Improving the energy efficiency of residential buildings in Brazil by changing the geometry of ceramic bricks

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Abstract. The performance of a building's thermal and energy systems is greatly affected by its building envelope. In Brazil, residential buildings typically utilize masonry walls with coatings. Masonry materials, such as the block models, influence their energy efficiency and cost is a limiting factor to improve performance. One possible cheap way to modify thermal properties is to explore new geometries of ceramic blocks. This study introduces new ceramic block geometries for structural masonry, adapted from a commonly used 14 cm thick commercial models in Brazil. The thermal properties were evaluated numerically using Abaqus software. Additionally, the study presents the findings of an energy simulation conducted on housing models in cities like Fortaleza and Curitiba using Energyplus software. The results show potential for reducing energy consumption in colder months while having a minimal impact on energy consumption in hotter climates for a comfortable temperature.

Keywords: building envelope; energy savings; thermal performance

1 Introduction

Construction systems with improved thermal properties are crucial for user comfort and energy efficiency. Different climate zones in Brazil necessitate specific strategies and requirements for various building components, such as external walls and roofs. Criteria for external envelope performance include thermal transmittance, thermal capacity, ventilation area, and translucent surface area. Enhancing thermal comfort and energy efficiency can involve using masonry hollow clay blocks with better thermal properties. However, this can increase costs, influenced by clay consumption, void percentage, firing energy, and transportation. Studies have explored improving thermal block properties through composition changes [1–4], but significant improvements can also be achieved by modifying the block geometry without altering the raw material.

The thermal properties impact related to hollow block geometry has been the subject of different studies [5–10], involving hole accounting, thicknesses of internal walls and thermal bridge reduction. Applying these concepts to commercial masonry blocks is one way to enhance thermal and energy efficiency in buildings. The total thermal resistance R_{tot}, of a flat building component, consisting of perpendicular layers to the heat flux, shall be calculated by the expression (1):

$$R_{tot} = R_{si} + R_1 + R_2 + \cdots + R_n + R_{se} \tag{1}$$

where R_{si} represents internal surface resistance, $R_{1\ to\ n}$ represents design thermal resistance of each layer and R_{se} represents external surface resistance. Thermal transmittance corresponds to the inverse of thermal resistance. Different ways of increasing thermal resistance according to these parameters, and others mentioned in the scientific literature for the masonry unit, are presented in Table 1.

Table 1. How to increase thermal resistance according to the related parameter in masonry unit geometry

Parameter	How to increase thermal resistance
Number of voids rows	Increase the number of void rows [7, 8, 12]
Void thickness in the block section	Increase the thickness of the void, based on the ISO 6946 [13] standard, to improve thermal resistance up to a limit value that depends on the void format.
Web width in the direction of the heat flow	Reduce the thickness of internal web walls [8, 12]
Staggered or 'in-line' voids	Avoid thermal bridges in the block by arranging void perforations in quincunx [6]. For blocks with the same proportion of voids, the use of a staggered arrangement for rectangular holes has a considerable effect [12]
Void shape	Modify the vertical holes of rectangular shapes to a rhomboid shape, which reduced thermal transmittance in simulation studies by finite elements performed by Dias et al. [14] and Morales et al. [6]. For blocks with the same proportion of voids, rectangular void shapes achieved more efficient results than circular ones [12]
Hollow ratio	Increase hollow ratio (HR), which tends to significantly decrease heat transfer from the outside to the inner side of the block [12].
Unit length	Increase unit length [8].
Thermal bridge in the vertical joint region	Prolong hole perforations in the tongue and grooved area, to avoid the tongue and groove thermal bridge [6].
Mortar distribution in the joints	Use thin-layer mortar joints [8]. Use discontinuous horizontal joints [8]. Use dry vertical joints or partially filled mortar joints with mechanical locking [8].

Brazil's diverse climate zones present different challenges: cooling in northeast cities and also cooling and heating in southern cities. This study numerically evaluates how new clay block geometry improves thermal properties and the resulting energy consumption in a building. The new geometry was simulated in the Brazilian context, showing no significant increase in clay consumption compared to the reference block. The study assumes that clay consumption and mechanical resistance are related to the percentage of voids. Given the simplicity of rectangular hollow geometry and low thermal difference from other formats, this work considered the rectangular void model as the most suitable for conducting the first stage of studies on the improvement of thermal properties from two reference models, standardized by ABNT NBR 15270 [11] .

2 Methods

Steps involved in this study include the definition of the new block geometries to be used, and afterwards two simulation techniques: a numerical study, through finite element applications with the aid of Abaqus software to obtain the thermal transmittance of new ceramic block geometries; and a energy efficiency simulation in a dwelling, using EnergyPlus software. For thermal analysis, as reference models, two typical ceramic blocks for structural masonry were chosen, obtained from a supplier catalogue which meets the Brazilian standard ABNT NBR 15270 [11]. These blocks, with 140 mm of thickness, are classified into mechanical resistance categories EST40 and EST60, whose properties are presented in Table 2.

Table 2: Block properties (source: supplier catalogue).

Block model	Size (mm)	Weight (kg)	Mechanical resistance (MPa)	Prism resistance with mortar of 4.0 (MPa)	Net area/gross area (percentage of voids) (%)	U value (Thermal transmittance) (2.5 cm mortar layer + masonry unit + 2.0 cm mortar layer) (W/m².K)
EST40	140x190x290	4.90	4.0	2.5	33	Not reported
EST60	140x190x290	6.10	7.0	3.5	41	2.1

Regarding the geometry change, some premises were adopted. At first, for each reference masonry unit, minimum wall thickness measures provided by the ABNT NBR 15270 [11] standard for clay blocks with vertical voids were adopted. The mortar distribution was maintained using the same format as the reference block. In the second stage, the following changes were made: a discontinuity was introduced into the side shell of the block, to reduce the thermal bridge effect; horizontal mortar distribution was altered to avoid a thermal bridge through the mortar; and the vertical joint of the mortar filled the entire height in all cases, with 1 cm of thickness and 3 cm of depth. Figure 1 shows reference blocks and alternative geometries. A comparison between the properties of the blocks, with both the common geometry and the new geometries, including the relationship between net area and gross area, is presented in Table 3. Masonry unit dimensions were not changed.

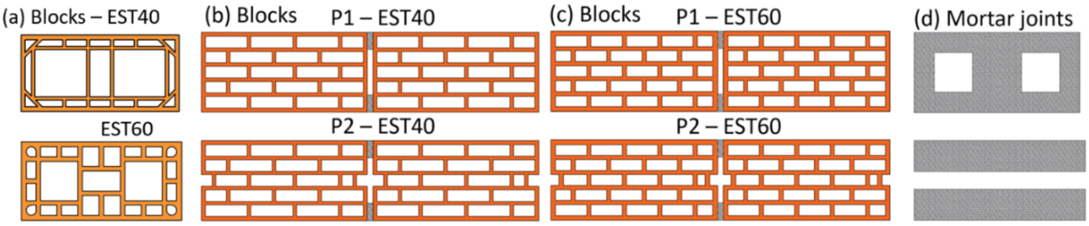


Figure 1. (a) reference blocks; (b) alternative P1 geometries for EST 40; (c) alternative P1 geometries for EST 60; (d) mortar joints distributions for P1 and P2.

Table 3: Masonry unit dimensions.

Model	External dimensions (cm)	Net Area/Gross Area (%)	Shell/web thickness (mm)
EST40	14x19x29	33	7 and 9/ 6
P1-EST40	14x19x29	35	7/ 6
P2-EST40	14x19x29	35	7/ 6
EST60	14x19x29	41	9/ 8
P1-EST60	14x19x29	42	8/ 7
P2-EST60	14x19x29	42	8/ 7

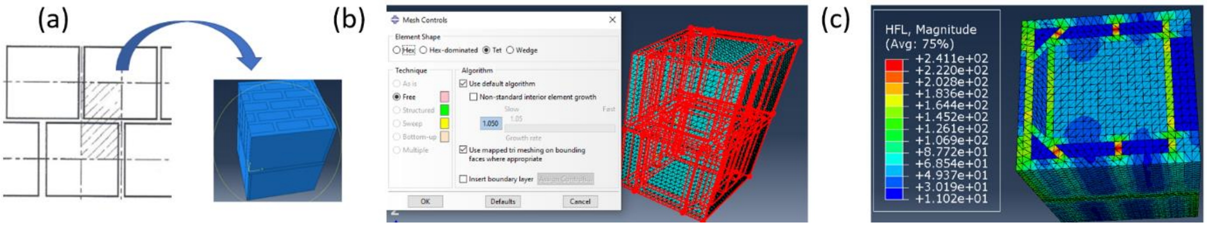
2.1 Numerical simulation procedure using finite elements

Before conducting a masonry unit simulation in the Abaqus software, which is one of the objects of study of this work. Validation was performed with an example model provided by annex D in the EN 1745 [15] standard adapted into a three-dimensional format, with a height of 20 cm. Simulations were run in serial. For the simulation procedure, the coefficients for thermal conductivity were specified, $\lambda = 1.05$ W/(m^2. ºC) and $\lambda = 1.15$ W/(m^2. ºC) respectively. These coefficients were based on ABNT NBR 15220 [16] standard. In the specific case of ceramic material, the value considers a specific mass between 1800 and 2000 kg/m^3. For the air voids present in the masonry, where heat transmission phenomena occur through conduction, convection and radiation, equivalent thermal conductivity coefficients were adopted by the procedure described in Standard EN ISO 6946 [13], adopting a linear analysis in software. The temperature of 20° C was adopted to obtain the black body radiation coefficient. Three-dimensional modelling was established using a repetitive masonry unit. The tie connection type was considered to allow the conduction of heat flow between the modelled elements.

A temperature gradient between the two faces was established at 20°C (40°C and 20°C) to generate a heat flux and equations were solved in a steady-state. A mesh with triangular tetrahedral elements, including voids and joints, was adopted to discretize masonry units. Using the software, the heat flow was obtained in the masonry stretch. The thermal transmission coefficient was obtained by expression (2):

$$\mathrm{U} = \frac{\sum \mathrm{Fl}}{\Delta \mathrm{TLh}} \tag{2}$$

where Fl represents the sum of the heat flow reaction in one of the faces submitted to the flow, obtained in the software through the sum of the heat flow reaction; ΔT Represents the temperature difference (20 ºC in this work); Lh represents the area of the face obtained by multiplying measurements (0.15m x 0.2m in this work). Figure 2 shows repetitive masonry unit (a) and finite element mesh (b)and heat flux (c) results obtained for a masonry unit.



Element Shape: ○ Hex ○ Hex-dominated ● Tet ○ Wedge

Technique: ○ As is ● Free ○ Structured ○ Sweep ○ Bottom-up ○ Multiple

Algorithm:
☑ Use default algorithm
☐ Non-standard interior element growth
Slow 1.05 Fast
1.050
Growth rate
☑ Use mapped tri meshing on bounding faces where appropriate
☐ Insert boundary layer

Figure 2. (a) Repetitive Masonry unit; (b) Finite element mesh; (c) heat flux.

2.2 Energy efficiency numerical analysis in housing buildings

This step analyzes energy requirements for rooms with walls built using different masonry units: EST40 and P1-EST40. Simulations were conducted using EnergyPlus software [17], which allows comprehensive energy simulations for buildings, including heating, cooling, lighting, and water use. The building thermal zone calculation method is a heat balance model. Air in each thermal zone can be modelled with uniform temperature throughout. EnergyPlus requires two input files: an IDF file describing the building model, occupancy pattern, and material specifications, and an EPW file with the climatic data for the simulation location.

One of the main challenges of a project is to reduce energy requirements for heating or cooling to maintain thermal comfort. Improving envelope thermal insulation is a key strategy for enhancing building efficiency. The simulation model adopted in this work followed an adaptation of the reference model obtained by Schaefer and Ghisi [18], through the clustering process of housing unit projects in Florianópolis, Brazil. The model presents 37 m² house comprising two bedrooms, one bathroom and a combined living room and kitchen, as shown in Figure 3. Openings (glass windows) correspond to 5.61% of the area of the south façade, 7.5% of the area of the west façade, 5.61% of the north façade area, and 9.77% of the east façade area. Table 4 presents construction patterns. For this, the following configurations and adaptations were chosen for the house: house 1, with a flat roof and glass windows; house 2 with a ceramic tile roof and glass windows; and apartment with glass windows and two façades.

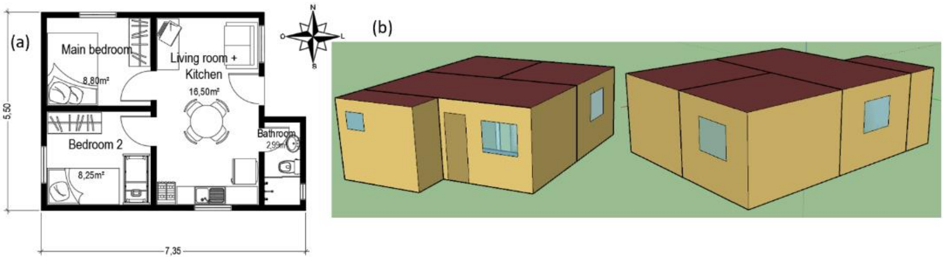


Figure 3. (a) Reference housing plan; (b) prospective façades of the housing unit

Table 4: main characteristics of the construction systems

Construction elements	Layers	Thickness (m)	Conductivity λ(W/(m.K))	Density (kg/m³)	Cp J/kg.K	U (W/(m².K))
Floors	Concrete	0.1	1.15	2400	1000	8.32
	Mortar	0.03	1.15	2000	1000	
	Ceramic tile	0.0075	1.05	2000	920	
Walls (EST 40 block)	Mortar	0.025	1.15	2000	1000	2.82
	Clay block	0.14	0.450	688	932	
	Coating mortar	0.025	1.15	2000	1000	
Walls (P1 EST 40 block)	Mortar	0.025	1.15	2000	1000	
	Clay block	0.14	0.290	723	932	1.90

	Coating mortar	0.025	1.15	2000	1000	
Roof, made with layer of ceramic tiles and reinforced concrete slab	Ceramic tile	0.01	1.05	2000	920	3.80
	Air gap (R=0,21 m^2.k/W)	variable	-	-	-	
	Concrete	0.05	1.15	2400	1000	
Flat roof - concrete waterproofing	Concrete	0.1	1.15	2400	1000	8.85
	Bitumen sheet	-	-	-	-	
	Mortar	0.03	1.15	2000	1000	

The analysis included different weather conditions for Curitiba and Fortaleza, using Test Reference Year (TRY) climatic files. The evaluation considered occupancy and usage by a family of four (metabolic rate: 108 W/person in the living room, 81 W/person in bedrooms), with the following characteristics:

- Room occupancy: Bedrooms from 00:00-07:00 and 22:00-00:00 with 2 people; 14:00-18:00 with 1 person; living room from 18:00-22:00 with 2 people;
- Electrical equipment usage: 14:00-21:00 in the living room, with 120W equipment power;
- Artificial lighting: 06:00-08:00 and 22:00-24:00 in bedrooms (60W); 06:00-08:00 in the living (100W);
- Window opening: 07:00-00:00 and 22:00-00:00 in bedrooms; 16:00-22:00 in the living room
- Comfort temperature: 18°C to 26°C, obtained by Schaefer and Ghisi [18];
- A ventilation model configured by the airflow network object, present in the EnergyPlus software, which considers natural ventilation according to the climatic file and no air renewal between roof and ceiling (slab).

3 Results and discussion

3.1 Thermal transmittance (U)

The results of the thermal transmittance, obtained after the described procedures, are presented in Table 5. It can be observed that the reduction related to the masonry units ranged from 31.7% to 36.1% in geometric changes. When considering a wall with mortar coating of 2.5 cm on one side and 2.0 cm of coating on the other, including values of internal (Rsi) and external (Rse) surface resistance, with the values of 0.13 and 0.04 m^2.K/W respectively, thermal transmittance decreases to values ranging from 21.3% to 25.2%.

Table 5: Main thermal properties of walls

Masonry unit model	Net Area/Gross Area (block) (%)	U masonry unit ($W/m^2.K$)	Reduction in U masonry unit (%)	Thermal Resistance ($m^2.K/W$)	U wall ($W/m^2.K$)	Reduction (U wall) (%)
EST 40	33	3.212	-	0.311	1.921	-
P1 EST 40	35	2.067	35.6	0.484	1.443	24.9
P2 EST 40	35	2.054	36.1	0.487	1.437	25.2
EST 60	41	3.398	-	0.294	1.987	-
P1 EST 60	42	2.321	31.7	0.431	1.562	21.3
P2 EST 60	42	2.310	32.0	0.433	1.558	21.6

The use of a staggered arrangement and the increased number of rows has influenced significantly U-reduction (35.6% for P1 EST 40 and 31.7% for P1 EST 60) compared to reference units. On the other hand, the discontinuity introduced into the sides shell of the block and changed horizontal mortar distribution in P2 masonry units could provide low significant U-reduction (0.63% for P2 EST 40 and 0.47% for P2 EST 60) when compared to P1. The thermal transmittance in the wall is lower than in the masonry unit, an effect provided by the insertion of the coating layers. This effect occurs because the coating layers have the same thermal resistance value for both types of walls and influence the result of the U wall. Finally, these results suggest that internal geometric modifications, even without changes in external measures and without a significant increase in the consumption of materials, can provide changes in thermal properties.

3.2 Energy simulation results

The EnergyPlus results show average monthly energy consumption to maintain comfort temperatures (18°-26°C). Figure 4 (a and b) illustrates the energy used in July (high heating) and February (high cooling) in Curitiba. The house with a flat roof had the highest consumption due to its high thermal transmittance. The house with a ceramic roof had lower consumption, and the apartments had the lowest. The apartment typology was configured with adiabatic south and part of the east walls, as well as the ceiling and floor, to simulate typical condominium settings. The ceramic roof, having lower transmittance than the flat roof, presented lower energy consumption.

Changing the geometry from the EST 40 block to the P1 EST 40 block led to significant long-term heating savings. In July, the highest heating consumption month, the reductions for house typologies with a ceramic roof, flat roof, and apartments were 11.2%, 9.0%, and 34.0%, respectively. The substantial reduction in apartments is due to predominant heat exchange through external walls, where the block's thermal properties have a greater influence. However, for cooling energy, the change in block geometry did not show significant differences. This may be attributed to the adopted mode for opening doors and windows, which are kept open at temperatures above 18°C from 7 am to midnight. In Fortaleza, a city with high humidity and higher average temperatures than Curitiba, the reduction in cooling consumption was minimal, reinforcing that the impact of block geometry change is less relevant due to the door and window opening procedure Figure 4 (c and d).

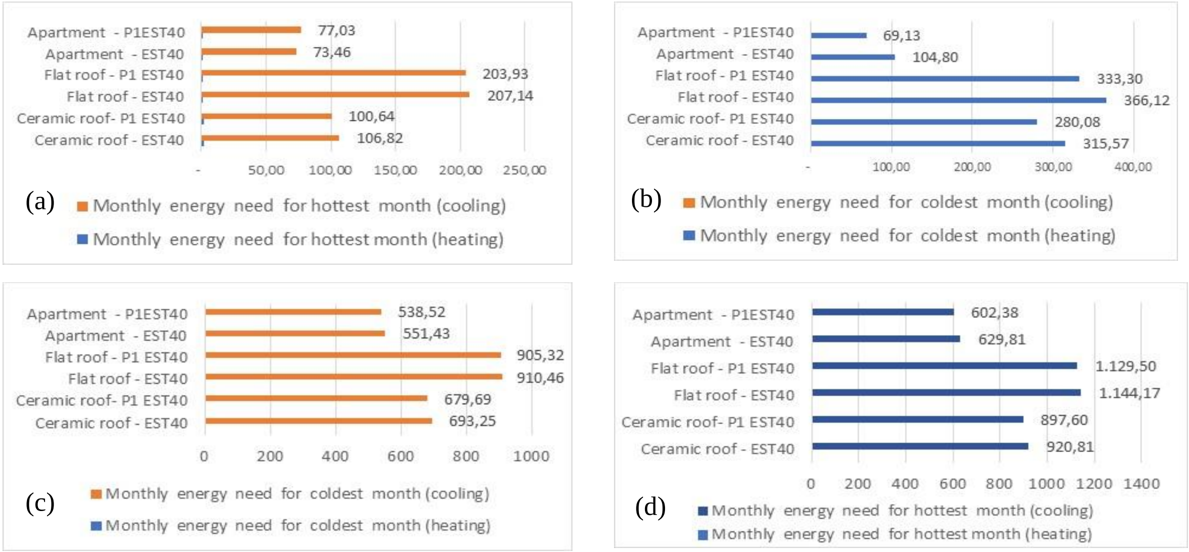


Figure 4. Monthly Energy (KWh/month) for: Curitiba, February (a) and August (b); Fortaleza, June (c) and December (d).

The energy analysis did not simulate HVAC systems configured in Energyplus software. The energy savings results represent total thermal energy required for cooling or heating to comfort temperature. Due to the presented results, it can be inferred that new blocks show a potential to obtain energy savings and better thermal comfort when compared to traditional masonry units.

4 Conclusions

A new clay block geometry was developed from modifications to a commercial reference model, resulting in improved thermal properties without significant material additions. The geometry consists of simple rectangular voids in the longitudinal direction of the wall with alternating patterns. Simulations of two prototypes showed transmittance reductions of 35.6% and 36.1% compared to the EST-40 reference unit, and reductions of 31.7% and 32% compared to the EST-60 reference unit. This geometry does not suggest increasing costs and logistical distribution changing, since it maintains the clay consumption and the same external dimensions.

Energy simulations using EnergyPlus software were conducted for housing projects in Curitiba and Fortaleza, Brazil. The altered block, P1 EST 40, significantly reduced energy during winter in Curitiba. However, in Fortaleza and during Curitiba's summer, energy savings were negligible due to the high temperatures and the design specifications for opening schedules of windows and doors. The greatest energy savings were observed in apartment typologies, where walls are the primary heat transfer mechanisms. In houses with flat roofs, where heat transfer occurs mostly through the ceiling, the impact of block transmittance reduction was minor during winter.

The findings are crucial for discussing block geometry improvements for energy efficiency in Brazil. Due to the limitations of this research, future research should focus on developing complementary masonry block families, architectural typologies that enhance energy efficiency in warmer months, evaluating mechanical characteristics changes due to block modifications, and simulating energy consumption and internal temperatures with varying occupation patterns and HVAC system usage.

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