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Improvement Proposal of Bottom-Up Approach for the Energy Characterization of Buildings in the Tropical Climate

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Abstract: The energy characterization of buildings can be done by bottom-up methods such as energy simulation models (samples or archetypes). A sample consists of the selection of real buildings and an archetype is a theoretical building that represents them. Nevertheless, both approaches have shortcomings for the creation of energy models. This work proposes to improve the sampling approach from the validation of input data, and calibration of models by individual adjustment processes. The studied category corresponds to multi-family buildings of median incomes from the Metropolitan Area of Bucaramanga (Colombia). This study presents the energy model of five existing buildings and an archetype, calibration results, energy characterization, and comparative analysis between both approaches. The sampling approach indicates that housing units and general services demand an average of 76.9% and 23.1% of consumed energy, respectively. The average energy consumption by housing units is 22.38 kWh/m^2·year caused by appliances (85.3%), lighting (11.2%), and air conditioning (3.5%). The archetype presents similar results for the energy consumption of housing units (kWh/m^2·year), but notable differences concerning a specific behavior of inner spaces, being the sampling approach more accurate to characterize to a building category.

Keywords: multi-family buildings; energy behavior; dynamic energy modeling; sample; archetype

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1. Introduction

Buildings make an important contribution to energy use and greenhouse gas emissions worldwide. In 2019, the energy consumption by buildings represented 35% of global energy consumption and 38% of whole related emissions [1,2].

Within critical actions to reduce energy consumption by buildings and to move towards decarbonization of the construction sector, the definition and implementation of energy efficiency regulations and programs, as code and labeling systems, allow for the qualification of the energy performance of buildings [1].

In the Colombian framework, the Ministry of Housing, City, and Territory issued Resolution 0549 in 2015, which established the energy and water-saving percentage of obligatory fulfillment for new buildings of several typologies according to climate type [3]. As part of technical studies for making this regulation, a process of energy characterization was developed in the country, specifically for typologies as low-income residential, normal residential, offices, hospitals, and hotels, for four cities: Bogotá, Medellín, Cali, and Barranquilla, which represent the cold, temperate, dry-hot and humid-hot climates, respectively. From this characterization, an energy simulation model was made for each building typology (archetype) and city. These models allowed defining the potential energy saving of several energy efficiency strategies applicable to buildings.

To work towards a scenery of building with better energy efficiency in Colombia, the Ministry of Mines and Energy, Ministry of Science, Technology, and Innovation, and the

Universidad Industrial de Santander established technical guidelines to create an energy-labeling system of buildings—ELSB. Its creation demands a detailed comprehension of the energy behavior of the buildings [2,4,5]. In general, this is carried out in four steps: (i) selection of a representative sample of buildings belonging to the building category; (ii) collection of detailed data of buildings; (iii) characterization of energy behavior of selected buildings through methods of modeling and engineering; and (iv) extrapolation and application of obtained results taking into account the number of buildings of the category [4].

According to a literature review, the characterization of the energy behavior of a group of buildings can be done from two kinds of methods: top-down and bottom-up [2,6]. The top-down methods are based on the correlation of energy demand with climate parameters and economic factors (energy price, investment, and income, among others) [2]. Generally, these methods are used widely for macroeconomic analysis with historical data.

On the other hand, the bottom-up methods use models of buildings that represent the category in [2,5]. They can be classified as statistical methods based on historical data and engineering methods that allow determining the energy consumption according to models based and physical principles, building characteristics, and the use of the equipment and inner spaces [5,6]. These representative energy models of buildings allow the prediction of energy consumptions and estimating the impacts of the potential implementation of energy efficiency strategies [7]. The later can be energy simulation models [4,7] classified as archetypes and samples.

The archetypes are energy simulation models created (no reals) from a combination of several characteristics common or representative of a building category with similar attributes [5], while a sample is a group of real buildings that represents the whole category.

Potentially, the use of a building sample can more accurately reflect the heterogeneity of a category of existing buildings than an archetype. Nevertheless, a significant number of representative buildings or an expert analysis is necessary to ensure that the characteristics of the sampling are convenient to extrapolate the results [5].

The energy characterization by sampling or archetype has some disadvantages. First, the uncertainty of input data, as detailed use of appliances and behavior of users, reduces the reliability of the energy modeling [7–11]. Frequently, the energy characterization studies are limited for data availability, for that the analysis team tends to complete the lack information according to their expertise [5,12,13]. Second, there are insufficiencies of the detail level of results to describe the energy behavior of the buildings category and, thus, to identify energy-saving measures and their impact [5,12].

Third, an inappropriate classification of the stock of existing buildings or a wrong selection of the representative buildings directly affect the validity of the results of energy characterization for the category [12,14].

Some improvements against these disadvantages consist of carrying on segmentation of stocks buildings by common characteristics considering housing typologies, climatization type, and construction period, among others [13,15].

Given that user behaviors strongly determine the energy consumption, ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) has suggested an occupancy schedule for residential building energy simulations [16]. However, this is not satisfactory because such a schedule depends on climate, culture, and available technology (lighting and climatization), among others. Therefore, some studies opt to define patterns of behavior of users (e.g., occupancy and use of equipment) [7,13,15–18], which is mainly possible because it is available building energy databases obtained from surveys or national studies.

Concerning the above, this work proposes the application of the sampling approach (bottom-up) to carry out the energy characterization of a group of buildings belonging to the median income multi-family building category from the Metropolitan Area of Bucaramanga (MAB), considering the Colombian context and aimed to support the establishment of an ELSB.

A categorization of the buildings is done according to the socio-economic status, which influences the area of housing units, construction system, materials, number of appliances, and occupation regime, among others.

Given that the energy database for MAB is unavailable for this building, this study proposes to validate the input data from visits to the site to corroborate technical information obtained in plans, surveys to users, and collected electricity bills for each inner space (housing units and general service), which strengthens the quality of energy modeling.

Concerning the calibration process, most studies conduct only one adjustment process using the monthly/annual energy consumption for the whole housing building. For that reason, it is proposed to increase the number of adjustment processes as follows: one process for general services area and as many processes as typologies defined for housing units. This allows improving the accuracy of the results of the simulation.

This article is structured as follows: initially, the methodology describes the selection of representative buildings, collection of information, energy modeling, construction of the archetype for the category (median income multi-family buildings), and planning of energy simulations (Section 2). Subsequently, analysis of the results presents the main findings related to calibration of energy models, use and distribution of energy consumption, thermal comfort, heat gains and heat losses, comparative analysis between improved sampling approach and archetype approach, and the discussion (Section 3). Finally, the conclusions are presented (Section 4).

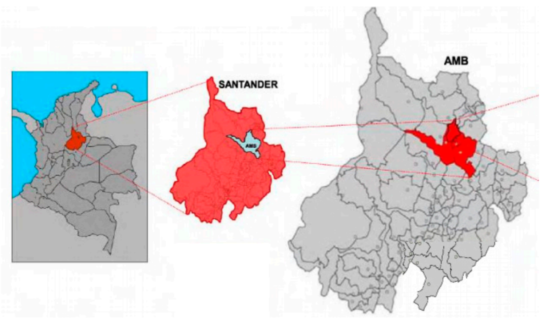
2. Methodology

This Section describes the energy characterization process of a group of multi-family buildings, which consists of five (5) phases: the selection of the representative buildings (Section 2.1), collection of information (Section 2.2), energy modeling of the selected buildings (Section 2.3), energy modeling of the archetype (Section 2.4), and planning of energy simulations (Section 2.5).

2.1. Selection of the Representative Buildings

This study is conducted in the Metropolitan Area of Bucaramanga (MAB), which is located at 7.13° North and 73.13° West. Its average solar irradiation is 4.8 kWh/m^2/day, which varies between 2.0 and 7.6 kWh/m^2/day. This city has a warm climate and is 960 masl. Table 1 presents general climate data of this tropical city [19,20].

Table 1. General climate data from Bucaramanga.



Parameter	Value
Average annual precipitation	1279 mm
Average ambient temperature	24 °C (During the day) 27 °C (Sunlight hours)
Average maximum temperature	31 °C
Average solar irradiation	4.8 kWh/m^2/day
Wind speed	1.0–1.5 m/s

A selection process allowed conforming a group of five residential buildings from a total of fifteen potential existing buildings. This process included the participation of experts of the construction sector of the MAB for the application of these criteria: socioeconomic classification, age of the building, time occupation greater than one year, representativity of the buildings belonging of the category, availability of information about the design (architectural, electrical, and mechanical), and no application of the energy efficiency measures. Table 2 presents some general characteristics of the sample or selected buildings (B1 to B5).

Table 2. General characteristics of the sample of selected buildings.

Building	Levels	Basements	Levels of Apartments	Average Area per Apartment (m^2)	Average Occupancy per Apartment (people)
B1	9	3	7	78.11	2.8
B2	12	0	12	57.52	4.0
B3	20	2	20	58.50	3.4
B4	21	0	16	88.07	2.5
B5	12	0	12	54.80	2.7

2.2. Collection of the Input Information

Table 3 relates sources and required information for developing the energy models of the buildings belonging to the sample. The technical teams of the companies that participated in the construction of these buildings delivered information about three design areas: architecture, electrical engineering, and mechanical engineering.

Table 3. Sources and required information for the development of the energy model of the selected buildings.

Source	Topic	Information
Construction company	Architecture	Plans of floor and facades and architectonical details
	Electrical system	Electrical loads
	Mechanical system	Air conditioning
Visit and survey	Building	Architectonical details
	Use	Occupancy of inner spaces, characteristics and use of appliances, and use of general services
Electricity company	Bill	Monthly energy consumption by users and general services

The architectonical design provided floor plans of each level, façade plans, architectonical details of windows, compositions of several elements of the envelope (roofing, external walls, internal walls, intermediate levels, and floor on ground level). The electrical design allowed knowing the lighting system and power specifications of pumps for the hydro-sanitary system and elevators. The design of the mechanical system of the building provided information about climatization equipment.

The visits in situ and surveys to users allowed validating architectonical details and establish the average occupation of housing units and the use of hydro-pneumatics pumps and elevators, appliances (computers, TV, fridge, and miscellaneous, among others), lighting system and if exists, air conditioning.

Additionally, the local electricity company shared data about monthly and annual energy consumptions of apartments and general services area of each selected buildings, which is part of the information required for validating the energy models.

Table 4 presents the main technical characteristics of the design (architectural, electrical, and mechanical) of selected buildings.

2.3. Energy Modeling of the Buildings Belonging to the Sample

The energy models of the buildings of the sample were made using the energy simulation tool DesignBuilder v6 (DESIGNBUILDER SOFTWARE LTD, Stroud, UK), which is a commercial graphical interface of the EnergyPlus (powerful simulation engine).

The energy modeling process consists of three steps: geometrical model, assignation of data to the model, and adjustment of the energy model. The geometrical model is based on the information provided by architectural plans.

Table 4. Architectural, electrical, and mechanical characteristics of the sample of buildings.

Building	B1	B2	B3	B4	B5
Constructive system	Traditional system with frame (portico) structure	An industrialized system with plate structure and concrete walls	An industrialized system with plate structure and concrete walls	Traditional system with frame (portico) structure	An industrialized system with plate structure and concrete walls
Window to wall ratio—WWR	16%	19%	17%	17%	25%
Configuration of external walls	Walls with clay bricks, frieze, stucco, inner painting. Total thickness: 15 cm	Concrete Wall, filler, and inner painting, graniplast (outdoor). Total thickness: 13 cm	Clay brick, filler, and inner painting, graniplast (outdoor). Total thickness: 13 cm	Clay brick, stucco, inner painting, and outdoor painting. Total thickness: 16 cm	Clay brick, filler, and inner painting, graniplast (outdoor). Total thickness: 15 cm
U-value ($W/m^2{\cdot}K$) external walls	1.702	3.249	1.630	1.630	1.774
Configuration of roofing	Lightweight concrete slabs, drywall ceiling, and inner painting. Mortar, asphalt cloth, and reflective paint for the outdoor surface. Total thickness: 45 cm	Solid concrete slabs, stucco, and inner painting. Mortar, asphalt cloth, and reflective Paint for the outdoor surface. Total thickness: 16 cm	Solid concrete slabs, stucco, and inner painting. Mortar, asphalt cloth, and reflective Paint for the outdoor surface. Total thickness: 16 cm	Lightweight concrete slabs, air layer, drywall ceiling, and inner painting. Mortar, asphalt cloth, and reflective paint for the outdoor surface. Total thickness: 46 cm	Solid concrete slabs, stucco, and inner painting. Mortar, asphalt cloth, and reflective Paint for the outdoor surface. Total thickness: 16 cm
U-value ($W/m^2{\cdot}K$) Roofing	1.62	2.76	2.87	1.81	2.77
Lighting power density—LPD (W/m^2)	4.61	2.22	1.11	4.33	2.83
Electrical load density (W/m^2)	24.47	31.49	18.64	20.77	21.55
Air conditioning system	Only for the main bedroom of an apartment per floor (9000 BTU)	Only for the main bedroom of some typologies o apartments (9000 BTU)	NO	NO	NO
Elevators	2 × 10 HP	1 × 7.5 HP	1 × 10 HP	2 × 8 HP	1 × 6.5 HP
Total area of housing unit (m^2)	4920.9	4145.0	6844.9	4932.0	2981.8
Total area of general services (m^2)	888.4	456.6	1295.2	1444.0	333.0

The data assigned to the geometrical model can be presented in four categories: (i) use, (ii) enclosure and inner materials, (iii) electrical loads (lighting, appliances, and common or general loads), and (iv) mechanical systems (climatization).

The use data correspond to occupancy regime and density of people in inner spaces, characteristics of users as metabolic activity and clothing, and ambient control for the building (e.g., setpoint of temperature for air conditioning and minimum lighting level for each inner space). The material data relates the composition (materiality and thickness) of constructive elements (external walls, internal walls, intermediate slabs, roofing terrace, and floor on the ground), glazing characteristics (the type of glass, percentage, and opening scheduled for windows), and characteristics of shading elements.

The data of electrical loads relates to the number, power, and schedule of use of common or general electrical loads (elevators and pumps) and housing units (appliances). Additionally, it is necessary to register information of the lighting system as the number, type, and power of luminaries, operation schedule, and operational control (e.g., on/off or dimming). The data of mechanical systems provided are type, efficiency, thermal capacity, and operation schedule of air conditioning units. Specifically, the units of the cooling system used are mini-splits that allow controlling the temperature in individual inner spaces. A mini-split has two main components: an outdoor compressor and an indoor airhanding unit. It is modeled as a packaged terminal air conditioner (PTAC) in DesignBuilder, which is a compound object made up of an outdoor air mixer, DX cooling coil—single speed, electrical coil, and constant volume supply air fan.

Figure 1 presents the representative energy models of the category of the median income multi-family residential buildings.

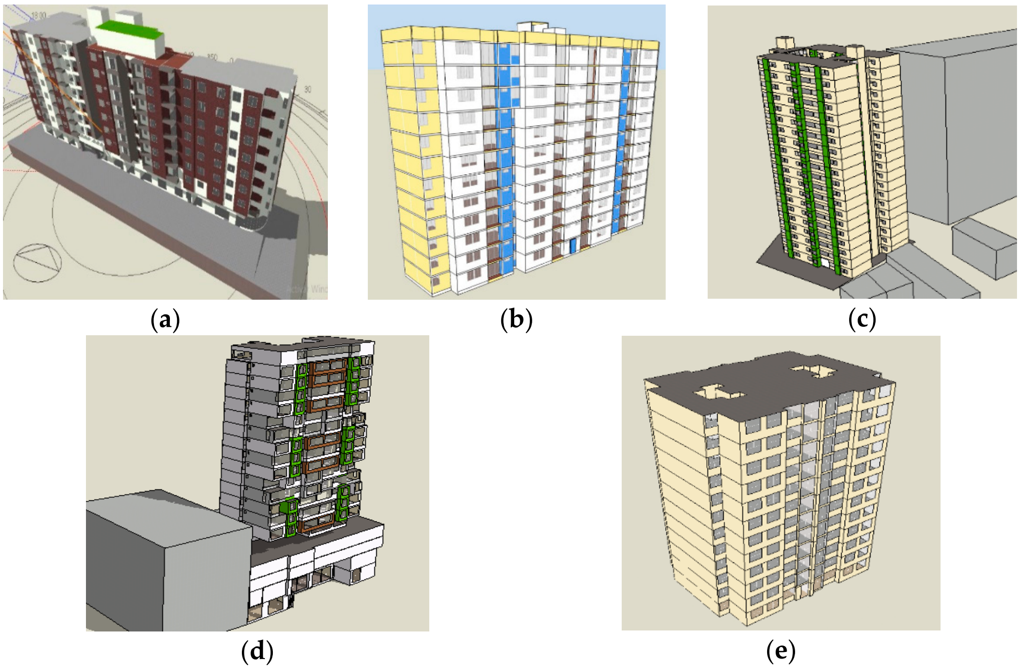


Figure 1. Representative energy models of the selected buildings: (**a**) B1; (**b**) B2; (**c**) B3; (**d**) B4; and (**e**) B5.

The validity of the energy models can be reached through a calibration process, which consists of mainly three steps: comparison between the comparison of simulated data and measured data, identification of the error causes, and adjustment of input data (e.g., the physical parameter of the buildings, occupancy behavior, or schedule and rated power of equipment) [21].

Mainly, a calibration process describes by the literature of use energy consumption as the analysis variable [14,21–31], although the inner temperature can also be used [21,22,24].

The energy consumption data of buildings can be obtained from databases (local or national), bills, or a set of energy meters for monitoring specific areas or services (e.g., HVAC, lighting, appliances, etc.). In general, the calibration process of the energy models of single dwellings uses databases [13,14,18] or bills [24,31], while this process can be supported by bills [21–23,25,28–30] or a set of energy meters [21,23,24,28,30] for commercial or school buildings.

Due to that most studies were done in template zones, the comparison of simulated data and measured data is done for each month during a year, which allows appreciating the seasonal effect on energy consumption.

Considering these findings, it is important to note that the energy consumption of buildings of this study does not suffer affected seasonal affectation because MAB is located in the tropical zone, thus, it is possible to use the data of annual energy consumption as the analysis variable for the calibration process.

Although the calibration process could be done using energy consumption data for the whole building, this work proposes to conduct the calibration of energy models in two phases: adjustment for housing units and adjustment for common areas or general services. This allows reducing inaccuracies in the representation of the actual behavior of some inner zones of the buildings [32–34].

Figure 2 presents the process applied to the adjustment for housing units (Phase 1). Initially, it is necessary to define the number of comparison typologies, n_t, where each one represents a set of thermal zones or housing units, n_{hut}, which have similar characteristics such as area, the number of rooms, presence of air conditioning unit, and annual energy consumption. The segmentation of housing units of multi-family buildings for calibration purposes is the main difference with respect to previous works.

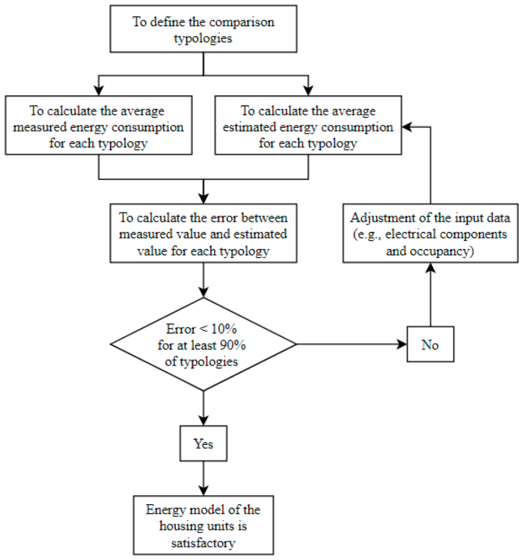


Figure 2. Adjustment process for typologies of the housing units of a building.

Subsequently, the estimated value of annual energy consumption for each housing unit belonging to the typology is obtained from the simulation results, $ec^e_{t,hut}$, with which is possible to determine the estimated value of annual energy consumption by typology, EC^e_t, as Equation (1) shown.

$$EC^e_t = \frac{1}{n_{hut}} \sum_{hut=1}^{n_{hut}} ec^e_{t,hut} \quad (1)$$

Simultaneously, the average measured value of energy consumption for the n_{hut} housing unis of each typology, EC^m_t, is calculated according to electricity bills or report of the local electricity company for each housing unit, $ec^m_{t,hut}$, as Equation (2) shows. Note that a typology must only consider those areas with effective real occupancy (12 months per year).

$$EC^m_t = \frac{1}{n_{hut}} \sum_{hut=1}^{n_{hut}} ec^m_{t,hut} \quad (2)$$

The adjustment process consists of reducing the error between the average values obtained (simulated and measured) of each typology, e^{adj}_t, as Equation (3) indicates, from the improvement of the energy model, which is satisfactory when e^{adj}_t is lower than 10% for the 90% of n_t.

$$s^{adj}_t = \frac{EC^m_t - EC^e_t}{EC^m_t} 100\% \quad (3)$$

The second phase applies to common zones or general services. First, the common zones or general services are identified, n_{gs}, such as hallways, stairs, lobby, basements, pumps and engine rooms, and social rooms, among others. Second, the values of energy consumption of each general service, ec^e_{gs}, and the whole building, EC^e_{gs}, are estimated as Equation (4) shown. Meanwhile, the measured energy consumption of general services is determined according to historical data. The estimation error, e^{adj}_{gs}, as Equation (5) indicates and must be lower than 10% for considering that this part of the energy model is satisfactory.

$$s_t^{adj} = \frac{EC_t^m - EC_t^e}{EC_t^m} 100\% \quad (4)$$

$$s_{gs}^{adj} = \frac{EC_{gs}^m - EC_{gs}^e}{EC_{gs}^m} 100\% \quad (5)$$

2.4. Energy Modeling of the Archetype

Table 5 presents the technical characteristics of the archetype, which is used for carrying out the analysis of the performance sample approach.

Table 5. Characteristics defined for the representative archetype of the category of the median income multi-family buildings located in the Metropolitan Area of Bucaramanga.

Characteristic	Value/Specification	Characteristic	Value/Specification
Number of floors with apartments	15	U-value of glasses	5.8 W/m^2·K
Basements	0	Solar heat gain coefficient—SHGC	82%
Number of apartments per floor	6	Effective opening for natural ventilation	50%
Whole area of apartments	5215.5 m^2	Lighting power density—LPD (W/m^2)	3.72 W/m^2
Average area per apartment	58.0 m^2	Electrical load density (W/m^2)	31.13 W/m^2
Area of common zones	917.9 m^2	Elevators	12.5 HP
People per apartment	4	Composition of roofing	Lightweight-concrete
Height	2.7 m	Finish of roofing	Painted asphalt cloth
Window to wall ratio—WWR	40%	Composition of external walls	With a core of masonry
U-value of external walls	2.77 W/m^2·K		
U-value of roofing	2.20 W/m^2·K	Composition of external walls	Frieze and stucco for both sides
Thickness of glasses	3 mm		

Figure 3 presents the archetype of the category of median income multi-family buildings made using DesignBuilder. The estimation error of energy consumption, s_{arc}^{adj}, is calculated by Equation (6), where EC_{arc}^e is the density of estimated annual energy consumption by the archetype (kWh/m^2·year) and $\overline{EC}_{nb}^m$ is the density of average measured values of annual energy consumption of the n_b buildings represented by archetype (kWh/m^2·year), which is calculated by Equation (7), where EC_b^m is the density of the measured energy consumption of the building b (kWh/m^2·year). The energy model of the archetype is satisfactory when s_{arc}^{adj} is lower than 10%.

$$s_{arc}^{adj} = \frac{\overline{EC}_{nb}^m - EC_{arc}^e}{\overline{EC}_b^m} 100\% \quad (6)$$

$$\overline{EC}_{nb}^m = \frac{1}{n_b} \sum_{b=1}^{n_b} EC_b^m \quad (7)$$

2.5. Energy Simulations

The characterization of the energy behavior of the buildings (sample) and the archetype is based on the annual simulation with an hourly step, for that is used a file of climate data made with historical data of several weather stations located in the MAB. Such characterization consists of determining the total annual energy consumption, specific annual energy consumptions (lighting, appliances, and air conditioning), indices of thermal comfort (% PPD, PMV, and hours of discomfort according to ASHRAE), and heat gains and losses.

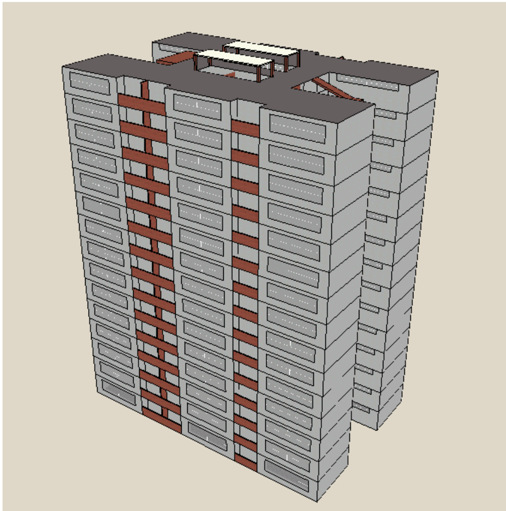


Figure 3. The representative archetype of the category of the median income multi-family buildings.

3. Results and Discussion

This Section presents the results of the calibration process (Section 3.1), energy consumption (Section 3.2), thermal comfort (Section 3.3), and heat gains and losses (Section 3.4) of the energy models of the sample; also, it exposes the comparative between sample approach and archetype approach (Section 3.5).

3.1. Calibration of the Energy Models Belonging to the Sample

Table 6 allows knowing the number of typologies of housing units defined for each building, where B3 presents only one typology because all apartments are the same and their energy consumption (measured) are similar. This table also summarizes the adjustment process of energy models of the buildings belonging to the sample, which includes average values of errors s_t^{adj} for n_t typologies of each building, initial error value (first iteration), and final error value when s_t^{adj} is lower than 10% for at least 90% of n_t.

Table 6. A brief report of the adjustment process of typologies of housing units for each energy model belonging to the sample.

Building	Number of Typologies	Initial Error	Iterations of Adjustment	Final Error	Adjustments Made
B1	9 (1 with AirC)	45.72%	3	2.58%	Timetables of the use of some electrical loads Timetables of the use of air conditioning (AirC) units
B2	6 (All with AirC)	13.66%	3	3.10%	Timetables of the use of some electrical loads Timetables of the use of air conditioning (AirC) units
B3	1	39.48%	1	3.04%	Configuration of the operation of the lighting system Rated power of some electrical loads
B4	4	28.15%	2	4.25%	Rated power of some electrical loads Timetables of the use of some electrical loads Timetables of the use of lighting system
B5	2	5.34%	0	5.34%	NA

The average initial error of energy models was 26.47%. This error could be reduced due to the detailed reviewing of surveys and reports of visits in site; specifically, the occupancy schedules of inner spaces and the use of appliances and air conditioning units were updated. After the adjustment process, the estimation error of representative energy models decreases between 2.58% and 5.34%. The energy models with air conditioning units demanded 3 iterations.

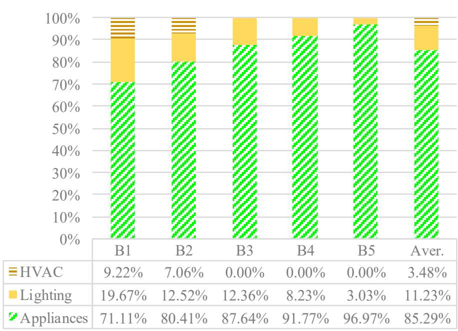
3.2. Energy Consumption

Table 7 presents the annual energy consumption (kWh/m^2·year) of the models of the sample. It is worth noting that indicator I1 relates to the total energy consumption of each building (kWh/year). Whereas the indicators I2 and I3 are associated to the specific energy consumption for housing units and general services; note that these indicators are calculated based on the total areas of total areas of housings units and general services shown in Table 4. Results of energy simulations indicate that buildings B2, B3, and B5 have higher energy consumptions (23.37, 21.84 y 21.32 kWh/m^2·year). While buildings B1 and B4 present energy consumptions lower than 20 kWh/m^2·year. These differences are caused by the use intensively of LED lamps and elevators with efficient motors of 8 HP or lower in these buildings.

Table 7. Indicators of energy consumption that describe the behavior of the buildings that represent the category of the median income multi-family buildings.

Indicator		B1	B2	B3	B4	B5	Average
I1. Total annual energy consumption of the building (kWh/year)		142 598.4	121 235.4	199 788.0	138 912.4	83 249.2	137 154.9
I1.1 Housing units	(kWh/year)	111 028.6	106 237.0	154 007.3	84 536.5	71 736.1	105 509.1
		77.9%	87.6%	77.1%	60.9%	86.2%	76.9%
I1.2 General services	(kWh/year)	31 560.8	14 998.4	45 780.7	54 375.9	11 513.1	31 645.8
		22.1%	12.4%	22.9%	39.1%	13.8%	23.1%
I2. Annual energy consumption of housing units (kWh/m^2·year)		22.57	25.63	22.50	17.14	24.06	22.38
I2.1 Energy consumption by appliances (kWh/m^2·year)		16.05	20.61	19.72	15.73	23.33	19.09
I2.2 Energy consumption by lighting (kWh/m^2·year)		4.44	3.21	2.78	1.41	0.73	2.51
I2.3 Energy consumption by AirC (kWh/m^2·year)		2.08	1.81	-	-	-	0.78
I3. Annual energy consumption of general services (kWh/m^2·year)		35.52	32.84	35.35	37.66	34.57	35.18
I3.1 Energy consumption by elevators (kWh/m^2·year)		11.17	11.39	4.47	6.41	20.61	10.81
I3.2 Energy consumption by pumps (kWh/m^2·year)		22.06	18.99	29.70	22.79	12.68	21.24
I3.3 Energy consumption by lighting (kWh/m^2·year)		2.29	2.46	1.18	8.46	1.28	3.13

Figure 4 shows the distribution of the energy consumption of each building. For housing units, electrical equipment (appliances and other electrical loads) uses the most amount of energy, between 71.11% and 96.97%, being greater than 87.6% for building without air conditioning units. The consumption by lighting is on average 11.23%, varying between 3.03% and 19.67%. The intense use of LED lamps of 12 W explains mostly the low consumption by lighting in B5.



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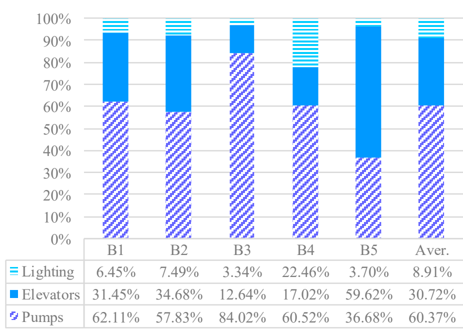

(**b**)

Figure 4. Distribution of the energy consumption for the buildings belonging to the sample: (**a**) housing units and (**b**) general services.

Regarding the air conditioning consumption, only B1 and B2 have this service for some typologies of apartments, representing between 7.06% and 9.22% of the total energy consumption. The other buildings are designed to reach the climatization of inner spaces by natural ventilation. So, a first finding of applying bottom-up methodology from the sampling approach consists of noting that is not convenient to standardize the use of air conditioning units for the building of this category.

On the other hand, the simulations reveal that consumption distribution for zones of general services represents on average 23.1% of the total energy consumption of the buildings. From this use, the higher consumption is caused by elevator and hydro-pneumatics pumps (89% on average). Lighting represents near to 11%. As with housing units, artificial climatization has low representation for common areas.

3.3. Thermal Comfort

Table 8 presents the main thermal comfort parameters for the buildings belonging to the sample. Results indicate that the predicted percentage dissatisfied (PPD) for this category of buildings is between 16% and 37%. This value tends to increase for inner spaces in higher levels and buildings with larger exposed envelope area to the solar irradiance, such as B5. The orientation of the building, such as in B1, and the lack of outdoor shading element, such as in B5, are decisive to define the thermal comfort conditions, that according to predicted mean vote (PMV) varies between 0.0 and 1.0, that is to say between neutral and slightly warm for most of the buildings. From PPD and PMV data, it is possible to identify a linear correlation between these indicators from follows expression: $PMV = 3.8112 \cdot PPD - 0.2342$, with R^2 equal to 0.9495, which corroborates the thermal comfort finding.

Table 8. Parameters of the thermal comfort for the buildings belonging to the sample.

<table>
<tr><th>Building</th><th>PPD</th><th colspan="2">PMV</th><th>ASHRAE 55 SIMPLE</th><th>ASHRAE 55 Adaptative</th><th>Observations</th></tr>
<tr><td>B1</td><td>36.9%</td><td>+1.20</td><td>Thermal sensation between slightly warm and warm</td><td>15.4%</td><td>53.3%</td><td rowspan="2">The building has air conditioning units into the main bedroom for a typology of housing units.</td></tr>
<tr><td>B2</td><td>24.6%</td><td>+0.59</td><td rowspan="4">Thermal sensation between neutral and slightly warm</td><td>24.1%</td><td>52.9%</td></tr>
<tr><td>B3</td><td>16.1%</td><td>+0.41</td><td>-</td><td>3.1%</td><td rowspan="3">The building is naturally climatized</td></tr>
<tr><td>B4</td><td>25.3%</td><td>+0.73</td><td>-</td><td>15.0%</td></tr>
<tr><td>B5</td><td>23.1%</td><td>+0.70</td><td>-</td><td>19.5%</td></tr>
</table>

Another parameter considered is the percentage of discomfort hours, which can be evaluated from two standards: (i) ASHRAE 55 Simple applied to zones with artificial climatization and (ii) ASHRAE 55 Adaptative applied to zones with only natural ventilation [35]. For buildings B1 and B2, the discomfort is near to 53% (ASHRAE 55 Adaptative), which is due to ambient temperature (mostly between 25 and 30 °C) and relative humidity (mostly higher than 75%). The use of air conditioning units significantly reduces the discomfort time to 15.40–24.10% (ASHRAE 55 Simple).

For buildings B3, B4, and B5, it possible to evidence that natural ventilation is an effective strategy to provide thermal comfort because allows ensuring it more the 80% of the time, even is approximately 97% for B3. This shows the relevance of natural ventilation as a strategy to reach thermal comfort in buildings of this category considering the warm tropical conditions of the MAB.

3.4. Heat Gains and Heat Losses

Table 9 presents the results about heat gains and losses for the buildings belonging to the category. The main heat gain (43.40–68.84%) is caused by the affectation of the solar irradiance through the glazing of the buildings (C4). Highlight the annual heat gain value for B5 that reaches 70.5 kWh/m^2, which is a building with WWR near to 30% in the main façade and with few shading elements for mitigating the incident direct solar irradiance.

Table 9. Heat gains and heat losses of the buildings belonging to the sample (kWh/m^2).

	Gain/Loss	B1		B2		B3		B4		B5	
C1	People Sensible Heat Addition	18.62	21.13%	31.75	26.40%	21.57	22.44%	13.05	16.19%	5.12	5.00%
C2	Lights Sensible Heat Addition	3.97	4.50%	3.21	2.67%	2.78	2.89%	1.41	175%	0.73	0.71%
C3	Equipment Sensible Heat Addition	14.89	16.90%	20.61	17.13%	19.72	20.52%	15.73	19.52%	23.31	22.76%
C4	Window Heat Addition	48.39	54.91%	52.21	43.40%	46.44	48.31%	43.71	54.24%	70.50	68.84%
C5	Interzone Air Transfer Heat Addition	0.31	0.35%	2.72	2.26%	0.22	0.23%	3.39	34.21%	0.25	0.24%
C6	Infiltration Heat Addition	0.40	0.45%	0.006	0.00%	0.44	0.46%	0.003	0.00%	0.19	0.19%
C7	Opaque Surface Conduction and Other Heat Addition	1.55	1.76%	9.78	8.13%	4.95	5.15%	3.29	4.08%	2.31	2.26%
	Total additions	88.13		120.29		96.12		80.58		102.41	
C8	Window Heat Removal	10.48	12.12%	15.05	13.59%	10.11	10.90%	3.43	4.26%	19.82	34.31%
C9	Interzone Air Transfer Heat Removal	10.60	12.26%	26.00	23.48%	5.06	5.45%	29.79	36.97%	0.81	1.40%
C10	Infiltration Heat Removal	59.09	68.32%	49.86	45.03%	60.87	65.61%	28.17	34.96%	0.59	1.02%
C11	Opaque Surface Conduction and Other Heat Removal	6.32	7.31%	19.81	17.89%	16.74	18.04%	19.19	23.81%	36.55	63.27%
	Total removals	86.49		110.72		92.78		80.58		57.77	

Electrical equipment (C3) is the second heat gain of greatest relevance (19.37%), mainly in B5. The third heat gain is related to the occupancy (C1) with an average value of 18.23%. Highlight the case of B2 with a heat gain of 31.75 kWh/m^2·year because is a building with four inhabitants per housing unit. Concerning heat gain by lighting, its representativity varies between 0.71% and 4.50%, being higher in B1 that has an LPD value of 4.61 W/m^2.

The building belonging to this category tends to present heat gain by opaques enclosures (C7) lower than 5 kWh/m^2·year. Nevertheless, this heat gain is almost 10 kWh/m^2·year for B2 because most enclosures are made in concrete (confined building system) with high values of U-value in comparison with other buildings; besides, the envelope is exposed significantly to solar irradiance, overall, during the afternoon.

Regarding heat losses, natural ventilation (C8, C9, and C10) is responsible for more than 78%. This result coincides with the percentage of the thermal discomfort found. The higher heat losses by windows occur in B5, which is expected considering that this building has the greatest glazing area of this sample.

3.5. Comparative Analysis between Sample and Archetype

To determine the aggregated value of selecting a sample of the building to represent a category of the buildings, it is necessary to make a comparative analysis with the archetype shown in Figure 3. Table 10 presents the results of annual energy consumption (kWh/m^2·year). The archetype demands 23.95 kWh/m^2·year. This value is only 7% higher than the average value of the sample.

Concerning the uses of the energy consumption in archetype, 93.7% of energy is demanded by appliances in housing units, while exceeds 17% of the result obtained for buildings of the sample. The energy consumption by lighting is only 6.3% that is 60% lower than the average value for the sample (11.22%).

The general services represent 29.0% of the total energy consumption for the archetype, with a value of 55.70 kWh/m^2·year that is 21.09% greater than energy consumption found for the sample (46.0 kWh/m^2·year).

Table 11 shows that values of PPD and PMV are 26.66% and +0.83, respectively, which indicates that thermal comfort conditions provided by the archetype are slightly warm being results similar to those obtained by the sample of buildings. The thermal discomfort is substantially high with a value of 90.9% according to ASHRAE 55 Adaptative, which can be reduced to 51.5% according to ASHRAE 55 Adaptative for zones with air conditioning units. Note that these results do not represent the diverse operating conditions found for buildings belonging to the sample.

Table 10. Comparison of the energy consumption between average values of the sample and the archetype.

Indicator		Sample (Average)	Archetype
I1. Total annual energy consumption of the building (kWh/year)		137 154.9	176 018.4
I1.1 Housing units	(kWh/year)	105 509.1	124 895.4
		76.9%	71.0%
I1.2 General services	(kWh/year)	31 645.8	51 123.0
		23.1%	29.0%
I2. Annual energy consumption of housing units (kWh/m^2·year)		22.38	23.95
I2.1 Energy consumption by appliances (kWh/m^2·year)		19.09	22.44
I2.2 Energy consumption by lighting (kWh/m^2·year)		2.51	1.51
I2.3 Energy consumption by AirC (kWh/m^2·year)		0.78	-
I3. Annual energy consumption of general services (kWh/m^2·year)		46.0	55.70
I3.1 Energy consumption by elevators (kWh/m^2·year)		10.81	36.70
I3.2 Energy consumption by pumps (kWh/m^2·year)		21.24	18.35
I3.3 Energy consumption by lighting (kWh/m^2·year)		3.2	0.65

Table 11. Parameters of the thermal comfort for the archetype.

Building	PPD	PMV		ASHRAE 55 SIMPLE	ASHRAE 55 Adaptative	Observation
Archetype	26.66%	+0.83	Thermal sensation between neutral and slightly warm	90.9%	51.5%	The building does not have an air conditioning system.

Table 12 relates the results about heat gains and losses. The total heat gains amount to 146.98 kWh/m^2 that represents an increase of 50.7% concerning the average value obtained for the sample (97.51 kWh/m^2). The main cause is the incoming solar irradiance through windows, as well as occurred for the sample, although its value of 103.34 kWh/m^2 (70.31%) is significantly higher to values shown in Table 9 (43.71–70.50 kWh/m^2).

Electrical equipment and occupancy are another two relevant heat gains, with values of 21.17 kWh/m^2 (14.40%) and 20.31 kWh/m^2 (13.82%), respectively. These also correspond to second and thirds places of representativity of heat gains for buildings of the sample, whose average values are 18.85 kWh/m^2 y 18.02 kWh/m^2, which indicates increasing of 12.31% and 12.71% from the archetype.

Despite to low U-value of the enclosures (2.77 W/m^2·K in walls y 2.20 W/m^2·K in roofing), which means a low thermal quality of them, such heat gain is only 0.25 kWh/m^2, a value substantially lower to related in Table 9 (1.55–9.78 kWh/m^2). This is caused by the orientation of the archetype that reduces appreciably the exposure of the opaque area of the envelope to the incident solar irradiance.

The heat losses reach 146.98 kWh/m^2 that represents an increase of 71.6% to the average value of the sample (85.67 kWh/m^2). This evidences that the archetype removes heat more effectively from inner spaces in comparison with analyzed buildings. This is due to two aspects: (i) the opening schedule (6 a.m. to 7 p.m.) coincides with the period of greater heat gain by solar irradiance and (ii) the orientation facilitates the heat dissipation through opaques enclosures.

Table 12. Heat gains and heat losses related to the archetype (kWh/m^2).

	Gain/Loss	Value	Percentage
C1	People Sensible Heat Addition	20.31	13.82%
C2	Lights Sensible Heat Addition	1.51	1.03%
C3	Equipment Sensible Heat Addition	21.17	14.40%
C4	Window Heat Addition	103.34	70.31%
C5	Interzone Air Transfer Heat Addition	0.15	0.10%
C6	Infiltration Heat Addition	0.25	0.17%
C7	Opaque Surface Conduction and Other Heat Addition	0.25	0.17%
	Total additions	146.98	
C8	Window Heat Removal	21.35	14.53%
C9	Interzone Air Transfer Heat Removal	14.33	9.75%
C10	Infiltration Heat Removal	65.02	44.24%
C11	Opaque Surface Conduction and Other Heat Removal	46.28	31.41%
	Total removals	**146.98**	

3.6. Discussion

The construction of the energy models and the energy characterization of the buildings allowed identifying common and differentiating aspects between sample approach and archetype approach. Concerning energy models, both approaches use the same information collected utilizing design plans (architectural, electrical, and mechanical), visits, and surveys. However, the definition process of the archetype is complex because requires involving experts [5] or applying data refining methods [8] to represent correctly the buildings of a category. However, it is not possible to ensure satisfactory performance of the archetype.

The procedure proposed to calibrate the energy models belonging to the sample disaggregates the energy behavior of the whole building in several zones (typologies of housing units and area of general services) for the same number of adjustment processes. This allows constructing energy models more reliable in comparison to those models obtained from an adjustment process considering only the total energy consumption of the buildings (traditional process), and even more if the comparison is done concerning the archetype.

Results from energy characterization of buildings (sample and archetype) show similar results of total energy consumption (kWh/m^2) and thermal gains by equipment and occupancy. However, there are marked differences in the energy behavior between buildings belonging to the sample and, thus, with the archetype, such as thermal comfort (PPD, PMV, and thermal discomfort hours) and total values of thermal gains and losses.

While the influence of the solar irradiance is critical for all buildings of the category, the intensity of its affectation on each building depends on parameters as orientation, WWR, and U-values of external walls and roofing.

For the archetype, the energy behavior is subject to the representative characteristics defined for the category of buildings. Therefore, a wrong selection of these characteristics causes the construction of an energy model and obtaining results unsatisfactory.

Conducting studies like this allows characterizing the energy consumption of segmented stocks of buildings, especially for region or countries as Colombia, where there are unavailable buildings energy databases. So, these representative energy models of buildings allow predicting energy consumptions and estimating the impacts of the potential implementation of energy efficiency strategies, which is necessary to support the process for establishing energy-labeling system of buildings. For helping this process, it is necessary to start with the detailed segmentation of the stock buildings and, later, to select representative buildings.

4. Conclusions

The analysis of the energy behavior of a building category can be addressed by bottom-up methodology from two energy analysis approaches: a representative building (archetype approach) or a group of buildings (sample approach). An archetype is a fictitious building that pretends to represent reliably the buildings belonging to a category. Its validation consists of an adjustment process of the total energy consumption for the whole building considering the simulated value and the measured value. The use of the sampling approach consists of the modeling and analysis of the real building, which allows for the true characterization the energy behavior of housing units.

This work presents the analysis of the group of buildings that are stratified according to socioeconomic conditions. It proposes two improvements to apply to the sampling approach: (i) validation of input data through surveys and inspection visits and (ii) increase the number of the adjustment processes, one for general services area and as many as the number of typologies defined for the housing units, where a typology is a set of these units with the similitude of area, the number of rooms, presence (or not) of air conditioning units, and annual energy consumption (measured).

Results obtained for the analyzed building category (median income multi-family) evidence that the archetype is acceptable to make general analyses, but that it is limited for characterizing the detailed energy behavior of a building category, while the sampling approach allows for a more accurate characterization of the energy behavior of inner spaces and, thus, supporting the making decision process about energy strategies to reduce energy consumption.

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