

Article

# Energy performance simulation in buildings composed of natural and organic materials within the Moroccan rural areas of the Atlas Mountains

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**Abstract:** The construction field uses up over one-third of the global energy consumption and contribute to 40% of CO<sub>2</sub> emissions according to the International Energy Agency (IEA) and the 2020 annual reporter of United Nation, Goal 11 (Make cities inclusive, safe, resilient and sustainable) which discusses sustainable, safe and efficient buildings. Therefore, Morocco has a commitment to this program by publishing the law 47-09 of energy efficiency. This work aims to study the energy efficiency of two types of building, a conventional and a natural building. Conventional building is constructed using concrete, while the natural one uses sand clay and straws. As for the technique of making the natural building, it perpetually follows the same approach accustomed in rural zones of Atlas Mountains in Morocco. In this research we also simulate, temperature and humidity variation inside these buildings using TRNSYS software. Sketch Up software was employed to design these houses. The weather database is used for a typical meteorological year (TMY). In the case of natural building, many building configurations were simulated: roof insulation, floor insulation, different types of glazing and sun protection. What's more, the thermal comfort is revealed to be more conspicuous in the case of natural building.

**Keywords:** energy efficiency, natural building, conventional building, TRNSYS software, temperature, humidity, energy consumption

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## 1. Introduction

The energy transition scenario takes into account the energy performance of buildings whose consumption should decrease by 22% or 72 Mtoep of energy savings in 2040 [1]. Buildings are checked for the embodied energy related to fabrication of main structure, foundation, flooring, finishes, furniture, maintenance and electric work[2].

Building's standards require the use of materials that reduce energy consumption [3]. Accordingly, the maximum value was fixed at 50 kWh/m<sup>2</sup> per year on average for the five functions of: heating, hot water production, lighting, cooling and auxiliaries (fans, pumps...) [4]. The special feature is embodied in the fact that houses must be constructed with the use of low energy-intensive materials leading thus to a cutback of

the greenhouse gas CO<sub>2</sub> (carbon dioxide) released into the atmosphere, in comparison to conventional houses. Traditional building materials are very efficient to maintain indoor thermal comfort and to trim down external emissions.

Many studies have taken a keen interest in energy efficiency of houses built by natural materials like adobe, clay, or rammed earth, occasionally mixed with natural fibers such as rice husk [5-6] and studied Direct Solar Floor (DSF) and Earth-Air Heat Exchanger (EAHE) of these types of houses [7].

Césaire and al. [8] improved the thermal comfort of houses in a hot-dry climate by using compressed earth blocks instead of hollow concrete blocks in the design of exterior walls. Moreover, the profiles of thermal discomfort vary depending on the wall designs and building spaces. Cassandra and al. [9] tested the thermal conductivity and the vapor transmission performance, as well as the combustibility of the material. It has been established that wood and hemp batt insulation products show thermal conductivity in the same range as expanded polystyrene, the vapor can diffuse and flow through the natural insulation up to three times more than with cellular synthetic insulation. Natural insulation materials are highly combustible, nonetheless, they have short ignition times, making them safer than the expanded polystyrene.

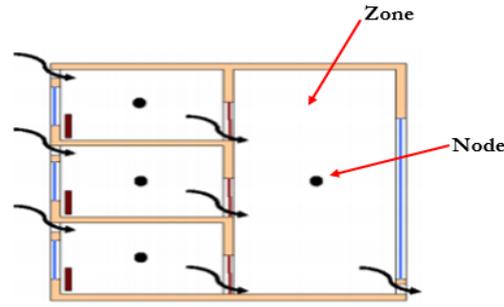
Peñaloza and Jaramillo [10] evaluated the energy savings that can be obtained by installing an EAHE in a tropical climate in Colombia. The enhancement of energy effectiveness, in the construction sector, can be attained by the development of new materials, with improved properties, superinsulating accoutrements, and phase change accoutrements [11].

In our study, we simulate thermal characteristics of natural and conventional houses by using three types of glazing (simple, double and triple), roof and low floor insulation also fixed sun protection in order to compare thermal comfort inside these houses. Data of temperature and humidity outside the buildings applied for a typical meteorological year (TMY).

## **2. Materials and Methods**

### *2.1- The numerical model*

In the present study we used the numerical software TRNSYS 16 and type 56 [12] to simulate the variation of temperature and humidity during the year between conventional and natural buildings to eventually draw up conclusions. In the case of natural buildings, the materials put to use are sand clay coupled with straw [13], as for the conventional buildings, the applied material is concrete. Numerous studies were based on this modelisation for the purpose of evaluating the thermal performance of each building and its energy needs [14]. The formulation of the material plays an important role in augmenting its energy efficiency: for example, the use of fibre decreases the thermal conductivity of the material [15]. TRNSYS uses a multizone approach, where building zones are represented by nodes that can exchange many types of flux (Figure 1).



**Figure 1:** Multizone modelisation approach

The convective heat flux to an air node "i" is calculated as follows:

$$\dot{Q}_i = \dot{Q}_{\text{surf},i} + \dot{Q}_{\text{inf},i} + \dot{Q}_{\text{vent},i} + \dot{Q}_{\text{gc},i} + \dot{Q}_{\text{cplg},i} \quad (1)$$

$\dot{Q}_{\text{surf},i}$ : Convective heat flux from inside all surfaces (KJ/h)

$$\dot{Q}_{\text{surf},i} = U_{w,i} A_{w,i} (T_{\text{wall},i} - T_{\text{air}}) \quad (2)$$

where:  $U_{w,i}$ : Transmission coefficient of a wall in zone "i" ( $\text{W}/\text{m}^2\cdot\text{K}$ ),  $A_{w,i}$ : Surface of a wall in zone "i" ( $\text{m}^2$ ),  $T_{\text{wall},i}$ : Wall surface temperature in zone "i" ( $\text{K}$ ),  $T_{\text{air}}$ : Air temperature ( $\text{K}$ ).

$\dot{Q}_{\text{inf},i}$ : Infiltration gains (air flux from outside only)(KJ/h).

$$\dot{Q}_{\text{inf},i} = \dot{V} \rho C_p (T_{\text{outside},i} - T_{\text{air}}) \quad (3)$$

Where:  $\dot{V}$ : Volume air flow ( $\text{m}^3\cdot\text{h}^{-1}$ ),  $\rho$ : Volumic mass ( $\text{Kg}\cdot\text{m}^{-3}$ ),  $C_p$ : Specific heat capacity ( $\text{J}\cdot\text{Kg}^{-1}\cdot\text{K}^{-1}$ ),  $T_{\text{outside},i}$ : outside temperature of zone "i" ( $\text{k}$ ).

$\dot{Q}_{\text{vent},i}$ : Ventilation gains (air flux from a user defined source, like a HVAC system)(KJ/h).

$$\dot{Q}_{\text{vent},i} = \dot{V} \rho C_p (T_{\text{ventilation},i} - T_{\text{air}}) \quad (4)$$

Where:  $T_{\text{ventilation},i}$ : Air temperature from ventilation ( $\text{K}$ ).

$\dot{Q}_{\text{gc},i}$ : Internal convective gains (by people, equipment, illumination, radiators, etc.)(KJ/h).

$\dot{Q}_{\text{cplg},i}$ : Convective gains due to air flow between zones (KJ/h).

$$\dot{Q}_{\text{cplg},i} = \dot{V} \rho C_p (T_{\text{zone},i} - T_{\text{air}}) \quad (5)$$

Where:  $T_{\text{zone},i}$ : temperature of the zone adjacent to zone "i".

## 2.2- Radiative Heat Flows (only) to the Walls and Windows

Meanwhile, the radiative transfert on an air nodal in the TRNSYS type 56 distinguishes between short wavelength exchanges that are less than  $2.5 \mu\text{m}$  and wavelength greater than  $2.5 \mu\text{m}$ ; the radiative exchange of a wall surface temperature node is expressed in equation (6):

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,i,w_i} + \dot{Q}_{\text{sol},w_i} + \dot{Q}_{\text{long},w_i} + \dot{Q}_{\text{wall-gain}} \quad (6)$$

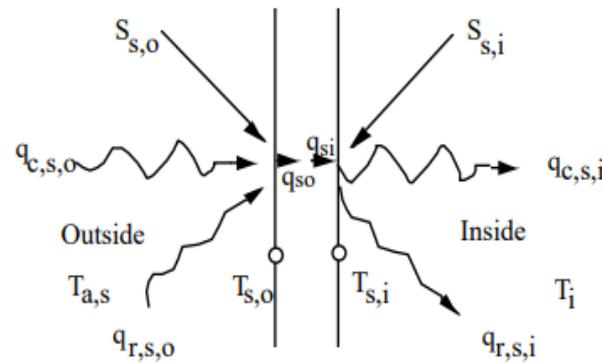
Where:  $\dot{Q}_{r,w_i}$ : The radiative gains for the wall surface temperature node(KJ/h),  $\dot{Q}_{g,r,i,w_i}$ : The internal radiative gains received by a wall (KJ/h),  $\dot{Q}_{\text{sol},w_i}$ : The solar gains received by a wall through the windows(KJ/h),  $\dot{Q}_{\text{long},w_i}$ : The gains through heat

exchange by radiation between one wall and the other walls of zone (KJ/h),  $\dot{Q}_{wall-gain}$  :  
The specific radiative heat flow at a given wall.

### 2.3- Envelope scale transfer modeling

The Mitalas and Arsenault methode is used in TRNSYS to model the walls because it allows accurate calculation of near walls in transient regime.

Figure 2 presents the heat fluxes and temperatures that characterize the thermal behavior of a wall or window.



**Figure 2:** Heat flux and temperatures of a building wall[12]

In figure 2:

$S_{s,i}$  is short wavelength radiation absorbed by the interior surface (solar and radiative gains)(KJ/h).

$S_{s,o}$  is short wavelength radiation absorbed by the exterior surface (solar gains) (KJ/h).

$q_{r,s,i}$  is long net wavelength flow exchanged with all other surfaces in the area (KJ/h).

$\dot{q}_{r,s,o}$  is net radiative flow exchanged with all surfaces outside the zone (KJ/h).

$\dot{q}_{w,g,i}$  is gain in the wall or in the window area defined by the user (KJ/h).

$\dot{q}_{s,i}$  is conductive flow in the wall to the internal surface (KJ/h).

$\dot{q}_{s,o}$  is conductive flow into the wall from the external surface (KJ/h).

$\dot{q}_{c,s,i}$  is convective flow from the internal surface of the wall to the air in the area (KJ/h).

$\dot{q}_{c,s,o}$  is convective flow from the external surface of the wall to the ambient air (KJ/h).

$T_{s,i}$  is temperature of the internal surface of the wall (K).

$T_{s,o}$  is temperature of the external surface of the wall (K).

$T_i$  is node temperature of zone i (K).

$T_{a,s}$  is temperature of the ambient air (K).

The conduction heat transfers at the wall surfaces are expressed in equations (7) & (8).

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,0}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \quad (7)$$

$$\dot{q}_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,0}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^k \quad (8)$$

Where: The superscript  $k$  refers to time (h). The current instant is  $k=0$ , the subsequent instant is for  $k=1$ , etc. The timebase on which these calculations are based is specified by the user within the TRNBuild description,  $a_s^k, b_s^k, c_s^k, d_s^k$ : wall surface thermal behavior coefficients at time  $k$ ,  $T_{s,0}^k$ : Temperature of the external surface of the wall at time  $k$ ,  $T_{s,i}^k$ : Temperature of the internal surface of the wall at time  $k$ ,  $\dot{q}_{s,0}^k$ : conductive flow into the wall from the external surface at time  $k$ ,  $\dot{q}_{s,i}^k$ : conductive flow in the wall to the internal surface at time  $k$ .

The wall is considered as a black box and defined by four coefficients ( $a_s, b_s, c_s, d_s$ ) which represents wall thermal behavior, these time series coefficients are determined in the TRNBuild program which integrates the thermo-physical properties of each layer constituting the wall.

#### 2.4- Thermal load of a zone

The temperature in a building zone (thermal node) is calculated by TRNSYS using equation (9):

$$C_i \frac{d}{dt} T_i = \dot{Q}_i \quad (9)$$

$C_i$ : The thermal capacity of zone  $i$  ( $J.kg^{-1}.K^{-1}$ ),  $\dot{Q}_i$ : The net thermal gain (KJ/h), it's a function of  $T_i(K)$  and temperatures of all the other zones adjacent to zone  $i$ .

#### 2.5- Calculation of convective coefficients and thermal inertia

In TRNSYS the default calculation of convection heat transfer coefficients is only valid for internal building surfaces, these coefficients are calculated according to the equation (10).

$$\alpha_{conv} = A(T_{sur} - T_{air})^B \quad (10)$$

Where:  $\alpha_{conv}$  is convection heat transfer coefficient ( $w/m^2.k$ ),  $T_{surf}$ : Surface temperature ( $^{\circ}C$ ),  $T_{air}$ : Air temperature ( $^{\circ}C$ ),  $A$ : Correlation coefficient ( $kj.h^{-1}.m^{-2}.k^{-1}$ ),  $B$ : Correlate exponent.

The  $A$  and  $B$  coefficients can be modified here to accommodate different approaches from heat transfer research. Standard values are taken from the literature[12].

TRNSYS software considers the thermal capacity of a thermal zone as equal to 1.2 multiplied by the zone surface value.

#### 2.6- TRNSYS inputs and outputs

In all simulations using TRNSYS the following considerations are taken into account: initial temperature and humidity of the air inside all thermal zones are acquired at  $20^{\circ}C$  and 50% respectively, no internal heat gain (unoccupied building), a constant infiltration rate of 0.5 for all areas and soil temperature equal to  $14^{\circ}C$ .

TRNSYS inputs are: building dimensions, weather data for TMY, orientations of the different surfaces of the building envelope, the different layers of the walls of each zone, construction materials (thickness, thermal conductivity, capacity, density), the

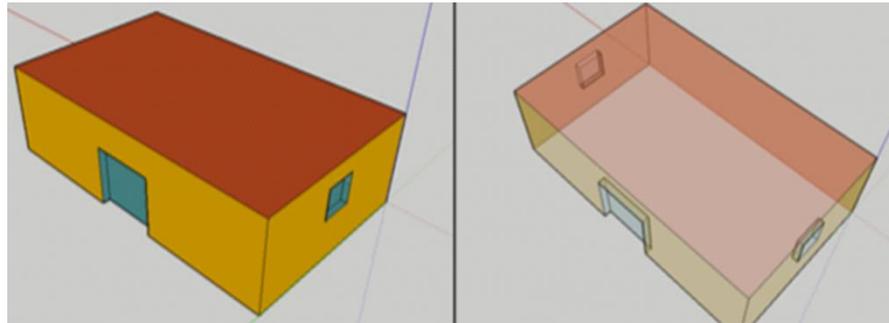
openings (type, orientation, dimensions, the loss coefficient and the transmission coefficient), infiltration and the calculation step (1h for each iteration).

TRNSYS outputs are temporal variation of temperature and zones humidity.

## 2.7- Presentation and description of the simulated building

### 2.7.1- Dimension and zoning of building

The studied building is a single floor that includes a single zone (Figure 3) of 60 m<sup>2</sup> of surface and 180 m<sup>3</sup> of volume, with two windows in the East and West and a main façade oriented to the north. Table 1 portrays windows characteristics of this building.



**Figure 3:** The 3D building image by SKetchUP software

**Table1. Windows characteristics of the studied building**

Orientation of Windows	Height (m)	Width (m)	Type of glazing
East	1	1	Single glazing
West	1	1	Single glazing

### 2.7.2- Constitutions and thermo-physical characteristics of the building walls

The walls components for the natural building are divulged in table 2 as for the ones that concern the conventional building they're illustrated in Table 3. Table 4 on the other hand, uncovers the thermo-physical characteristics of the building walls material used in the natural and conventional buildings.

**Table 2:** The wall's components of the natural building

Walls	Constitutions	Thickness e (cm)
Exterior walls	Earthenware	1.5
	Sand clay and straws	40
	Earthenware	2
The low floor	Wood	1
	Concrete	30
The roof	Wood	15

**Table 3:** The wall's components of the conventional building

Walls	Constitutions	Thickness e (cm)
Exterior walls	Coating-sand-plaster	1
	Hollow brick	20
	Concrete	2
	Cement plaster	1
The low floor	Marble	2
	Concrete	6
	Reinforced concrete	6
	Stone	20
The roof	Plaster	2
	Hardened concrete	16
	Reinforced concrete	6
	Concrete	3
	Tiles	1.2

**Table 4:** The thermophysical characteristic of the building walls used material

Thermal characteristics of materials			
Materials	Thermal conductivity $\lambda(KJ/h.m.K)$	Specific heat C $(KJ/Kg.K)$	Density $\rho$ $(Kg/m^3)$
Earthenware	2.16	1.5	1500
Sand clay with straws	0.603	1.17	580
Wood	0.468	1.8	550
Concrete	7.56	0.8	2400
Coating-sand-plaster	2.232	1.2	1500
Hollow brick	0.972	1	650
Cement	5.4	1	1900
Cement plaster	4.14	0.92	1900
Marble	10.44	0.88	2600
Reinforced concrete	8.28	1	2300
Stone	5	1	2000
Concrete hourdi	4.801	0.65	1300
Tiles	9	5	2100
wood fibres	0.14	2.1	160

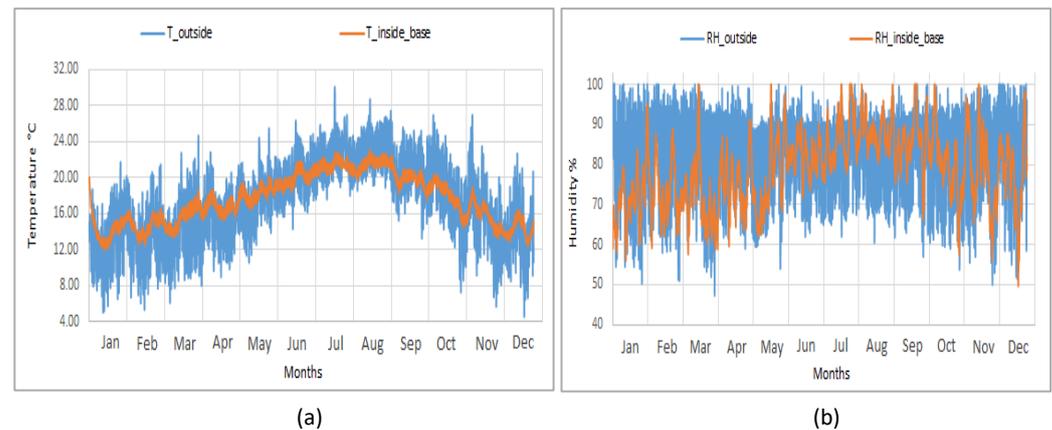
In this study we used one type of insulation for natural building, which is wood fibres, and the used insulations thicknesses are 5cm, 10 cm, and 15cm.

### 3. Results

#### 3.1 Natural single-zone building

TRNSYS simulations of temperature and humidity for natural single-zone building along the TMY are showcased in Figure (4-a). As we can see, both inside and outside temperatures of this building are higher in the summer season. Yet, in the winter, inside temperatures are greater than outside temperatures and this behavior is reversed in the summer. Moreover, during the whole year, inside temperatures has trivial fluctuations compared to the outside ones. All this highlights why a natural building had an energy efficiency.

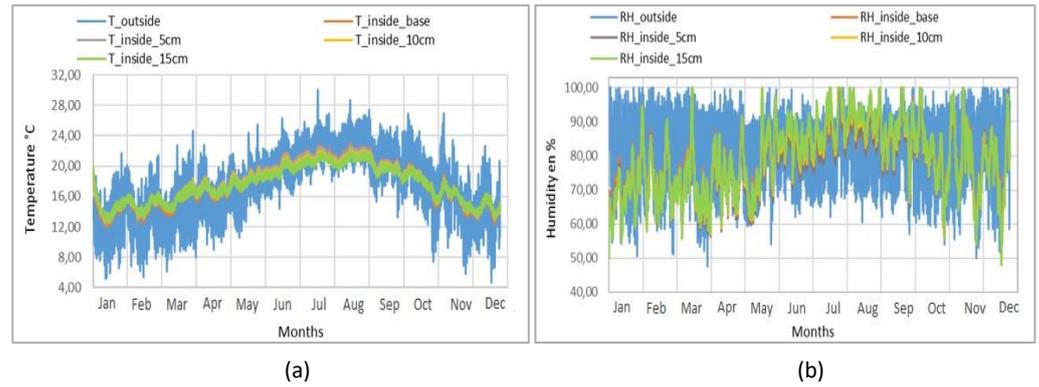
Figure (4-b) compares the outside and inside humidity of the building. Ostensibly, during the winter, the inside humidity is less than that of the outside and the contrary is observed during summer.



**Figure 4:** (a) TRNSYS TMY simulation of temperature T, (b) and relative humidity RH inside and outside of the natural single-zone building

##### 3.1.1. Natural single-zone building with roof insulations

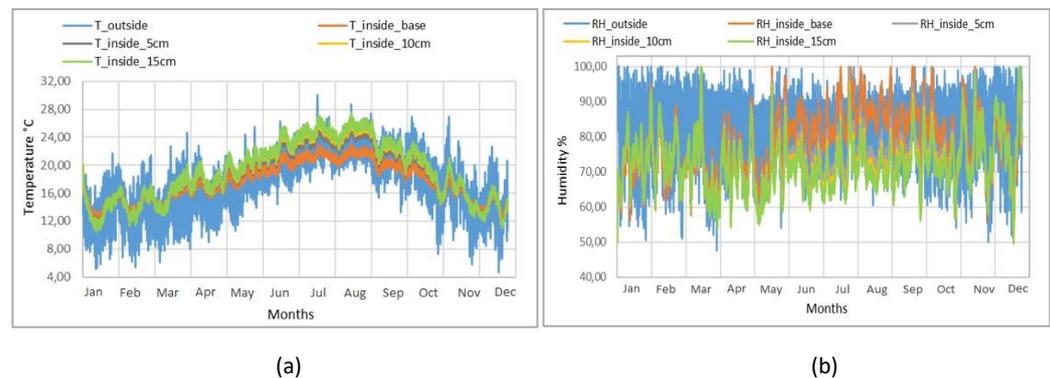
TRNSYS simulations of temperature for natural single-zone building with roof insulations along the TMY are expressed in Figure 5(a). It is abundantly clear that the presence of roof insulation has the effect of increasing the inside temperature during winter and decreasing it during summer. Alternatively, Figure 5(b) proves that roof insulations increase humidity, especially during summer.



**Figure 5:** (a) TRNSYS TMY simulation of temperature T, (b) and relative humidity RH inside and outside the natural single-zone building with roof insulations

### 3.1.2. Natural single-zone building with floor insulations

TRNSYS simulations of temperature for natural single-zone building with floor insulations along the TMY are illustrated in Figure 6(a). This figure demonstrates that with floor insulations and during winter period, the internal temperature moves towards the highest values above those of the daily external fluctuations. However, internal summer temperature are higher than external ones. On other hand, Figure 6(b) exposes that floor insulations decrease humidity, especially during summer.

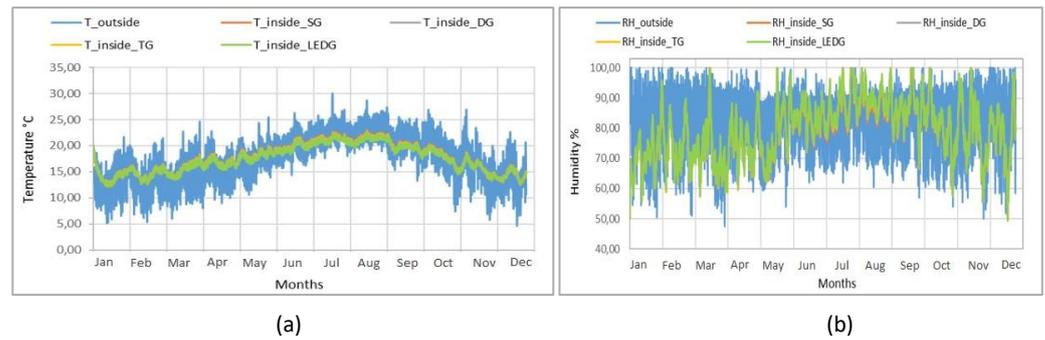


**Figure 6:** (a) TRNSYS TMY simulation of temperature T (b) and relative humidity RH inside and outside the natural single-zone building with floor insulations

### 3.1.3. Natural single-zone building with different types of windows glazing

Simulations are implemented for four types of glazing: single glazing (SG), double glazing (DG), triple glazing (TG), low emissivity double glazing (LMDG).

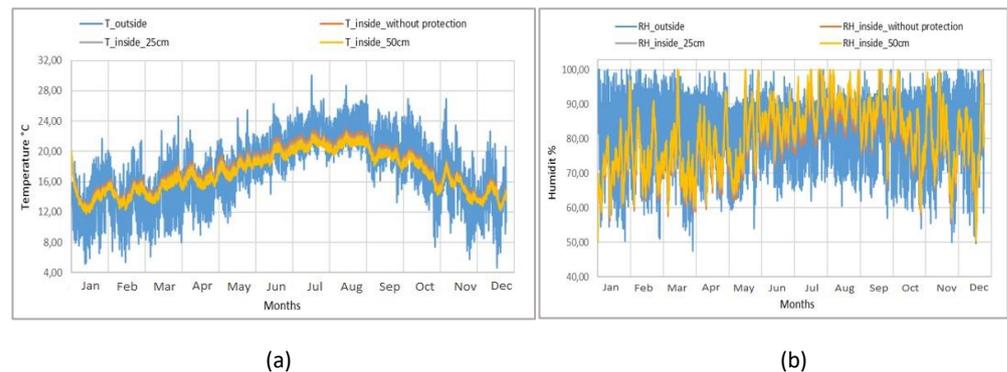
Figure 7(a) shows that the impact of glazing is more apparent in the summer, where we notice a dwindle in temperature reaching up to 2°C compared to the natural single-zone building with single glazing. Still, there was no notable impact on simulated humidity for the three type of glazing compared to single glazing (Figure 7(b)).



**Figure 7: (a)** TRNSYS TMY simulation of temperature T (b) and relative humidity RH inside and outside the natural single-zone building with different types of glazing.

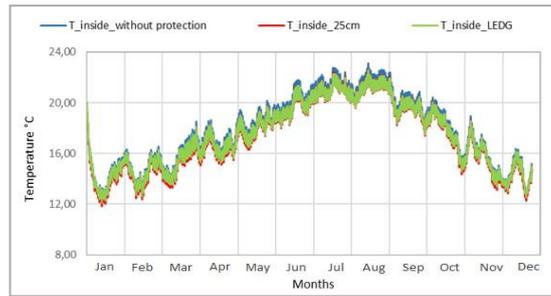
### 3.1.4. Natural single-zone building with fixed sun protections

Figure 8(a) presents TRNSYS simulation of temperature for a natural single-zone building with fixed sun protections above windows. From the figure, we can see that temperature drops by increasing the dimensions of the fixed sun protections for the whole TMY. Yet, no notable effect of fixed sun protections is simulated for humidity (Figure 8(b)).



**Figure 8: (a)** TRNSYS TMY simulation of temperature T (b) and relative humidity RH inside and outside the natural single-zone building with fixed sun protections

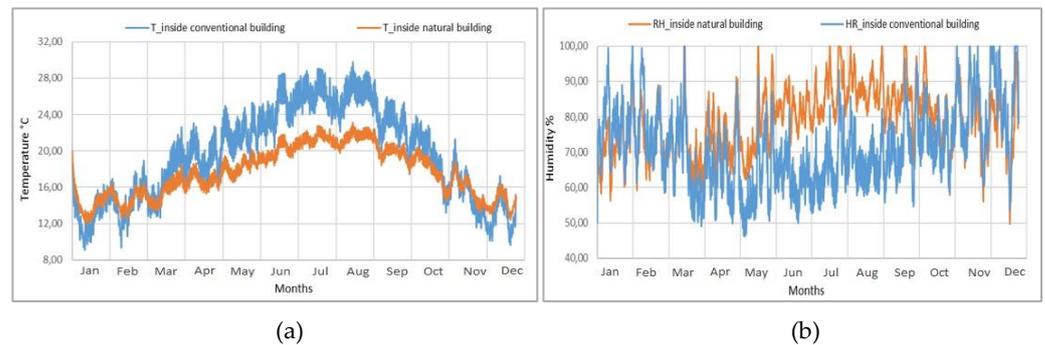
Figure 9 compare effects of permanent sun protections of 25 cm and LEDG on temperature inside natural single-zone building. This figure indicates that in the summer season, fixed sun protections and LEDG give the same results. Nevertheless, in the winter time LEDG enable an inside temperature higher than the one attained with fixed sun protections. Therefore, the fixed sun protections must be eliminated in the winter in order to increase inside temperature.



**Figure 9:** TRNSYS TMY simulation of the inside temperature  $T$  of the natural single-zone building with fixed sun protections of 25 cm and LEDG

### 3.2. Comparison between a natural building and a conventional building

TRNSYS simulations of temperature for natural single-zone building are compared with that of a conventional building along the TMY in Figure 10(a). The figure demonstrates that a natural building is somewhat synonymous with an energy efficient building owing to the fact that the temperature is curtailed, especially during summer. However, the conventional building provides better results when it comes to humidity, since humidity in natural building is higher than that found in conventional building (Figure 10(b)).



**Figure 10:** (a) TRNSYS TMY simulation of temperature  $T$  (b) relative humidity  $RH$  inside of the natural single-zone building and conventional single-zone building

## 4. Conclusions

The main aim of this paper was to study the energy efficiency of a conventional and a natural building. Concerning the conventional building; construction material was concrete, while in the natural building the construction material was sand clay and straw. Sketch Up and TRNSYS 16 software were used respectively to design these houses and to simulate temperature and humidity inside building. As for the weather database, it was used for a typical meteorological year (TMY). In the case of the natural building, simulations results exhibit that, during summer seasons, the building efficiency can be enhanced by using roof insulation, different types of glazing or sun windows protections. However, simulations demonstrate that insulating the floor of the natural building can increase inside temperature during summer, especially when increasing the thickness of the insulation. During winter seasons, simulations demonstrate that the building efficiency can be enhanced by using roof insulation, floor insulation or

different types of glazing. So, the thermal comfort is more guaranteed in the case of natural building in comparison to a conventional building. As perspectives of this study, we plan to focus on natural buildings that closely mimic and imitate those found in rural zones of the Atlas Mountains in Morocco. So, future simulations may subdivide the natural building to three or four zones and incorporate home furniture and residents. Also, simulations can be coupled with an optimization procedure to find optimal configuration including in the same natural building both floor insulation, roof insulation and glazing.

**Author Contributions:** Conceptualization, Mohammed Igouzal; Data curation, Hanane Es-sebyty and Bouchra Abbi; Formal analysis, Hanane Es-sebyty, Bouchra Abbi, Elena Ferretti and Mohammed Igouzal; Investigation, Hanane Es-sebyty, Bouchra Abbi, Elena Ferretti and Mohammed Igouzal; Methodology, Mohammed Igouzal; Supervision, Elena Ferretti and Mohammed Igouzal; Validation, Elena Ferretti and Mohammed Igouzal; Visualization, Hanane Es-sebyty and Bouchra Abbi; Writing – original draft, Hanane Es-sebyty and Bouchra Abbi; Writing – review & editing, Elena Ferretti and Mohammed Igouzal. All authors have read and agreed to the published version of the manuscript.

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