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ARTICLE

Evaluation and Simulation of the Effect of the Types of Glazing and the Choice of Materials on the Energy Efficiency of a Building

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ABSTRACT

Tunisia is one of the pioneering developing countries in terms of energy efficiency policy initiated since the mid-1980s. Indeed, energy efficiency has become one of the main pillars of the country's energy strategy, especially with the increase in energy prices. The main objective of this work is to give an idea of the impact that certain choices made during the design of a building can have on its energy balance, namely the orientation of the facades, the types of glazing and their surfaces, the choice of materials, etc. The calculation of the building's energy requirement was determined using the transient systems simulation program TRNSYS (version 18) with a modular structure.

1. Introduction

Energy efficiency is often considered the most important source of energy for a country. All scenarios that make projections, whether at regional, national or global level, by betting on large shares of non-fossil energy sources in the global energy mix are based on considerable reductions in primary energy demand in final energy consumption [1,2].

All sectors need to improve their energy efficiency, otherwise it will not be possible to decouple economic growth from energy demand and greenhouse gas emissions.

Buildings are the largest individual consumers of energy in the world, but they also offer the greatest individual potential for saving energy. Buildings must meet the user's need for comfort and maintain an acceptable level of interior comfort, day and night, all year round [3]. Low-

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energy buildings are of crucial importance for the future evolution of greenhouse gas emissions because, if they are not, population growth and the growing demands of the population for energy will household energy consumption will reach enormous quantities. During the past years, the average and specific energy consumption per household has increased in most regions of the world. Recently, this increase has been due to the growth of emerging economies such as China, India and South East Asia where more and more people can afford to use electrical household equipment and heating installations. In industrial countries, household energy consumption has increased for the following two reasons:

- The average household size has fallen, so that the number of households has increased and the number of basic household appliances has followed this trend;
- The average size of houses and apartments has grown, leading to an increase in heating, air conditioning and lighting needs and thirdly, the number of electrical appliances per household has itself increased.

Improving the energy efficiency of buildings is an important source of energy savings in developing countries, given the share that buildings represent in the demand for commercial energy in these countries (about 30% of the total electricity consumption in West Africa). Managers often consider energy expenditure as a fixed cost over which they have no control. However, appropriate techniques for the use and control of energy make it possible to achieve annual savings of around 10 to 15% in buildings in the tertiary sectors [4].

Tunisia has accelerated its action in terms of energy efficiency since the early 2000s by undertaking a diversification of its energy mix. This diversification aims to cope with the widening of the national energy deficit, which exceeded 4 Mtoe (million tonnes of oil equivalent) in 2015, reaching a rate of 56% [5]. The main characteristics of the energy sector in Tunisia are as follows [5]:

- A sharp increase in the demand for electricity and the great importance given to carbon energies by the national authorities;
- Continued construction of new gas-fired power plants (97% of current electricity production) to meet growing demand and save the country from power outages;
- Quasi-monopoly of electricity production by the public sector (81%).

Several studies have been carried out on buildings to determine the influence of several parameters on the energy balance [6-11].

Depending on the outdoor conditions and glazing size, windows are responsible for around 10% to 25% of the total heat loss [12]. Therefore, adjusting the window to wall ratio can lead to a considerable impact on energy compared with adjusting the external walls' thickness [13,14]. There are other parameters that considerably affect energy building performance such as the glazing type, the choice of materials and use of shading. The results of the study conducted by Cesari and Khoukhi [15,16] indicated that retrofitting may have a major influence on the building's energy pattern as well as the cost of the energy consumption.

The energy diagnosis of a building constitutes the realization of a complete assessment of the energy situation of the building. It pursues three objectives:

- Optimization of energy consumption;
- Identification of opportunities for using renewable energies locally;
- Improved occupant comfort.

In this context, this work consists in giving an idea of the impact that certain choices made during the design of a building can have on its energy balance by using dynamic thermal simulation using the transient systems simulation program TRNSYS (version 18) [17].

2. Impact of Building Form on the Energy Efficiency of Residential Buildings

Residential buildings have a different occupancy pattern and the daytime energy consumption is lower compared to non-residential buildings. Several studies have been carried out to identify the effect of orientation, shape, and window to wall ratio in residential buildings. In their experimental study, Hachem et al. [18] demonstrated that the number of shading facades and the ratio between the shading to shaded facade significantly affect the solar radiation on non-convex shapes. The study was based on residential buildings in cold climate including seven different shapes (square, rectangle, trapezoid, L, U, H and T). Bichiou and Krarti [19] conducted a research on single-family homes in the USA including five different locations. This research considered the building shape, window to wall ratio and orientation as important parameters for the optimisation. Three optimisation algorithms were considered and the optimal design reduced the life cycle cost by 10%-25% depending on the type of homes and climate.

3. Experimental Study

3.1 Simulation Software

There is a large number of software dedicated to energy simulation. The existing software differ from each other by the algorithms they use, by their user interface and by their vocations and their fields of application. The software used in this study is TRNSYS version 16 able to:

- perform dynamic simulations based on a modular approach;
- create new models in addition to those in the library of models of thermal systems and auxiliary components (weather data, histograms, …);
- solve systems of equations.

The TRNSYS software has been parameterized with the characteristic data of the base case using the TRNBUILD (Type 56) as well as the meteorological data of the city of Tunis. The calculation was made by fixing the calculation step at one hour for each iteration. A simulation was carried out to obtain the evolution of the average air temperature inside each zone as well as the energy needs for heating and air conditioning in useful energy.

3.2 Presentation of the Building

The building is located in the city of Tunis (Figure 1a) in the RT2 region at a latitude of 36°50'N, longitude of 10°14'E and an altitude of 3.00 m.

The hot season in Tunis lasts for three months, from June to September, with an average daily high temperature above 31 °C. The hottest month of the year in Tunis is August, with an average high of 34 °C and low of 22 °C. The cool season lasts for four months, from November to March, with an average daily high temperature below 18 °C. The coldest month of the year in Tunis is January, with an average minimum temperature of 8 °C and maximum of 16 °C.

The outside air temperature T_a (°C) and the solar radiation G_h (KWh) have a huge influence on the heating and cooling demand. These data are presented in Table 1.

Table 1. Daily average weather data for the Tunis region

Month	T_a (°C)		Gh (KWh)
	Max	min	
January	16	8	2.6
February	17	8	3.6
March	20	9	4.9
April	22	11	6.2
May	26	15	7.1
June	31	19	7.7
July	34	22	7.9
August	34	22	6.9
September	31	20	5.4
October	27	17	4.0
November	21	12	2.9
December	17	9	2.4
Average	24.6	14.3	5.1

The building can be described as follows :

- The floor area is 80 m² for a volume of 240 m^3. The ceiling height is 3.00 m. It consists of two rooms, living room, kitchen, toilet and hall. The entrance to the building faces north as shown in Figure 1b.
- Glazed surfaces represent 10% of the floor surface (which represents approximately 6.67% glazed surface per facade). Single-glazed windows have a heat transfert coefficient U = 6.32 W/m².K and a solar factor g = 0.85 [20].
- Number of occupants is 5 persons.
- The building is a rectangular shape with overall heat transfer coefficient (U) of 1.57W/m².K and 1.85W/m².K for external wall and internal wall, respectively.

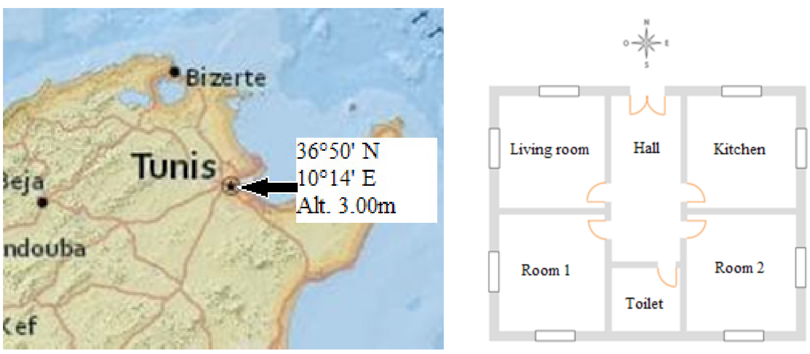


Figure 1. (a) : Topographic map of Tunisia showing the location of Tunis. (b) : Plan and orientation of the building located in the region of Tunis

- Comfort temperatures for heating and cooling are 24 °C and 20 °C respectively where the relative humidity is set 50% for cooling and 30% for heating.

The thermal performance of windows is evaluated mainly using the heat transfert coefficient U and the solar factor g. The combination of these characteristics makes it possible to obtain very interesting performances to minimize heating costs in winter and cooling costs in summer. In addition, the installation of mobile solar protection and closures acts on summer comfort and winter comfort. U-value translates the capacity of the window to maintain the interior temperature. The lower U, the more the window is insulating.

The solar factor reflects the ability of the window to transmit the heat of the sun. It is the ratio between the total energy transmitted through the bay, and the incident solar energy. The higher the solar factor, the greater the transmitted heat gains. In winter, this will help minimize heating consumption through free solar gain. In summer, on the contrary, the solar factor should be low, in order to limit the entry of heat through the windows, thus limiting the interior temperature.

The heat transfert coefficient U of a wall expresses the intensity of the heat flux which crosses a square meter of wall for a temperature difference of one degree between the inside and the outside. The lower this coefficient, the more the wall performs thermally. The heat transfer coefficient of a wall was calculated using the following formula (Equation 1):

$$U = \frac{1}{R_{si} + \sum_{i=1}^{n} \frac{e_i}{\lambda_i} + R_{se}} \tag{1}$$

where U is the heat transfer coefficient (W/m².K), R_{si} is the internal surface thermal resistance (m².K/W), R_{se} is the external surface thermal resistance (m².K/W), e_i is thickness of the layer of the corresponding material (m), λ is thermal conductivity of of the corresponding material, (W/m.K).

The lighting requirements for a residential building can not be easily generalised as it heavily depends on the occupant behaviour and the specific requirements. The average illuminance levels for various spaces (living, kitchen, rooms and bathroom) of single-family houses varies from 100 lux to 200 lux [21], and except for the kitchen, all the other zones require 100 lux ~ 150 lux illuminance level.

The dimensions of the different parts of the building are given in Table 2.

Table 2. Dimensions of the different parts of the building

Parts of the building	Length (m)	Width (m)	Height (m)	Area (m²)	Volume (m³)
Room1	4.00	4.00	3.00	16.00	48.00
Room2	4.00	4.00	3.00	16.00	48.00
Living room	4.00	4.00	3.00	16.00	48.00
Kitchen	4.00	4.00	3.00	16.00	48.00
Hall	6.00	2.00	3.00	12.00	36.00
Toilet	2.00	2.00	3.00	4.00	12.00
Total				80.00	240.00

3.3 Thermal Characteristics of Materials

The non-insulated exterior walls are made of hollow brick 15 cm thick with an exterior plaster of cement mortar and the interior of plaster. The internal walls are made of 10 cm hollow brick with a plaster coating on both sides. The ground consists of a layer of stone 20 cm thick followed by 10 cm of concrete, covered with tiles. The roof is made of concrete-slab with a thickness of 20 cm and a cement mortar screed and an interior plaster coating. Table 3 presents the thermal characteristics of the materials used in the building.

Table 3. Thermal characteristics of the materials

	Layers	Thermal conductivity λ (W/m.K)	Thermal capacity (KJ/Kg.K)	Density (Kg/m³)	Thickness (mm)	Total U Value (W/m².K)
External Wall	External plaster	1.15	1.34	1800	10	1.57
	Hollow brick	0.34	0.84	1920	150	
	Plaster	0.57	1.34	720	10	
Internal wall	Plaster	0.57	1.34	720	10	1.85
	Hollow brick	0.35	0.84	1920	100	
	Plaster	0.57	1.34	720	10	
Ground	Concrete screed	1.30	1.15	2200	50	0.85
	Stone	1.75	1.00	2350	200	
	Concrete	0.80	0.84	2240	100	
Roof	Concrete-slab	2.30	0.84	2240	40	054
	Slab	0.60	0.88	1000	160	
	Plaster	0.57	1.34	720	10	

3.4 Determination of Energy Requirement

The annual energy requirement of the building is shown in Figure 2. The values are around 9300 (KWH) for heating and 11180 (KWH) for air conditioning. The total annual requirement is therefore 20480 (KWH).

For our building with a total area of 80 m², the energy performance is around 256 KWH/m². This result is obtained if we consider that the air conditioning system has a coefficient of performance COP = 4 and the efficiency of the heating system is $\eta = 0.6$.

The Coefficient of Performance (COP) is the ratio between the heat produced and the energy consumed. The higher the COP, the less energy the air conditioner will use to heat the space.

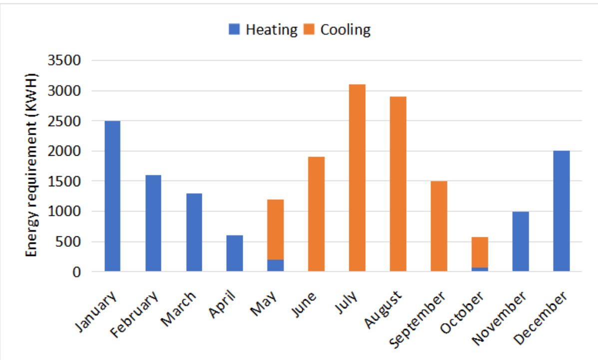


Figure 2. Monthly evolution of energy requirement

4. Energy Efficiency Measures

4.1 Orientation

The initial building oriented North-South has been modified and oriented East-West as shown in Figure 3.

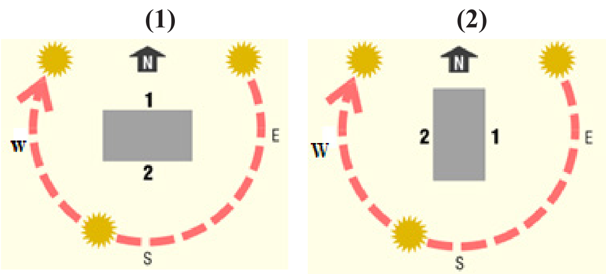


Figure 3. Orientation of the building. (1): North-South. (2): East-West

Figure 4 gives the results of the influence of the orientation of the building on its energy balance. We note that the demand for heating and cooling has been increased by 5% and 11% respectively for a total increase in thermal consumption of 3%. Indeed, for the facade facing north, it receives a little sunshine in the morning and evening. In the modified situation, it is oriented to the East and it receives solar gain only in the morning, but more significantly. We should therefore heat less in winter but cool more in summer.

For the facade facing south, it receives significant solar gain in the middle of the day. In the modified situation, the facade is oriented to the West and the sunshine occurs later. It is therefore necessary to heat more in winter. In summer, the end-of-day supplies will be stored in the building overnight and returned in the morning, so additional cooling will also be required.

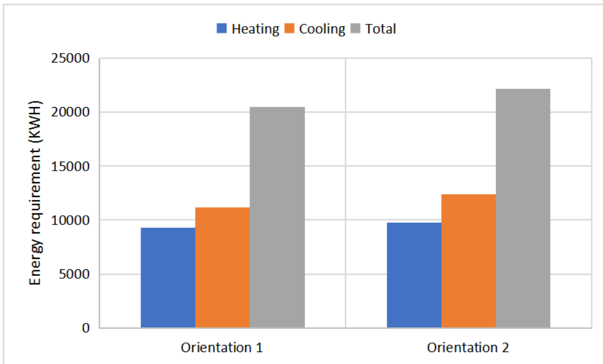


Figure 4. Annual energy requirement according to the building orientation

4.2 Glazed Surfaces

Figure 5 presents the results of the annual energy requirement for heating and cooling as a function of the percentage of glass surfaces in the building. According to the results, we note that the use of single glazing with a heat loss coefficient U=6.32W/m².K did not give an energy gain for all the facades, including that of the South.

For double-glazed windows, we note that it is absolutely necessary to avoid arranging them on the North facade under penalty of seeing its energy needs explode simultaneously with the increase in the glazed surface. For the other facades, an energy gain in heating was recorded in proportion to the increase in glazed surfaces, especially for the south facade where the gain is significant and stabilizes beyond half the surface of the facade. For the East and West facades the gain increased slowly to reach its maximum for a percentage of 40%.

For low-emission double glazing, we note a heating gain of 22.64% for the south facade. For the other three facades, the gain was 1% on average for 20% more glazed surface.

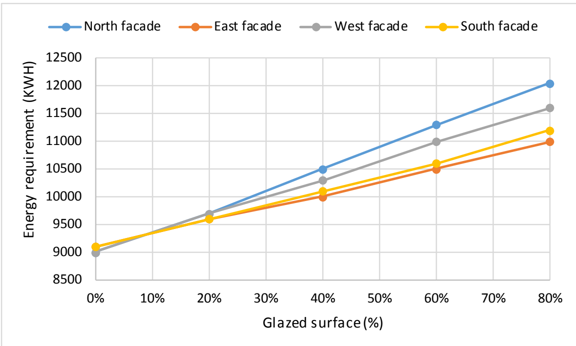
According to the results, we also notice that a window placed to the south can improve the heating balance. Indeed, in winter, since the sun remains low on the horizon, only windows facing south and without shade can really contribute to heating provided that their glazing is very insulating and fairly transparent to the radiation of the sun. In summer, on the other hand, the sun reaches all the facades, and the building can overheat if it is not equipped with solar protection.

We also note that windows facing east and west are more difficult to keep in the shade, because the sun reaches them at a lower angle on the horizon than windows facing south. Thus, it is advisable not to exceed:

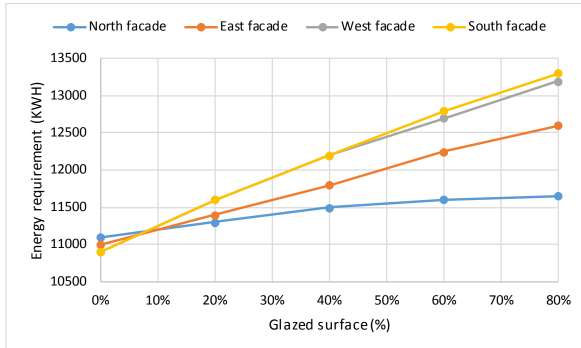
- 50% glazing on the south facades (a good compromise to take advantage of solar energy in winter without suffering too much overheating in summer).
- 20% glazing on the east and west facades (to avoid losses in winter and overheating in summer).
- 10% glazing on the north facades (to avoid heat loss in winter while still receiving light).

Single glazing

(a)

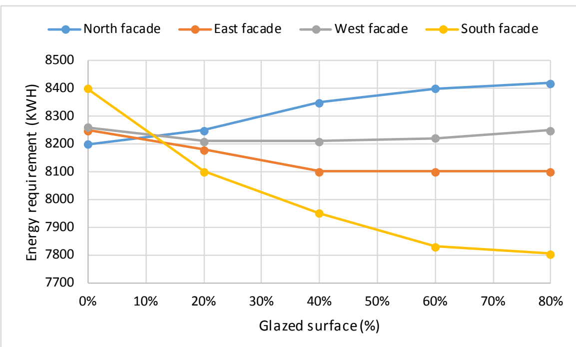


(b)



Double glazing

(a)



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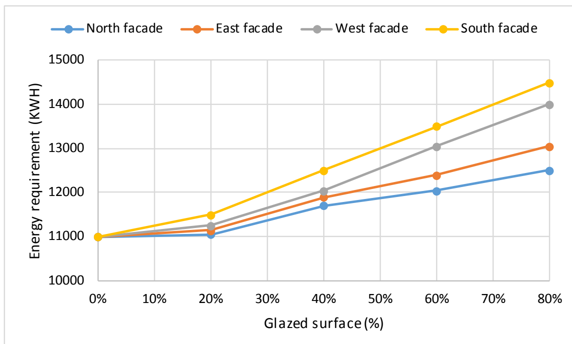
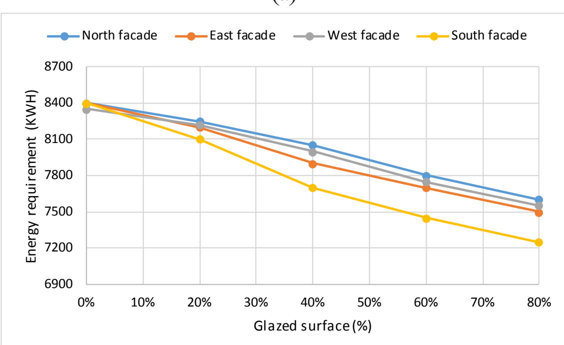


Low-emission double glazing

(a)



(b)

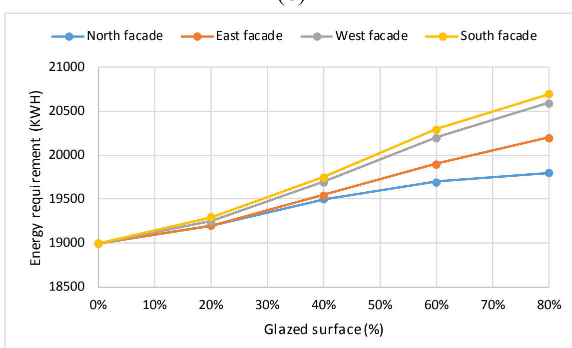


Figure 5. Annual energy requirement according to glazed surfaces.
(a): Heating requirement. (b): Cooling requirement

4.3 Movable Sun Protection

Solar protection reduces energy consumption by reducing summer solar gains. It limits air conditioning consumption while maintaining a stable and comfortable interior temperature. The exterior solar protection will block the heat before it enters the building. The dynamic nature of solar protection and the choice of the appropriate opening coefficient make it possible to maintain sufficient natural light intake to limit the use of artificial light and therefore energy consumption.

The solar protection chosen is that of external canvas roller blinds, with a solar factor of 0.2 determined according to NF EN 13363-2 standards [22]. The solar factor indicates the proportion of heat that enters the interior of a room of a building compared to the incident solar energy. The lower the coefficient, the higher the thermal comfort.

The external blinds are placed on the east, south and west facades, and are regulated facade by facade according to the minimum temperature of the rooms overlooking these facades.

According to the results presented in Table 4, we note that the annual solar contributions are thus reduced by 20%, which results in a reduction in the demand for cold by 30% but also by an increase in the demand for heat by 7%. This increase is probably due to less heat storage in the mass of the building.

Table 4. Annual energy requirement of the building with movable window sun protection

Energy requirement (KWH)	Without sun protection	With sun protection	Compared to the original building
Heating	9300	9985	7%
Cooling	11180	7830	-30%
Total	20480	17815	13%

4.4 Types of Glazing

Table 5 presents the different characteristics of the glazing to be installed in order to see their influence on the energy needs of the building.

Table 5. Glazing characteristics

Type of glazing	Dimension (m)	U (W/m².K)	Solar factor	Solar reflectance	Solar transmittance
Single glazing	0.80 x 1.00	6.32	0.85	0.08	0.83
Double glazing	0.80 x 1.00	3.24	0.75	0.15	0.73
Triple glazing	0.80 x 1.00	2.17	0.70	0.20	0.63
Low-emission double glazing	0.80 x 1.00	1.76	0.60	0.12	0.53

The results of the annual energy requirement according to the type of windows in the building are shown in Figure 6. We note that the quality of the glazing has a huge influence on the total energy requirement of the building. Indeed, the use of low-emission double-glazed windows brought an energy gain of 5.46%, while the use of triple glazing brought a gain of 4.97%. Consequently, the energy gain is not proportional to the number of glazing that constitutes the window but rather to its thermal quality.

We also note that the use of a window with a loss coefficient (U=1.76 W/m².K) three times lower than that of single-glazed windows (U=6.32 W/m².K) has brought a gain very modest compared to the investment cost, however the low-emission double-glazed window will be retained as the optimal case for our building.

Generally, the annual energy saving of a window depends on several factors: the two parameters specific to the window (U-value and g-value), its orientation, the climatic conditions and the parameters of the building [23].

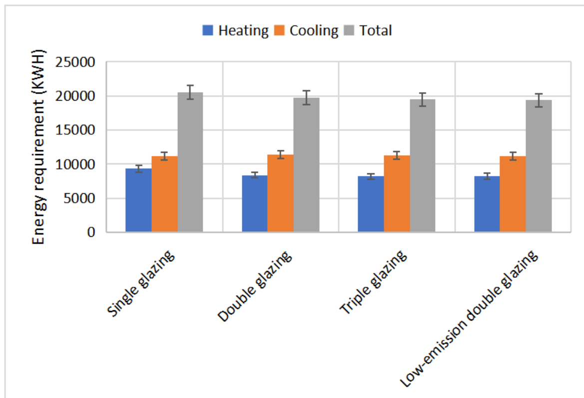


Figure 6. Annual energy requirement according to window types

4.5 Types of Building Materials

The building envelope plays a role of thermal separation between the interior and exterior atmosphere. It ensures the storage of heat in the building and then distributes it to the indoor and outdoor air [24-26].

Figure 7 gives the energy requirement of the building for some building materials. We note that the use of a double partition 30 cm thick allows a gain of 22% while the replacement of the hollow brick wall (e = 15 cm) by another hollow brick wall but of different thickness (e = 10 cm) allows a drop in energy performance of 11.20%. For a stone wall 45 cm thick, there is a reduction in energy consumption which can reach 11.70%.

The results also show that the energy requirement for air conditioning is greater than that for heating, which leads us to choose materials that allow passive cooling and lower the need for heating.

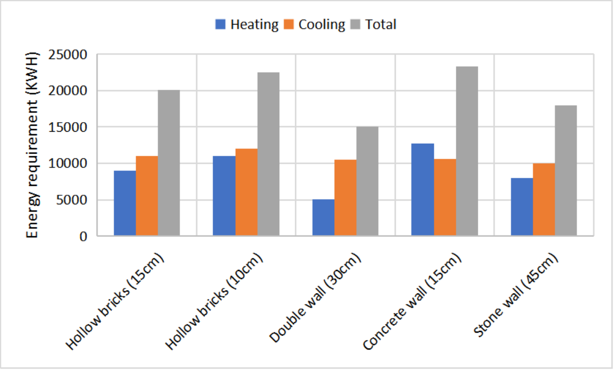


Figure 7. Annual energy requirement according to the type of building materials

4.6 Wall Insulation

Figure 8 gives the values of the building's energy requirements when using thermal insulation of the expanded polystyrene type with thermal conductivity λ = 0.042 W/m.K. We note that the insulation of the exterior walls and the roof with a thickness of 7 cm of polystyrene gave a reduction rate in energy consumption of 21% and 35% respectively. This difference is explained by the fact that the insulation of the roof allows the reduction of the energy need for heating and air conditioning, on the other hand the insulation of the exterior walls only allows the reduction of the need for heating.

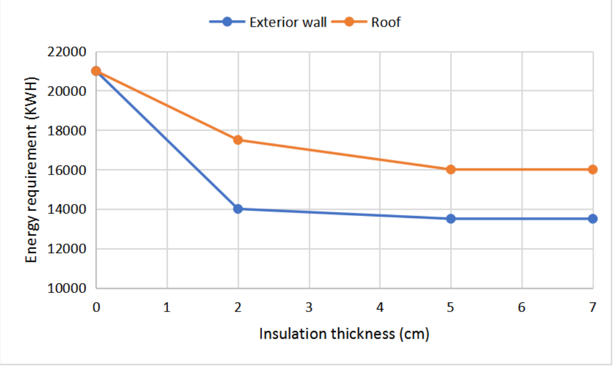


Figure 8. Annual energy requirement according to insulation thickness

5. Conclusions

This paper presented the impact that certain choices made during the design of a building can have on its energy balance. The following results can be deduced:

- Changing the North-South orientation of the building to East-West increased the demand for heating and air conditioning respectively by 5% and 11% for a total increase in consumption of 3%.
- The replacement of single-glazed windows with low-emission double-glazed windows brought an energy gain of 5.46%.
- The energy gain is not proportional to the number of glazing that constitutes a window but rather to the thermal quality of the window itself.
- The use of single glazing with a heat transfer coefficient U=6.32W/m².K did not result in an energy gain for all the facades, including the southern one. For double-glazed windows, it is absolutely necessary to avoid arranging them on the north facade, otherwise the energy needs will explode simultaneously with the increase in the glazed surface.
- The study of permanent solar protection showed that the energy requirement for heating increased inversely to air conditioning, which recorded a drop of more than 30%, ultimately arriving at a total energy gain of more than 13%.
- The building envelope has a significant impact on energy consumption. However, the replacement of the hollow brick wall (e = 15cm) by a double partition (e = 30 cm) resulted in a 22% drop in energy consumption.
- Insulation of the roof using expanded polystyrene 7 cm thick resulted in a 35% reduction in energy consumption. On the other hand, the insulation of the wall is not too profitable for a conditioned building.

The energy efficiency measures have brought an energy gain but in different proportions, this is how it is necessary to distinguish the order of priority according to the objective assigned and the financial means devoted. The effect of the equipment was excluded from the simulation since the objective of the study was to reduce the building's energy needs and not its consumption (final energy), this approach made it possible to distinguish the impact of the measures without it being altered by the operation of the equipment.

Conflict of Interest

There is no conflict of interest.

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