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# Fighting energy poverty in a typical Peruvian rural house

Gino Gutierrez<sup>1</sup>, Enrico De Angelis<sup>1</sup>

<sup>1</sup> ABC Department, Politecnico di Milano, Via Ponzio 31, Milano, Italy

Corresponding author: [enrico.deangelis@polimi.it](mailto:enrico.deangelis@polimi.it)

**Abstract.** This study evaluates a typical, informal construction in the Peruvian highlands of Cuzco, a site at an Equatorial latitude (13,5° S), approximately, 3.400 mamsl, with a subtropical highland climate (Köppen Cwb). Its aim is to compare low-cost passive retrofit strategies, applicable in cities and rural areas with similar climate, and validate a best choice. To carry out this study a dynamic energy simulation was performed, using the typical meteorological year (IWEC) provided by ASHRAE. The model was used to understand the effects of simple changes in the envelope configuration and the associated effect on infiltration, and their combination, on the indoor comfort and the energy performance of the building. The outcomes were displayed in a simple Energy-needs/transformation cost chart and a Pareto curve was selected, identifying an optimal subset of solutions. Adequate indoor conditions can be obtained with the implementation of only passive strategies, mainly empowering the thermal insulation of walls, roofs and windows using simple, low cost, local technologies, and the control of the heat transmission toward the soil: the energy poverty of the informal settlements of Cuzco can be fought with very simple initiatives, that require investments with a reasonably short return of investment.

## 1. Introduction

The energy retrofit of housing assets is a topic studied by many authors. The argument gained interest in the last twenty years, once it was recognized what a fundamental role the built asset in Green House Gas emissions played and that the low building replacement rate and the consequent need for transformation policies capable of improving the energy efficiency of existing buildings too and to a nearly zero-carbon (or carbon-negative) built environment was a reachable goal [1,2,3].

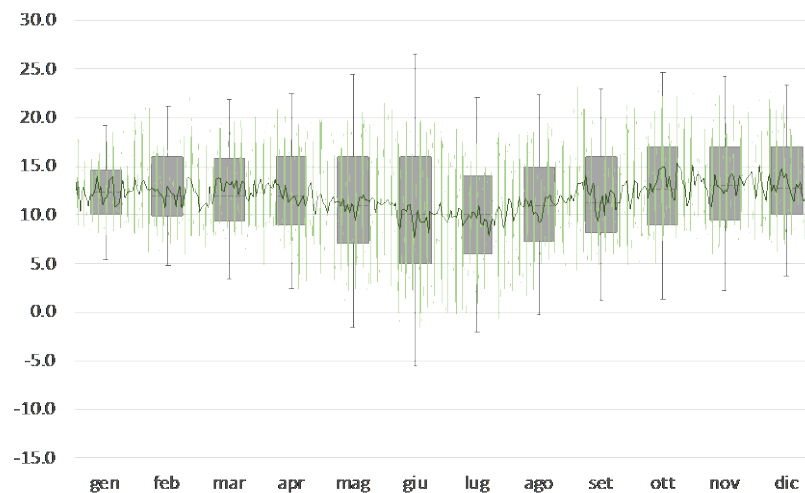
The current situation in the Peruvian construction field is surprisingly similar to other developing countries (India, for example [4]), where traditional construction technologies are mostly abandoned for modern but qualitatively poor ones, usually with very low thermal insulation performances.

This paper reports a study developed with the aim of identifying the best retrofit strategies for the specific climatic conditions of the Cuzco highlands, i.e. the solutions with the lowest possible retrofitting and operating costs (economical as well as environmental), privileging bio-based insulation [5] and passive strategies, capable to minimize the need for heating and cooling, the discomfort (and the related health risks) of a too cold (or too hot) living environment in winter (or summer) period, (defined, with reference to ISO 17772-2, as the number of hours during which the indoor operative temperature was foreseen to be outside the thermal comfort: below or beyond the interval 20-26°C).

The study was developed on a typical rural house; a range of feasible retrofit solutions were studied, and their effectiveness was evaluated, based on the results of a dynamic simulation of the state of the indoor environment and the amount of energy needed to heat or cool the building when needed.



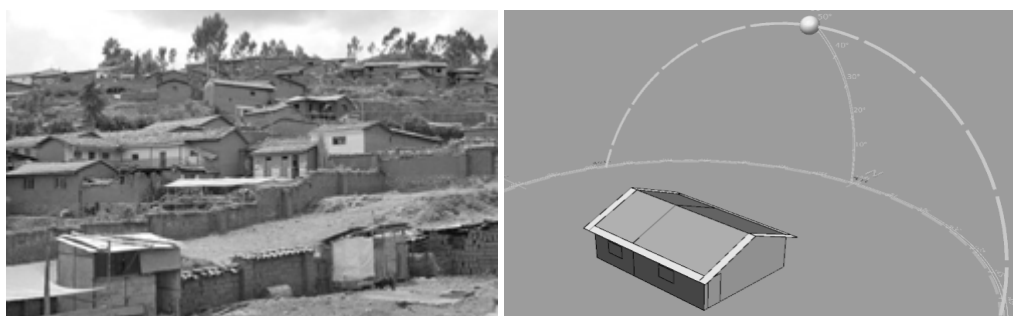
The city of Cuzco is located in the southeast part of Peru ( $13^{\circ}31' S$ ;  $71^{\circ}58' W$ ), at a very high altitude (3.400 mamsl); its climate is classified as “subtropical highland climate” (Köppen Cwb) and, the available typical weather year dataset (the ASHRAE IWEC/EPW file built with reference to the 1980-1999 period [6]) shows rainy summers, between October and March, and a dry, temperate, sunny and warm winter (from April to September), during which the average outdoor temperature ranges from  $14^{\circ}\text{C}$  to  $10^{\circ}\text{C}$  and the only “cold” character is the night frost, as we can see from Figure 1.



**Figure 1.** Outdoor air temperature in Cuzco Weather Year for Energy Calculations (WYEC). The boxes represent  $I_{25/75}$ , the 25 and 75% percentiles range, the whiskers, the outlier limit ( $\pm 1.5 \cdot I_{25/75}$ ).

## 2. The analyzed building

The typical Peruvian highlands house was defined as a single floor, rectangular shape, simple building, with an internal height ranging from 2.5 to 4 m under a pitched roof as in figure 2: two bedrooms with a dining-room/kitchen, sharing (40-60%) a gross floor area of  $70 \text{ m}^2$ . In its baseline configuration, the *roof* is realized with a simple, wavy metallic plate, supported by a light wood-frame and 0.3 m thick adobe perimetral and internal *walls*; the *floor* too is simple rammed earth. Windows, eventually, were chosen as little (four  $1.2 \times 0.9 \text{ m}$ ) wood-framed, simple-glass, windows, for a Window to Floor Ratio equal to about 8%, equally distributed on the two opposed North and South facing walls.



**Figure 2.** The analyzed building model (dx); a view of a real (informal) settlement in Cuzco (sx).

The Solar gains were calculated taking into account an average solar transmittance (referred to the whole window area) equal to 0.80, while the schedule of the internal gains (about 350 W, mainly due to occupancy loads) was simplified assigning, alternatively, the whole amount to daytime area, from 7 am to 9 pm, and to the rooms, in the rest of the day, neglecting the loads from appliances and artificial lighting. The infiltration and ventilation rate was set to 1.25 [1/h], in the baseline condition, and the

thermal comfort range was taken as the interval 20-26°C [7]. Eventually, the performances of the retrofit solutions were calculated in terms of:

- ☞ *percentage of hours* within the comfort range (in bedrooms and living room);
- ☞ *energy needs* (for an ideal heating plant, without any power limit and 100% efficiency) for keeping it within the comfort range, referred to the net floor area.

The first performance indicator was used to understand if the objective of keeping the percentage of hours lower than 10% was a feasible one, while the second was coupled to the (construction) cost of the retrofit strategy, to realize, in a dedicated chart, the whole set of combinations and their minimization Pareto curve.

**3. The retrofit strategies and their combination.**

The strategies were selected with reference to the technologies proposed by the *German-Peruvian cooperation project*, the *Department of housing, construction and sanitation* and the *National University of Engineering* [8,9]: the thermal insulation products used are two local, cheap, bio-based materials: the straw (“totora”, a new promising bio-based material), and a sheep wool. Totora panels measure, approximately, 1.3x2m with a thickness of 5cm, woven together with small ropes and few points of glue. A burlap fabric is a thick and rough fabric, easily accessible for a cheap price, durable, made of various types of natural fibres (in this case jute).

**Table 1.** Selected roof strategies description.

1. ROOF INSULATION	U value [W/m²K]	Cost (S./m²)	
1.0 = Wavy metallic plate supported by wooden frame structure (BASELINE).	7.14	-	
1.1 = Straw insulation (6 cm) supported by a plywood board from inside.	0.74	49.2	
1.2 = Airtight attic space separation with a burlap fabric separation layer.	2.97	21.3	
1.3 = sheep wool (6 cm) + straw (totora) insulation (10cm) supported by a burlap fabric.	0.36	67.5	
1.4 = 1.3 + 5 cm of straw (totora) insulation supported by a burlap fabric horizontally placed as ceiling.	0.26	85.3	

**Table 2.** Selected floor strategies description.

2. FLOOR INSULATION	U value [W/m²K]	Cost (S./ m²)	
2.0 – Rammed earth floor (BASELINE).		-	
2.1 = Stone bed (10cm) with a wooden frame (5cm) and a wooden board finish (2.5cm).	1.60	104.0	
2.2 = 2.1 + Mud mortar (5cm) over stone bed	1.45	108.3	
2.3 = Stone bed (10cm) with a mud mortar and straw layer (10cm) and a mud mortar finish (2.5cm).	1.99	18.6	
2.4 = 2.3 with a mud mortar and straw layer (20cm instead of 10cm).	1.36	33.0	

**Table 3.** Selected wall strategies description.

3. WALL INSULATION	U value [W/m <sup>2</sup> K]	Cost (S./ m <sup>2</sup> )	
3.0 = Adobe wall BASELINE (300 mm)		-	
3.1 = 3.0 + Tatora ETICS (50 mm):	0.70	38.3	
3.2 = 3.0 + Tatora ETICS (100 mm):	0.44	72.4	
3.3 = 3.0 + Tatora ETICS (200 mm):	0.25	140.7	

**Table 4.** Selected window/door strategies description.

4. WINDOW/DOOR RETROFIT	U value [W/m <sup>2</sup> K]	Cost (S. / m <sup>2</sup> )	
4.0 = wood-frame/single glass window	4.9	-	
4.1 = 4.0 + outdoor shutter (60 mm straw)	4.9-0.75	2.0	
4.2 = wood-frame/double glass window	1.47	5.5	
4.3 = 4.2 + outdoor shutter (60 mm straw)	1.47-0.53	12.4	
4.4 = 4.3 + insulated door (50 mm straw)	0.54	12.4+5.6	

**Table 5.** Thermal bridge reduction strategie.

5. GROUND CONTACT INSULATION	U value [W/m <sup>2</sup> K]	Cost (S.)	
5.0 = Simple foundation (stones)		-	
5.1 = Perimetral insulation (1mx150 mm EPS)	0.27	22.9	

These panels were eventually combined as indicated in Table 6, and a progressive reduction of the infiltration rate was supposed, given that in every insulation step the infiltrations are reduced. In addition, a conditional ventilation is implemented when the inside temperature is higher than 26°C, representing in this way the fact that people open the windows when this value is reached:

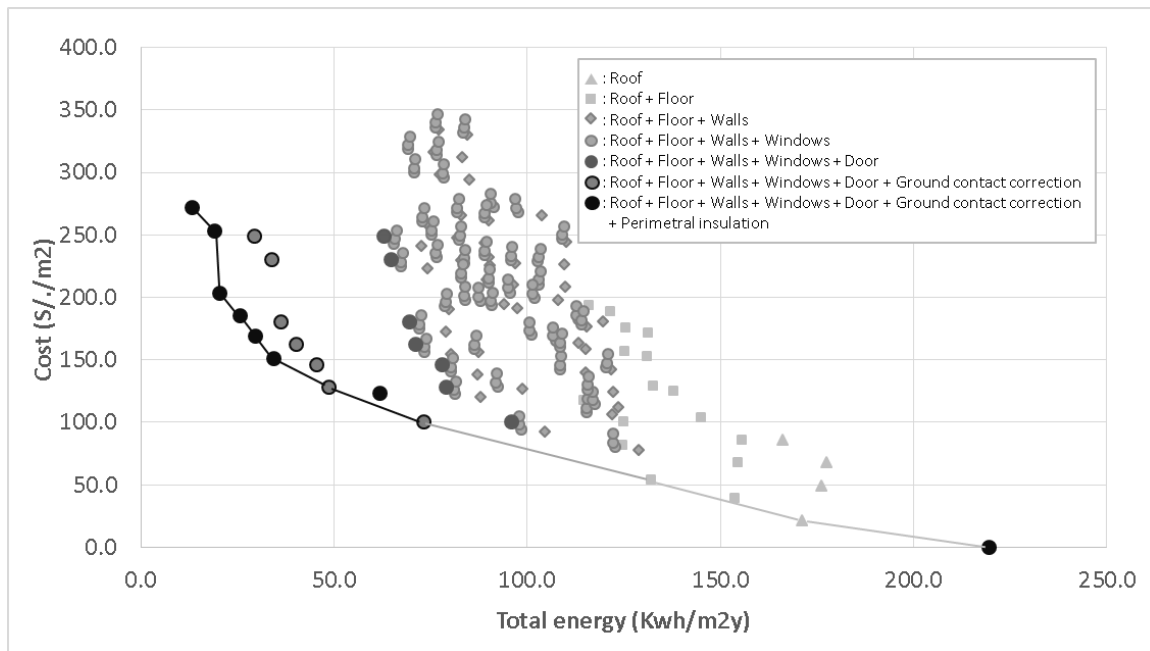
**Table 6.** Insulation + Ventilation Combinations

Steps	Description	Combinations	Infiltration + ventilation
Step 0	Baseline	1	1.25 ach
Step 1	Roof	4	0.75 ach
Step 2	Roof+Floor	4x4 = 16	0.75 ach
Step 3	Roof+Floor+Wall	4x4x3 = 48	0.60 ach
Step 4	Roof+Floor+Wall+Window	4x4x3x3 = 144	0.50 ach

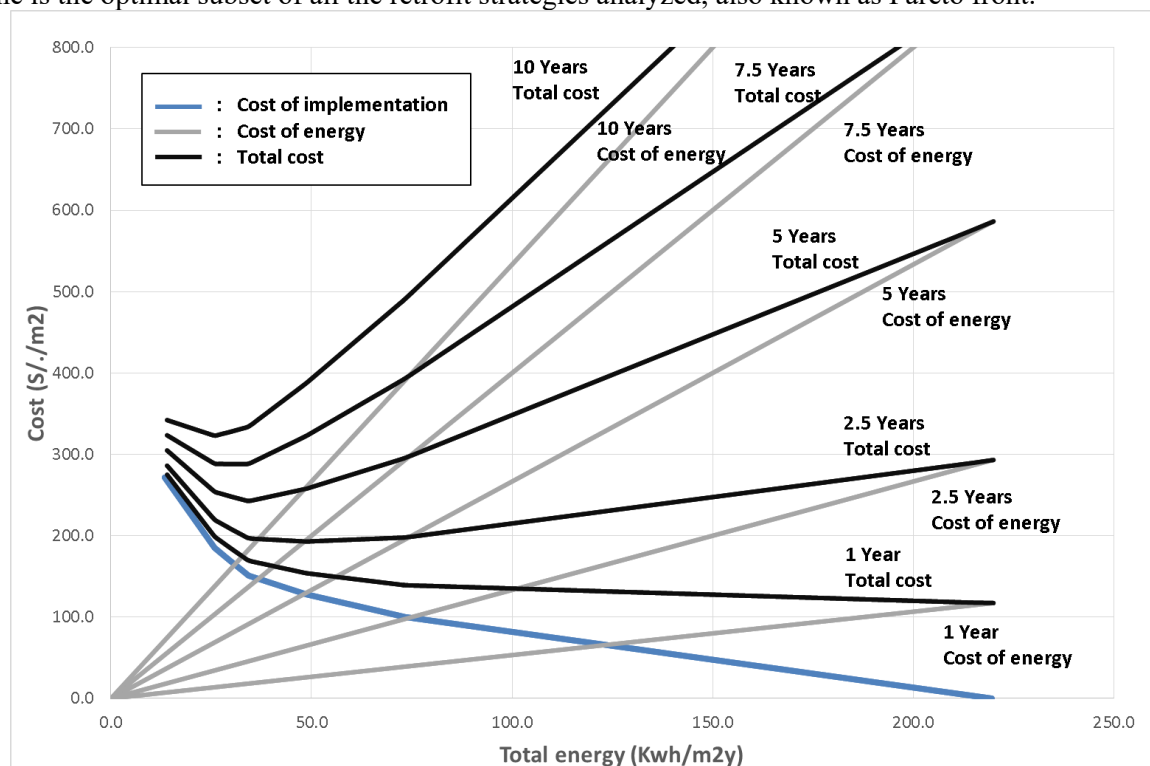
### 4. Results

In Figure 3, the chart reports the results in terms of reduction of the heating needs and construction cost for the main elementary strategies, as described in the previous paragraph and their combination.

In the Figure 4, the thickest line represents the optimal subset identified in the previous picture (the pareto optimal region). Four other straight lines are represented: these lines identify the operation cost from 1 to 10 years. We can – geometrically – add to this broken line, other ones, representing the operation cost for a specified service life (the cost of energy needed by an ideal system to keep the indoor thermal conditions beyond the lower limit in winter is proportional to the total energy needs for one year, times the number of years considered and the cost of energy per kWh). The longer the period the steeper the line (the energy cost has been taken equal to 0.53 S./kWh).



**Figure 3.** Representation of the construction costs (Y-axis) all the elementary and combined retrofit strategies analyzed, referred to their total energy needs per unit of net floor area (X-axis). The boundary line is the optimal subset of all the retrofit strategies analyzed, also known as Pareto front.



**Figure 4.** The cost of operational energy consumption is proportional to the time length considered (we draw different grey lines, for five different durations, i.e. acceptable return of investment times). These lines are summed to the Pareto front line, the ideal curve found in the previous picture, to identify, among them, the optimal configuration of the retrofit solutions (it exists only for periods longer than 2 years), for (transformation + operational energy) total costs.

The result is a series of total-cost curves with a concave form (except the case of a very short life of 1 year) that identifies an optimal minimum. The best solution for a 10 years return of investment is the following: Roof 1.3 + Floor 2.4 + Wall 3.3 + Window & Door 4.4 + ground contact correction.

## 5. Conclusions

The study gives encouraging results about the feasibility of a low cost retrofit strategy:

- It is possible to reach adequate indoor comfort conditions just with the implementation of passive strategies: mainly empowering the thermal insulation of walls, roofs and windows using simple, low cost, local technologies, and the control of the heat transmission toward the soil.
- It is possible to operate these retrofits with low cost, locally available, bio-based materials,
- It is possible to identify a (Pareto-optimal) subset of these strategies and, among these strategies, to identify a best one, establishing a reference service life and finding the minimum of the total (construction+operational) cost.
- The energy poverty of the informal settlements of Cuzco can be fought with very simple initiatives, that require investments with a reasonably short return of investment.
- The longer is the service life, the higher is the optimal energy performance. But the higher is the optimal energy performance, the higher must be the available investment capacity.
- To enhance indoor comfort as well as health conditions in informal settlements, where users do not own the property they live in, the communities should facilitate energy retrofit projects, showing controlled solutions, offering basic consultancy and training some reliable DIY, to minimize transformation costs.

However, a number of aspects are still to be investigated, such as the implementation of other passive strategies, for example, the use of skylights to reduce the need for artificial lighting. Both direct solar gains and indirect ones may be improved, for example using simplified Trombe walls or similar devices. Moreover, the evaluation of the durability of the bio-based materials solutions should be checked, since these materials might require more maintenance and substitution than the conventional ones.

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