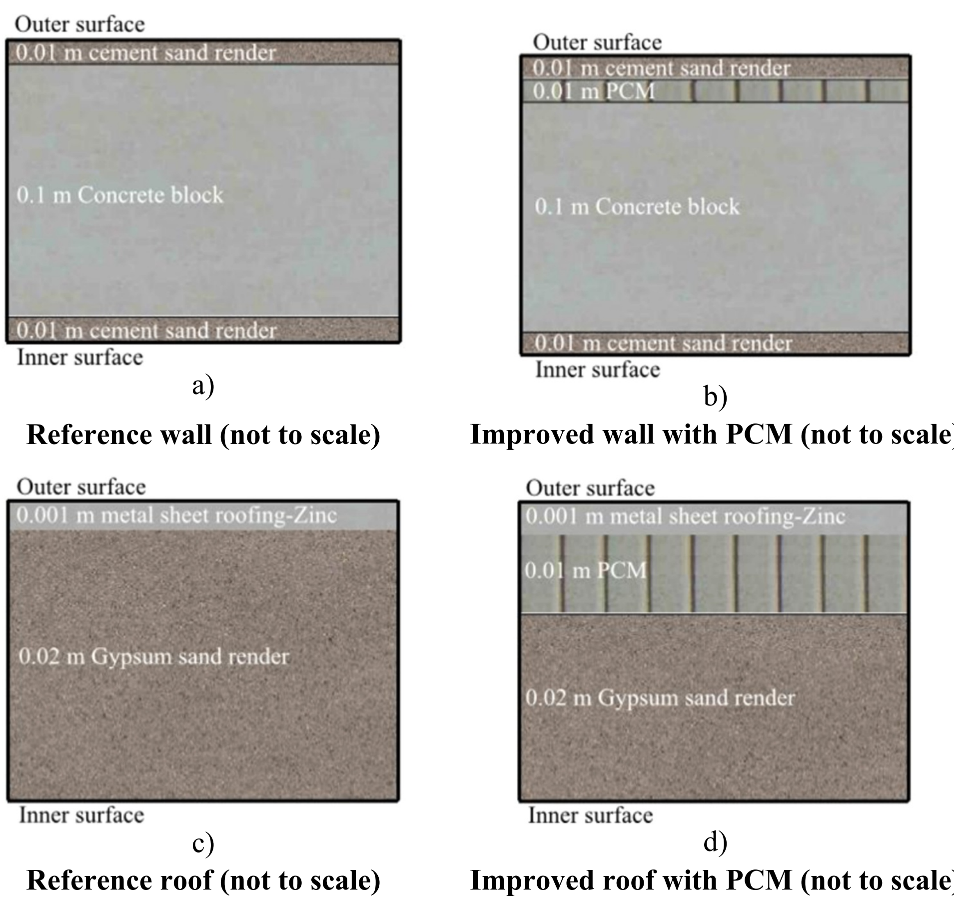


Fig. D1. Construction configuration for reference case and the improved case with the PCM a) Reference wall, b) Improved wall with PCM, c) reference roof, d) improved roof with PCM.

Appendix E

See Table E1

Table E1
Thermal resistance properties for wall and roof materials.

Material	Walls - U [W/m^2 K]	Roof - U [W/m^2 K]
Reference	2,51	6,06
GR-25	2,45	5,77
RT25-RT30	2,20	4,53
n-Octadecane	2,17	4,40
$CaCl_2$–$6H_2O$	2,41	5,50
BioPCM-Q21	3,31	4,61
BioPCM-Q23	3,31	4,65
BioPCM-Q25	3,31	4,65
BioPCM-Q27	3,31	4,65
BioPCM-Q29	3,31	4,65

Appendix F

See Table F1

Table F1
Scale of relative importance for the AHP method.

Definition	Intensity of importance
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
Intermediate importance	2, 4, 6, 8

Appendix G

See Table G1

Table G1
Comparison among criteria of materials for PCM in AHP method.

(Δh)	(T_m)	(Cp_s)	(Cp_l)	(k_s)	(k_l)	(ρ_s)
1	3	3	3	3	3	9
0,333	1	1	1	1	1	7
0,333	1	1	1	1	1	7
0,333	1	1	1	1	1	7
0,333	1	1	1	1	1	7
0,333	1	1	1	1	1	7
0,111	0,143	0,143	0,143	0,143	0,143	1

Appendix H

See Table H1

Table H1
Normalized decision matrix P_{ij} for AHP method.

Material	(Δh)	(T_m)	(Cp_s)	(Cp_l)	(k_s)	(k_l)	(ρ_s)
1	0,068	0,301	0,212	0,249	0,702	0,812	0,523
2	0,346	0,341	0,249	0,407	0,111	0,146	0,313
3	0,364	0,355	0,378	0,601	0,111	0,120	0,345
4	0,279	0,383	0,247	0,497	0,638	0,430	0,682
5	0,337	0,269	0,482	0,188	0,123	0,154	0,094
6	0,367	0,295	0,322	0,147	0,123	0,154	0,094
7	0,354	0,320	0,320	0,233	0,123	0,154	0,094
8	0,375	0,346	0,312	0,224	0,123	0,154	0,094
9	0,389	0,372	0,392	0,061	0,123	0,154	0,094

Appendix I

See Table I1

Table I1
Criteria weighting by the AHP (α_j) and balanced scales entropy (β_j), methods and compromised weighting (w_j) methods.

	(Δh)	(T_m)	(Cp_s)	(Cp_l)	(k_s)	(k_l)	(ρ_s)
α_j	0,345	0,127	0,127	0,127	0,127	0,127	0,021
β_j	0,214	0,253	0,235	0,143	0,027	0,073	0,057
w_j	0,440	0,191	0,178	0,108	0,020	0,055	0,007

Appendix J

See Table J1

Table J1
Decision matrix of COPRAS-G method.

Material	(Δh)		(T_m)		(Cp_s)		(Cp_l)		(k_s)		(k_l)		(ρ_s)	
1	40,77	49,83	21,15	25,85	1,08	1,32	0,99	1,21	1,08	1,32	0,9	1,1	1179	1441
2	208,8	255,2	23,94	29,26	1,269	1,551	1,62	1,98	0,171	0,209	0,162	0,198	706,5	863,5
3	219,15	267,85	24,93	30,47	1,926	2,354	2,394	2,926	0,171	0,209	0,1332	0,1628	778,5	951,5
4	168,3	205,7	26,91	32,89	1,26	1,54	1,98	2,42	0,981	1,199	0,477	0,583	1539	1881
5	203,04	248,16	18,9	23,1	2,457	3,003	0,747	0,913	0,189	0,231	0,171	0,209	211,5	258,5
6	220,95	270,05	20,7	25,3	1,6398	2,0042	0585	0,715	0,189	0,231	0,171	0,209	211,5	258,5
7	213,21	260,59	22,5	27,5	1,6317	1,9943	0,928	1,134	0,189	0,231	0,171	0,209	211,5	258,5
8	226,17	276,43	24,3	29,7	1,593	1,947	0,891	1,089	0,189	0,231	0,171	0,209	211,5	258,5
9	234,63	286,77	26,1	31,9	1,998	2,442	0,244	0,298	0,189	0,231	0,171	0,209	211,5	258,5

Appendix K

See Table K1

Table K1
Normalized matrix made of gray numbers.

Material	(Δh)		(T_m)		(Cp_s)		(Cp_l)		(k_s)		(k_l)		(ρ_s)	
1	0,021	0,026	0,091	0,111	0,065	0,080	0,086	0,105	0,290	0,355	0,321	0,392	0,448	0,548
2	0,108	0,132	0,103	0,126	0,077	0,094	0,140	0,172	0,046	0,056	0,058	0,071	0,268	0,328
3	0,114	0,139	0,107	0,131	0,117	0,143	0,208	0,254	0,046	0,056	0,047	0,058	0,296	0,362
4	0,087	0,107	0,116	0,141	0,076	0,093	0,172	0,210	0,264	0,322	0,170	0,208	0,585	0,715
5	0,105	0,129	0,081	0,099	0,149	0,182	0,065	0,079	0,051	0,062	0,061	0,074	0,080	0,098
6	0,115	0,140	0,089	0,109	0,099	0,121	0,051	0,062	0,051	0,062	0,061	0,074	0,080	0,098
7	0,111	0,135	0,097	0,118	0,099	0,121	0,080	0,098	0,051	0,062	0,061	0,074	0,080	0,098
8	0,117	0,143	0,104	0,128	0,212	0,118	0,077	0,094	0,051	0,062	0,061	0,133	0,080	0,098
9	0,122	0,149	0,112	0,137	0,268	0,148	0,021	0,026	0,051	0,062	0,061	0,074	0,080	0,098

Appendix L

See Table L1

Table L1
Pi, Ri, Qi and Ui values.

Material	Pi	Ri	Qi	Ui	Rank
1	0,060	0,023	0,089	66,303	9
2	0,090	0,024	0,117	87,534	8
3	0,107	0,025	0,134	100,000	1
4	0,095	0,029	0,117	87,713	7
5	0,094	0,018	0,131	97,535	4
6	0,087	0,020	0,120	90,036	5
7	0,088	0,021	0,119	89,202	6
8	0,102	0,023	0,131	98,224	2
9	0,104	0,024	0,131	97,818	3

Appendix M

See Table M1

Table M1
Weighted and normalized decision matrix, V_{ij} of TOPSIS.

Material	(Δh)	(T_m)	(Cp_s)	(Cp_l)	(k_s)	(k_l)	(ρ_s)
1	0,030	0,058	0,038	0,027	0,014	0,045	0,004
2	0,152	0,065	0,044	0,044	0,002	0,008	0,002
3	0,160	0,068	0,067	0,065	0,002	0,007	0,002
4	0,123	0,073	0,044	0,054	0,013	0,024	0,005
5	0,148	0,052	0,086	0,020	0,002	0,009	0,001
6	0,161	0,056	0,057	0,016	0,002	0,009	0,001
7	0,156	0,061	0,057	0,025	0,002	0,009	0,001
8	0,165	0,066	0,056	0,024	0,002	0,009	0,001
9	0,171	0,071	0,070	0,007	0,002	0,009	0,001

Appendix N

See Table N1

Table N1
The ideal and nadir ideal solutions of TOPSIS method.

	(Δh)	(T_m)	(Cp_s)	(Cp_l)	(k_s)	(k_l)	(ρ_s)
V^+	0,171	0,052	0,086	0,065	0,014	0,045	0,001
V^-	0,030	0,073	0,038	0,007	0,002	0,007	0,005

Appendix O

See Table O1

Table O1
Computation details for TOPSIS method.

Material	S_i^+	S_i^-	C_i	Rank
1	0,154	0,048	0,236	9
2	0,065	0,129	0,665	5
3	0,049	0,146	0,750	1
4	0,072	0,106	0,597	8
5	0,063	0,130	0,674	3
6	0,069	0,134	0,660	6
7	0,065	0,129	0,666	4
8	0,065	0,138	0,678	2
9	0,074	0,145	0,650	7

Appendix P

See Table P1

Table P1
Computation details for VIKOR method.

Material	E_i	F_i	P_i	Rank
1	0,828	0,440	1,000	9
2	0,400	0,153	0,263	5
3	0,231	0,069	0,024	2
4	0,359	0,155	0,236	4
5	0,426	0,191	0,471	8
6	0,458	0,148	0,395	7
7	0,414	0,107	0,270	6
8	0,348	0,112	0,153	3
9	0,266	0,108	0,000	1

Appendix Q

See Fig. Q1

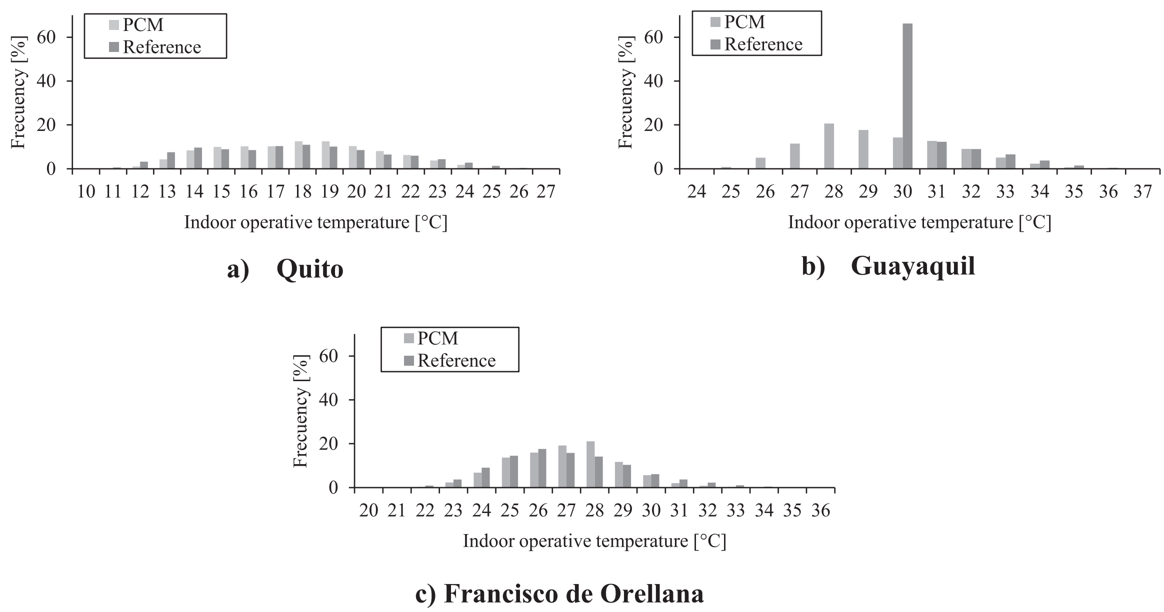


Fig. Q1. Results of the operative temperature distribution on one year span for the cities of a) Quito, b) Guayaquil and c) Francisco de Orellana.

Appendix R

See Fig. R1

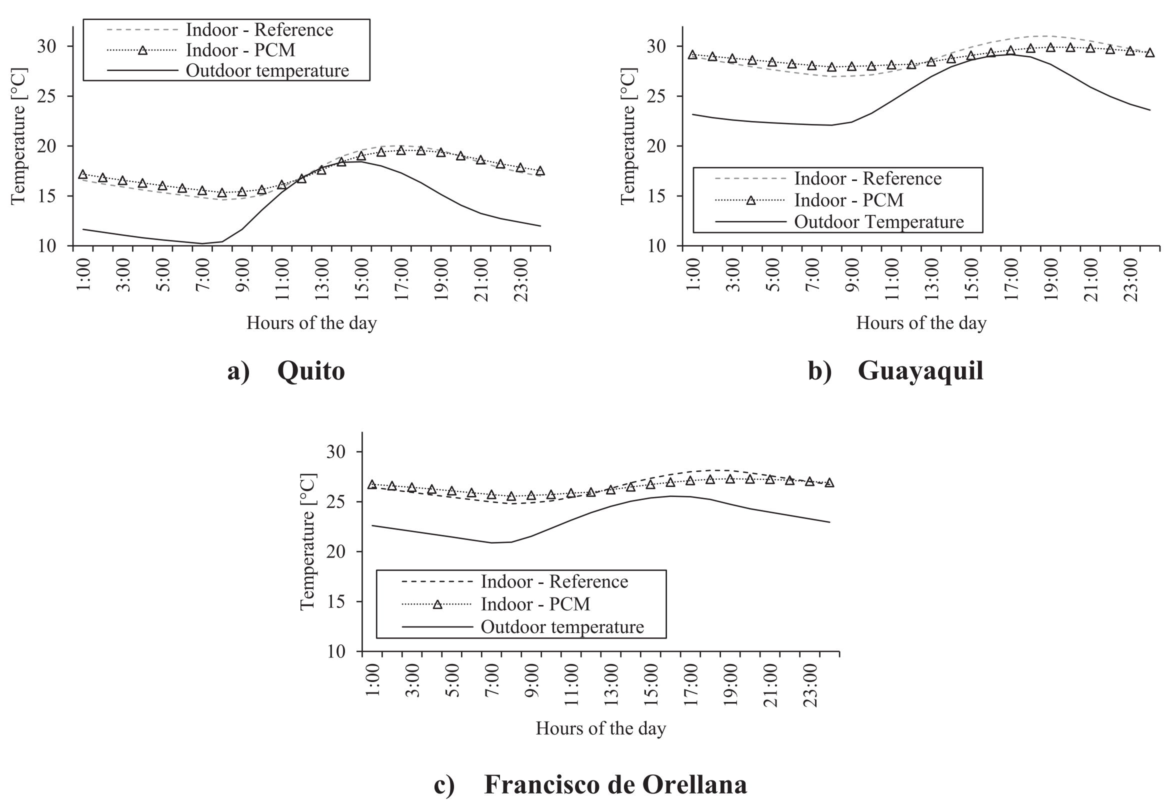
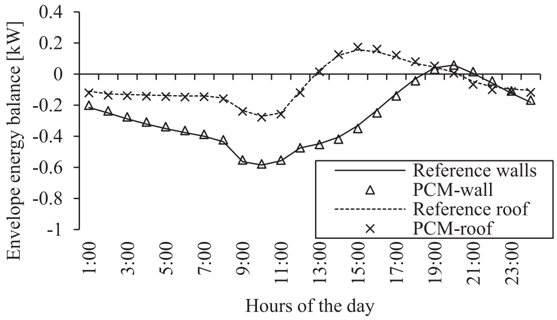


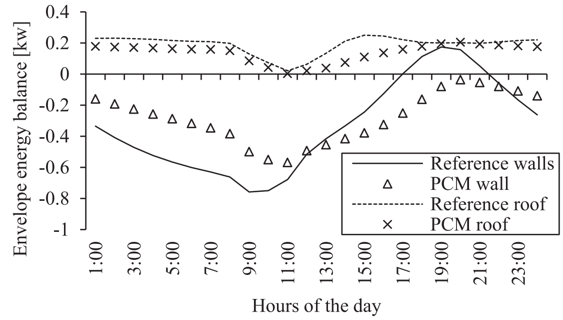
Fig. R1. Comparison between indoor and outdoor temperature for the cities of a) Quito, b) Guayaquil and c) Francisco de Orellana.

Appendix S

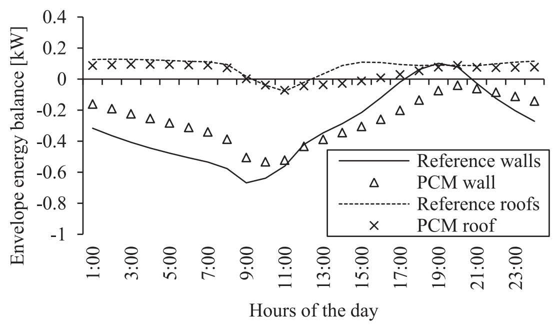
See Fig. S1



a) Quito



b) Guayaquil



c) Francisco de Orellana

Fig. S1. Comparison of envelope energy balance during a day between reference walls and PCM walls, reference roofs and PCM roofs, for the cities of a) Quito, b) Guayaquil and c) Francisco de Orellana.

Appendix T

See Fig. T1

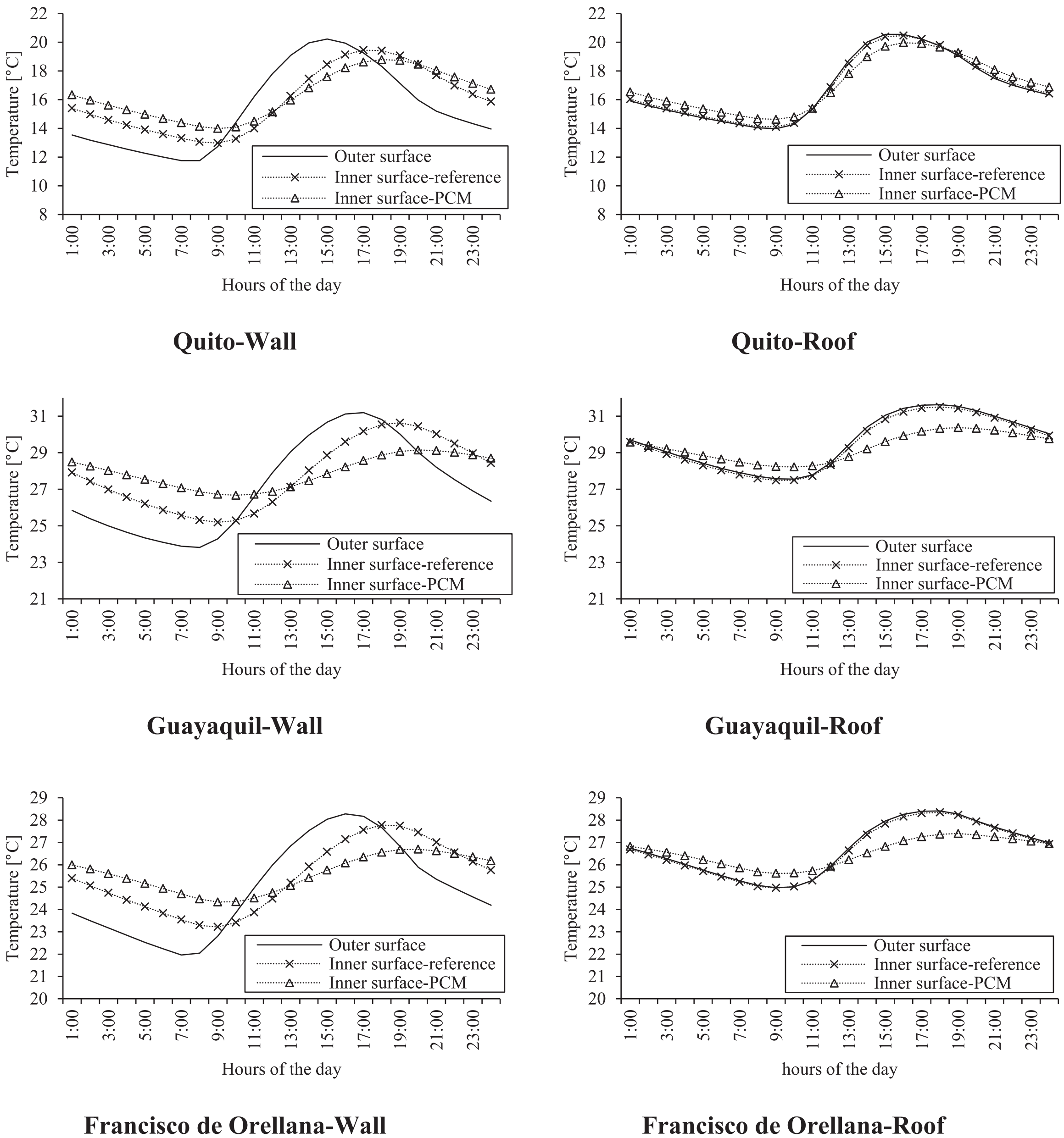


Fig. T1. Envelope surface temperatures.

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