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Methodological Approach for the Development of a Simplified Residential Building Energy Estimation in Temperate Climate

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Abstract: Energy ratings and minimum requirements for thermal envelopes and heating and air conditioning systems emerged as tools to minimize energy consumption and greenhouse gas emissions, improve energy efficiency and promote greater transparency with regard to energy use in buildings. In Latin America, not all countries have building energy efficiency regulations, many of them are voluntary and more than 80% of the existing initiatives are simplified methods and are centered in energy demand analysis and the compliance of admissible values for different indicators. However, the application of these tools, even when simplified, is reduced. The main objective is the development of a simplified calculation method for the estimation of the energy consumption of multifamily housing buildings. To do this, an energy model was created based on the real use and occupation of a reference building, its thermal envelope and its thermal system's performance. This model was simulated for 42 locations, characterized by their climatic conditions, whilst also considering the thermal transmittance fulfilment. The correlation between energy consumption and the climatic conditions is the base of the proposed method. The input data are seven climatic characteristics. Due to the sociocultural context of Latin America, the proposed method is estimated to have more possible acceptance and applications than other more complex methods, increasing the rate of buildings with an energy assessment. The results have demonstrated a high reliability in the prediction of the statistical models created, as the determination coefficient (R2) is nearly 1 for cooling and heating consumption.

Keywords: method of simplified calculation; energy consumption of buildings; multifamily residential building; temperate climate; Latin America

1. Introduction

Energy labelling of buildings and minimum requirements for insulation, solar control and performance of Heating, Ventilation and Air Conditioning (HVAC) systems emerged as tools to minimize the energy consumption and greenhouse gas emissions, improve the energy efficiency and promote greater transparency with regard to energy use in buildings [1].

The energy consumption of buildings is established by means of the relation between the energy demand and the performance of the mechanical space conditioning systems. The energy demand varies according to climatic conditions, the characteristics of the thermal envelope and the operative conditions of the building (occupancy, household appliance usage habits, equipment and lighting).

The first energy efficiency of building regulations emerged in the 1950s, in France, Switzerland and Germany, due to the concerns of the government entities to decrease the high heating energy consumption of buildings [2]. Rating initiatives emerged in the 1990s in United Kingdom, Germany and Canada with the objective to assess the energy efficiency and CO_2 emissions from buildings [3–5]. Currently, both regulations and rating schemes are very developed in the majority of these countries [2].

Regions in temperate climates represent the greatest territorial extension, with the highest population density, and so have the highest energy consumption. These countries cover 57% of the world population and are responsible of 68% of world's total primary energy consumption [6].

The temperate climates (C according to the Köppen classification)—Figure 1—are defined as having an average temperature above 0 °C in their coldest month but below 18 °C. Regarding the summer heat, "a" indicates the warmest month's average temperature is above 22 °C while "b" indicates the warmest month averages below 22 °C, but with at least four months averaging above 10 °C; and "c" indicates less than four months averaging above 10 °C. Countries like Morocco, Italy, Spain, Portugal, France, United States, Australia, Chile, Canada, Argentina, Brazil, Turkey, Switzerland, Greece, India, China, Japan, Mexico are examples of countries with locations with temperate climates [7].

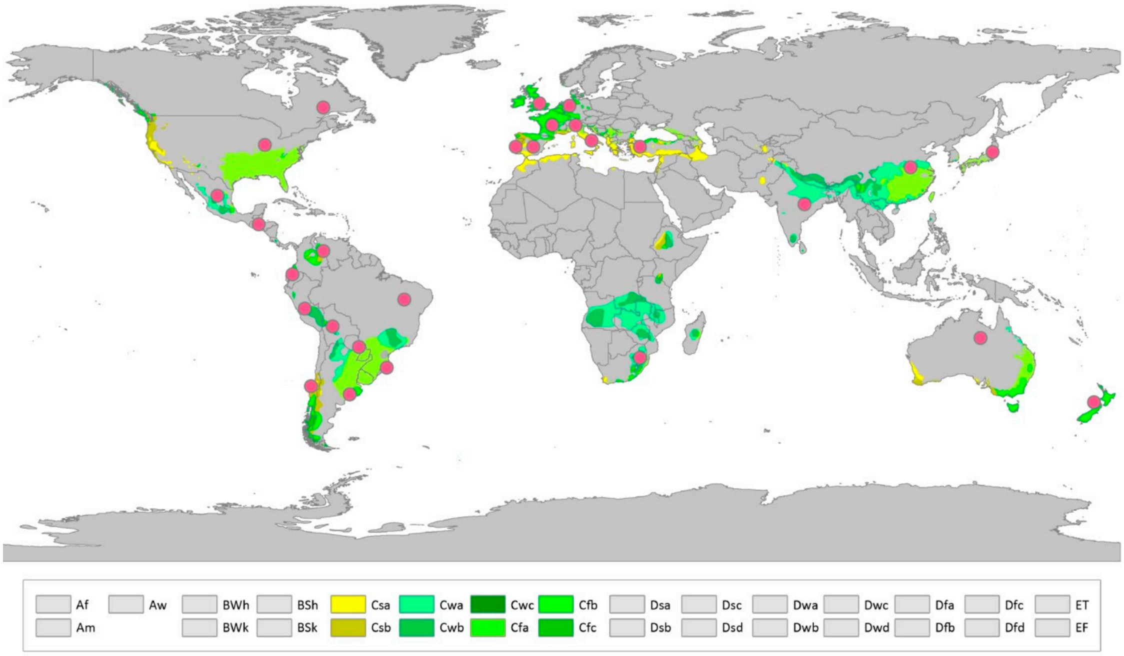

Figure 1. Development of building rating systems in temperate countries. Own elaboration adapted from the Köppen–Geiger climatic classification [7].

In order to know the energy rating context in countries with temperate climates, 47 initiatives for regulation and energy rating, distributed among 27 countries, were revised (Table 1). Almost half (48%) of the 47 initiatives revised are compulsory and cover the national territory. It has to be highlighted that, while all developed countries studies have energy efficiency regulations and energy rating schemes, not all emerging countries have the tools to assess the energy efficiency of their buildings.

Table 1. Building energy efficiency regulations and rating schemes in countries with temperate climates.

Country	Building Qualification System	Evaluation
	Africa	
Morocco	Thermal Regulation of Construction in Morocco—RTCM	C
South Africa	Energy efficiency in buildings—SANS 204	C
	Asia	
China	Evaluation standard for green building	C
China	Code for acceptance of energy efficient building construction	C
India	Energy conservation building code—ECBC	C
India	Green rating integrated habitat assessment—GRIHA	C
Japan	Design and Construction Guidelines on the Rationalization of Energy Use for Houses—Dcgreuh	R
Japan	Comprehensive Assessment System for Built Environment Efficiency—CASBEE	D, C
	Central America	
Costa Rica	Requirements for Sustainable Buildings in the Tropics—RESET	R
	Europe	
Germany	Passive house—Passivhaus	C
Germany	Energy Conservation Ordinance—EnEV	C
Spain	Technical building code—CTE	D
Spain	Energy certification of Spain	C
France	Energy performance diagnostic—DPE	C
France	Thermic regulation 2012—RT 2012	C
Italy	Decree 26 06 2015-Application of building energy performance calculation methodology and definition of minimum specifications and requirements for buildings (15A05198).	C
Portugal	Regulations on Thermal Behaviour of Buildings—RCCTE	D
Portugal	System for Energy and Indoor Air Quality Certification of Buildings	C
United Kingdom	Building Research Establishment Environmental Assessment Method—BREEAM	C
United Kingdom	Energy Performance Certificate—EPC	C
Swiss	Standard of thermal energy in building construction—SIA380/1	D
Swiss	Sustainable building standard—MINERGIE	C
Turkey	Thermal insulation requirements for buildings-TS 825	C
Turkey	Energy Performance Certificates	C
	North America	
Canada	Building Environmental Performance Assessment Criteria—BEPAC	C
Canada	Green Building Challenge—GBC	C
United States	Leadership in Energy & Environmental Design—LEED	C
United States	Building energy quotient—bEQ	C
Mexico	Sustainable Buildings Certification Program—PCES	C
Mexico	Mexican norm of sustainable building-NMX-AA-164-SCFI	D
	South America	
Argentina	Law 13059/03-Thermal Conditioning Conditions	R
Argentina	Energy performance in residential units—IRAM 11900	R
Argentina	Hygrothermal aspects and energy demand of buildings-Ordinance 8757/11	R
Brazil	Brazilian Building Labeling Program—PBE Edifica	C
Brazil	High environmental quality—AQUA BRAZIL	D
Brazil	Seal Blue House-SELO AZUL	R
Chile	Home Energy Rating—CEV	C
Chile	Sustainable Building Certification—CES	D
Colombia	Sustainable Construction Technical Regulation	R
Ecuador	Ecuadorian Construction Standard	R
Paraguay	Parameters of thermal comfort—NP 4901715	R
Peru	Thermal and Light Comfort with Energy Efficiency-EM.110	R
Uruguay	Reduction of energy demand for thermal conditioning-Resolution N° 2928/09	R
	Oceania	
Australia	Building Codes of Australia	C
Australia	Nationwide house energy rating scheme—NatHERS	C
New Zealand	New Zealand Building Code—NZBC	C

C = Energy consumption, D = Energy demand, R = fulfilment of normative requisites.

Due to the analysis of the application of these regulations and schemes, two contexts are highlighted: the European Union and Latin America.

In the European Union, policies and strategies of each country member are conducted by the European Directives, the directives 2002/91/CE [8] and 2010/31/UE [9] being the most influential in the implementation of energy efficiency regulations and of the building energy rating scheme. They require

European member states to achieve a particular result without dictating the means of achieving that result. Directives normally leave member states with a certain amount of leeway as to the exact rules to be adopted. Directives can be adopted by means of a variety of legislative procedures depending on their subject matter.

In Latin America, each country develops and implements the policies and strategies of its territory, as well as the regulatory framework for buildings. Not all Latin American countries have regulations focused on the energy assessment and energy efficiency of buildings. Furthermore, many regulations and energy rating schemes are voluntary [10].

The main compulsory initiatives in Latin America are the Brazilian Programme for Energy Labelling of Buildings (PBE Edifica) and the case of Rosario (Argentina). The first one requires an A level for new public buildings; the second one requires the fulfilment of certain values for thermal transmittance, risk of condensation, air permeability and cooling and heating thermal loads, established in the Ordinance 8757/11, in order to obtain the necessary licenses [10].

Regarding the assessed values of the building energy efficiency initiatives revised Table 1, in Latin America, 62% assess the achievement of certain requisites (thermal transmittance, solar factor, thermal capacity ...), 19% evaluate the energy demand and 19% focus on energy consumption. In Europe and the rest of the world, these proportions are different, with the main proportion of these initiatives centered on energy consumption, followed by the assessment of the energy demand, shown in Figure 2.

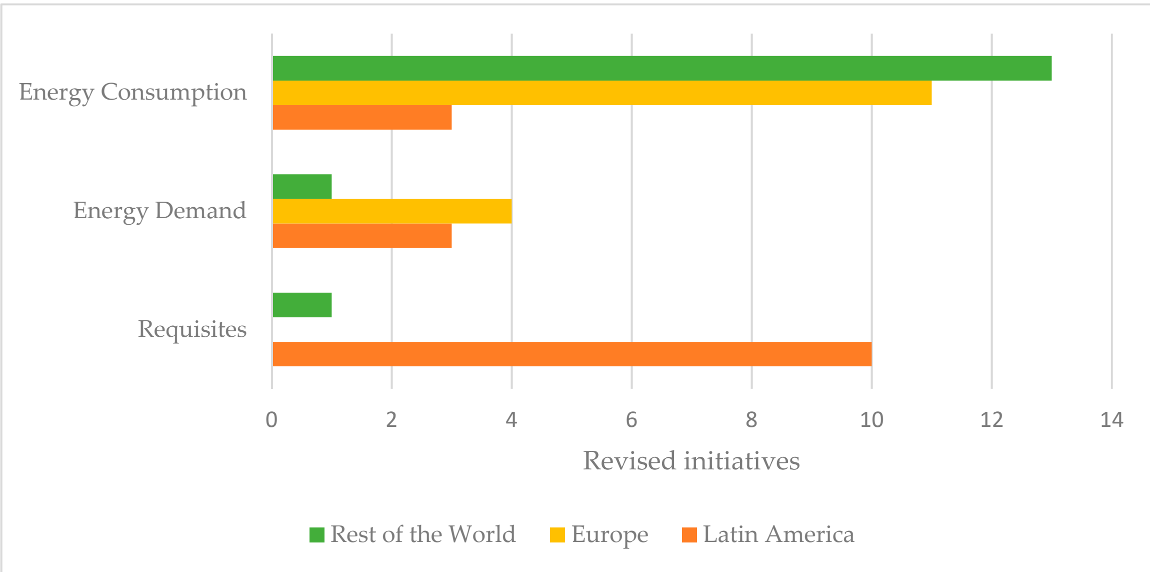

Figure 2. Evaluation criteria according to the regulations and certifications of countries with a temperate climate.

According to Krstić and Teni [11], building performance evaluation models can be classified as black, grey or white box. The black box is the model with the least information required to the user and the white box is the model with the highest information required to perform the energy evaluation of the building.

A black box model uses a simple mathematical or statistical model which relates a set of influential input parameters. The energy prediction under this model is based on a statistical approach according to a relevant database.

A white box model is based on building physics, and requires a detailed description of the building and its thermal systems. What is known as the general method, based on energy simulations using DOE 2 or EnergyPlus, which calculates the dynamic energy performance of the building [12], can be included in this classification. This model uses complex tools, requiring a high level of expertise, and consumes lots of time and resources [13].

A grey box model mixes both above-mentioned methods, as it requires certain key parameters identified from a physical model and the energy prediction is based on statistical methodologies. In these models, a rough description of the building geometry is enough.

The input data for simplified methods (black or grey box models) are diverse. The analysis of 43 simplified methods focused on energy consumption (Table 2) shows that the most common input data is weather data (16), followed by characteristics of the building (13), energy bills (13), occupancy loads (11), characteristics of the thermal envelope (8), characteristics of the HVAC systems (5), building typology (5) and other inputs. In total, 23 of those methods are destined to residential buildings, 14 for office buildings, 5 for commercial buildings and only one is for any use.

Table 2. Energy building performance simplified models: input data.

Year	Authors	Country	Typology	Input Data
1991	Bartels & Fiebig	Australia	R	HC
1994	LaFrance & Perron	Canada	R	W + EE + P
1995	Kreider et al.	United States	O	W + HC
1995	Hsiao et al.	-	R	O + HC
1996	Jaccard & Baille	Canada	R	HC
1998	Farahbakhsh et al.	Canada	R	B + O
1999	Fung et al.	Canada	R	B + W + EE + P + PE
2000	Kalogirou & Bojic	-	R	W + BE
2002	Shipley et al.	Canada	O	B + HC
2002	Lins et al.	Brazil	R	HC
2002	Mihalakakou et al.	Greece	R	W
2004	Shimoda et al.	Japan	R	O
2005	Parekh	-	A	B + O
2006	Petersdorff et al.	European Union	R	W + BE + T
2007	Kadian et al.	India	R	HC
2007	Raffio et al.	-	R	W + HC
2008	Swan et al.	Canada	R	B
2009	Hu	China	O	W + B
2010	Fumo	United States	R	HC
2010	Lam	China	C	B + O + EE
2010	Li	China	R	B
2010	Min et al.	United States	R	O + HC
2010	Wong et al.	-	O	W + BE + O
2011	Escriva-Escriva et al.	Spain	O	HC
2012	Melo	Spain	O	B + T
2012	Aranda	Brazil	C	B + W + EE
2013	Filippín	Argentina	R	HC + M
2013	Korolija	United Kingdom	O	B + T + EE + BE + O
2013	Zhou S. & Zhu N	China	O	W + BE
2014	Asadi	United States	C	BE + T
2014	Braun	United Kingdom	C	HC
2014	Fan	China	O	W
2014	Farzana	China	R	W + O
2014	Jain	United States	R	W
2014	Johnson	United States	R	O
2014	Mena	Spain	O	W
2014	Mastrucci	-	R	B + P
2015	Shams Amiri	United States	C	BE + T + O
2015	Salvetti	Argentina	R	B + O
2016	Pulido-Arcas	Chile	O	BE + EE
2017	Pino-Mejías	Chile	O	BE
2018	Nath Lopes & Lamberts	Brazil	O	W + B + BE + EE + O
2018	Ran Yoon	South Korea	O	O

Typology: R= residential, O = office, C = commercial, A = any type.W = weather, HC = historical consumption, B = building, BE = Building Envelope, EE = Equipment Efficiency, M = measured, O = occupation, P = demographic density, PE = price of electric power, T = typology.

The simplified method of Petersdoff, Boernans and Hamish [14] is based on five building typologies with eight different levels of thermal insulation simulated on three climatic regions of Europe: cold, moderate and warm. Wong, Wan and Lam [15] proposed a model for office buildings with daylighting controls in subtropical climates, considering four climatic variables, four envelope variables and the type of day. Korolija, et al. [16] developed a model to predict the energy consumption of HVAC in office buildings in the United Kingdom, from four building typologies, seven envelope variables, five HVAC systems and five operational variables. Nath and Lamberts [17] established a simplified model to estimate the cooling energy consumption of an office building by simulating it on 18 Brazilian cities. They modified 15 building parameters, 12 HVAC system variables and three occupancy variants. The cities were selected based on a classification of the Brazilian local climates-cities-on 18 groups based on an index built from degree-hours and enthalpy.

The presence of general methods in Latin America is very low and their application is very scarce. The lower amount of required information and the lower time consumption of the simplified methods have allowed many Latin American national initiatives to be based on simplified methods. In fact, more than 80% of the Latin American initiatives are simplified methods and are centered on energy demand limitation or in the establishment of minimum requirements of the thermal envelope. However, the application of these tools is reduced.

It has to be highlighted that the energy assessment based on the energy demand or the characteristics of the thermal envelope does not integrate all the present heat interchange processes and does not account for energy consumption and greenhouse emissions, as the performance of HVAC systems are not taken into account.

The main objective is to develop a simplified calculation model to estimate energy consumption in order to assess the environmental impact of the building stock and to guarantee a higher acceptance and application in Latin America, with the objective of increasing the number of buildings with energy evaluations. This work is focused on multifamily housing buildings due to their high representativeness, especially in cities with a population greater than 200,000 habitants [18].

2. Materials and Methods

In order to create a simplified energy consumption estimation model for residential buildings in temperate climates for Latin America, the next steps were followed, as shown in Figure 3:

1. Analysis of current energy building performance initiatives.
2. Data collection: case study, user energy performance and present environmental conditions.
3. Development and calibration of the energy model.
4. Simulation scenarios: locations and U-value thresholds and proposals for walls and roofs.
5. Energy consumption and linear regression.
6. Equations for energy consumption estimation.

The aim of the first step is the finding of the common parameters of the thermal envelope of the residential building energy performance initiatives for those countries of Latin America with cities located in temperate climates, in order to get the threshold values, which will conform the simulation scenarios.

The second step aims at gathering all necessary information needed to define and characterize the case study in order to build the energy model: the geometrical and constructive definition of the case study, the elaboration of the users' profile and the present environmental performance of the case study [19]. This case study, a residential building, is representative of this type of residence, as shown in the national office of statistics of each selected country.

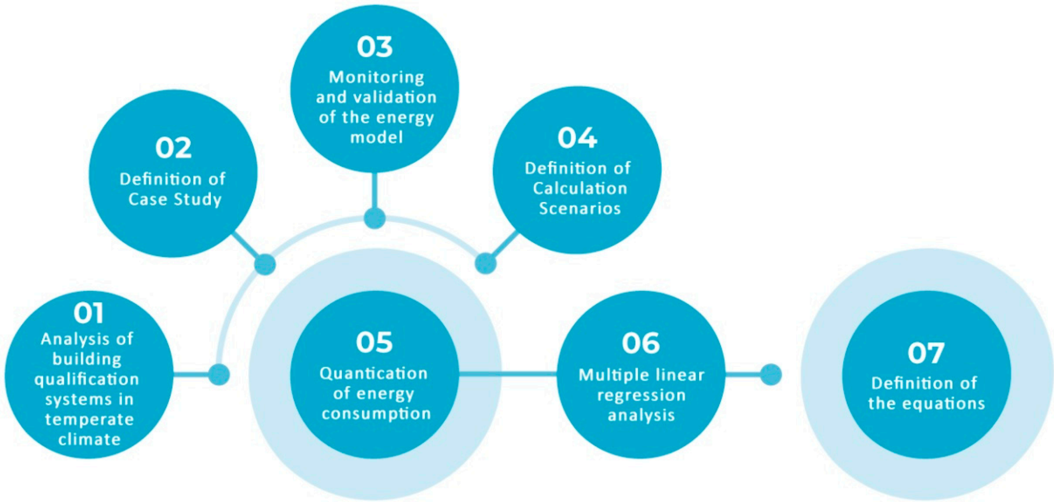

Figure 3. Scheme of the methodology created.

The third phase compares the monitored environmental performance of the case study with the simulated results in order to calibrate the energy model. Once the energy model was calibrated, the simulation scenarios were defined which are the function of the locations of the selected countries with temperate climates and the legislative threshold values for common thermal envelope parameters found in the first step. Finally, five constructive scenarios representing the variety of these threshold values are defined.

In order to get the energy consumption and its variation from the simulation scenarios, the thermal model of the original case study is simulated for each location of each country and for each location changing the constructive scenario according to its national requisites.

The correlation between the energy consumption data and the climatic variables is studied due to the development of linear regression statistical models where the most relevant variables are highlighted.

Finally, once these variables are identified, the correlational equations for heating and cooling estimation are defined, forming a simplified method for energy estimation based on few climatic data, easily available for building agents.

These steps can be grouped in two: development of the experiment and statistical analysis. The first group, covering the steps 1 to 4, is exposed in this chapter and the statistical analysis of the energy consumption and development of the correlational equations, steps 5 to 7, are shown in the results chapter.

2.1. Analysis of Current Energy Performance of Buildings Initiatives

Focused on Latin American context, the actual initiatives for energy performance of buildings centered on residential buildings were prioritized, which include objective requisites about comfort and energy efficiency. The initiatives for residential buildings from countries with at least five locations with temperate climate and the availability of weather files for EnergyPlus (epw) were selected.

The analysis also includes the Spanish scheme for being a referent in Latin America due to historical linkages and the use of a common language, among other factors. Furthermore, climatic similarities with the temperate regions of Latin America and their weather files for energy simulations are available, enabling a comparison between the Spanish minimum requisites and the Latin American threshold values [20–22].

Table 3 shows the National Building Energy Rating schemes, the mandatory standard that limits the characteristics of the thermal envelope and the parameters limited. In bold are the common parameters of the thermal envelope of the selected schemes.

Table 3. National Building Energy Rating (NBER) schemes for residential buildings and their correlated thermal envelope standard (TES) in Latin America and Spain.

Country	NBER and TES	Parameters of the Thermal Envelope
Argentina	IRAM 11900:2007 Law 13059:2003 IRAM 11604:2001 IRAM 11605:1996 IRAM 11625:2000 IRAM 11507-4:2010	**U-value: walls, roof**, floor, glazing Global losses coefficient Solar Heat Gain Coefficient (SHGC) Air infiltration rate Condensation risk
Brazil	PBE Edifica RTQ-R	**U-value: walls, roof** Thermal capacity: wall and roof Solar absorptivity for opaque enclosures Window to Wall ratio Natural ventilation factor
Chile	CEV Thermal Regulation	**U-value: walls, roof**, floor, glazing Thermal inertia SHGC Air infiltration rate
Mexico	Ecocasa NOM-020-ENER-2011 NOM-024-ENER-2012	**U-value: walls, roof**, floor, glazing Comfort range
Spain	RD 47/2007 RD 235/2013 Technical Building Code: Energy Saving Document (CTE DB-HE)	**U-value: walls, roof**, floor, glazing, internal partitions SHGC Air infiltration rate Condensation risk

The selected Latin American initiatives for energy efficiency of buildings were the Argentinian Thermal Conditioning Standards (Law 13059:2003) [23], the Brazilian Building Labelling Programme (PBE Edifica) [24], the Chilean scheme for Housing Energy Rating (CEV) [25] and the Mexican Programme Ecocasa [26].

In the Argentinian context there is an energy rating scheme for residential buildings, the IRAM 11900:2017 standard, but this is of voluntary fulfilment and is based on the requirements of the Law 13059:2003 which forces different IRAM standards related to the characteristics of the thermal envelope to be applied.

The Brazilian Programme includes the Technical Regulation of Quality for the Energy Efficiency Level of Residential Buildings (RTQ-R [27]), which limits the values of the different parameters of the thermal envelope according to the bioclimatic zone of the location. The Chilean context is similar; the Building Energy Efficiency Rating is based on the limited values determined in a specific legislative document called Thermal Regulation [28]. The Mexican Building Energy Rating is mandatory for new housing and is based on the calculation program of PassivHaus, which requires the minimum levels specified in the Official Mexican Standards (NOM), also compulsory. The Spanish context is similar to the Brazilian, Chilean and Mexican contexts: there is a Building Energy Rating scheme which also allows for the certification of the fulfilment of the thermal requirements of the thermal envelope.

The common parameter of the thermal envelope that is limited by the selected schemes is the thermal transmittance (U-value) of the external walls (vertical and horizontal, i.e., walls and roofs). So, this parameter is selected to be modified and then to build different simulation scenarios.

2.2. Data Collection

2.2.1. Case Study

Nowadays, more than 80% of the population of Latin America and the Caribbean live in cities [29]. Data from the Economic Commission for Latin America and the Caribbean (ECLAC) [30] show that the percentage of the population that lives in cities with more than 20,000 inhabitants in Argentina, Brazil, Chile and Mexico is 79.8%, 70.6%, 80.3% and 70.2% respectively. Furthermore, according to the Economic Commission for Latin America and the Caribbean (CEPALSTAT) [31], the percentage of urban housing in these countries is 90%, 83%, 86% and 76% respectively, with approximately 75% on property.

Housing buildings are the most representative building typology in countries with temperate climates and are the greatest energy consumers during their useful life [18]. In Spain, 68% of residential units are located in multi-family buildings, being the majority in cities with more than 5000 inhabitants. It was found that 56.3% of residential units have no thermal insulation [32]. This percentage is lower in Latin America, but still of relevance; 57% of the Chilean residential buildings are located in metropolitan cities; of this buildings, 81% are multi-family residential buildings [32]. In Argentina, 21.38% of residential units are located in multi-family buildings in cities with more than 20,000 inhabitants [33]. In Brazil, the average amount of multi-family buildings is 35% [34]. A lower presence of multi-family buildings can be found in Mexico [35].

The case study is a multi-family building based on traditional building fabric, designated to middle class families according to the Brazilian Programme "Minha Casa Minha Vida" Figure 4.

Figure 4. Case study: multifamily building.

The structure is of reinforced concrete; the external walls are based on brick masonry with a plaster layer on both sides; the windows are simple glazed with aluminum frame without solar protection; the roof is based on a concrete slab and aluminum–zinc tiles. The U-values are 2.51 W/m^2K for the external walls, 1.96 W/m^2K for roofs, 5.80 W/m^2K for windows and 2.88 W/m^2K for the internal floors.

The building is located in a plot of land at the center of Criciúma, Santa Catarina, Brazil, being 28°41′ South its latitude. According to Köppen classification, its climate is Cfa (humid subtropical climate), characterized by hot and humid summers, and mild winters [7]. According to the Brazilian Standard NBR 15.220: Thermal Performance of Buildings [36], Criciúma is located in climatic zone II, characterized by an annual average daily temperature higher than 18 °C, as shown in Figure 5. The urban land is mainly plane, the surrounding is based on isolated multi-family buildings, so there is no vegetation or other buildings to obstruct the solar incident radiation or exposure to wind.

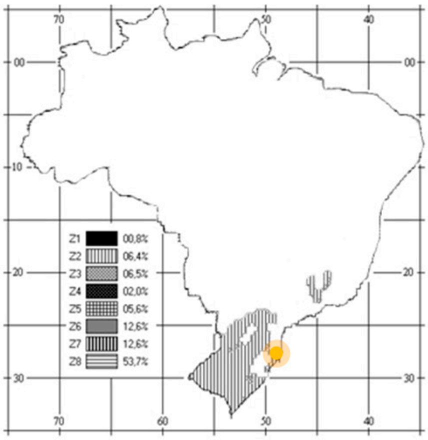

Figure 5. Location of Criciúma: zone II of the bioclimatic map of Brazil.

2.2.2. User Energy Performance

In order to define the occupancy and usage profile to be incorporated to the energy model, a survey of the inhabitants of the case study was carried out. A questionnaire was developed as a google formulary and sent by email to the responsible of each residential unit. From a population of 480 inhabitants, a response rate of 11% was recorded.

The focus of the survey was the understanding of those phenomena that could influence perceived comfort levels by recollecting information related to occupancy habits, HVAC preferences, possible modification of the internal covering, as well as perceptions about thermal comfort inside their dwellings.

The structure of the survey was composed of two introductory sections and four sections asking about occupancy, activities, timing, thermal comfort perception, air conditioning equipment and actions followed to reach thermal comfort Figure 6.

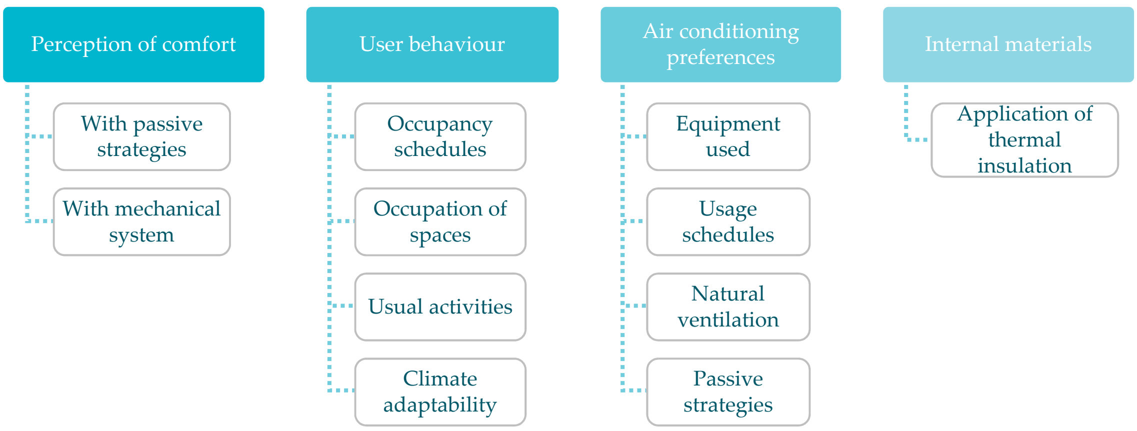

Figure 6. Fields of observation.

The introductory sections were informative and exposed the objective of the survey, its extent and the expected time to fulfil it. The first group of questions was focused on the identification of the users' opinion about their perceived thermal comfort under two situations: using or not using HVAC equipment. The following section asked about their habits: how they occupy and use their dwelling and how they are dressed while they stay at home. The next section focused on the preferences for using HVAC equipment: type of HVAC equipment, frequency of use, operation mode, natural ventilation and other passive strategies followed by the users. The last section asked about the constructive state of the dwelling in order to know if the thermal envelope had been modified.

The survey was based on multiple choice questions. An example can be found in Figure 7. Once the answers were received, they were analyzed in order to get statistical information about user behavior (an example is shown in Figure 8). Based on this statistical information, the user profile could be created.

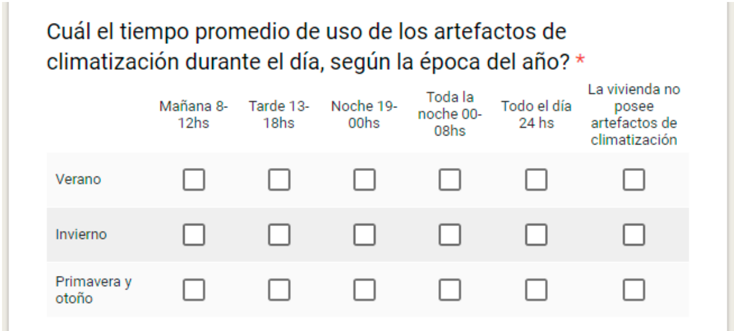

Figure 7. Multiple choice question example.

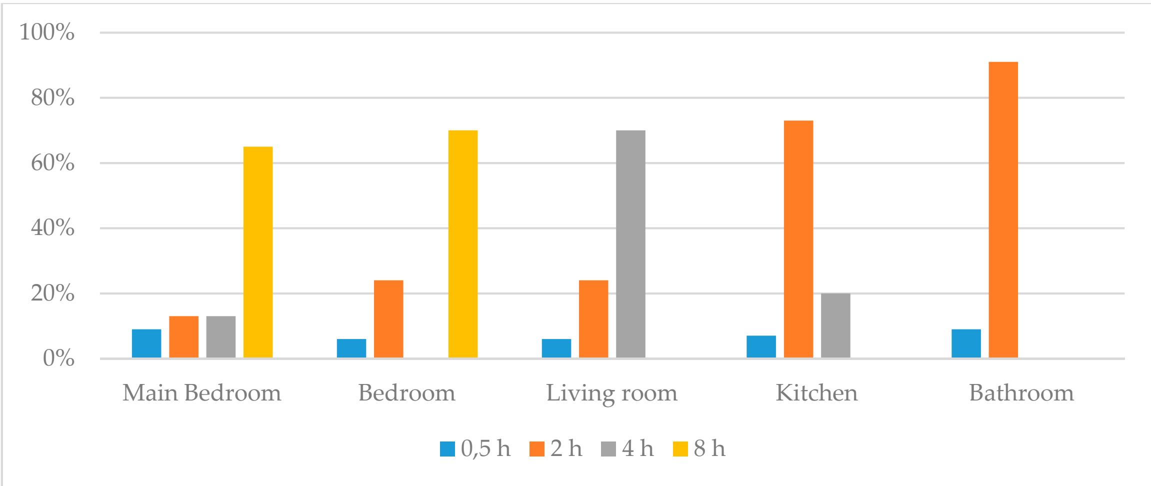

Figure 8. Statistical analysis of one of the questions of the survey.

The surveys showed that two-bedroom dwellings were mostly occupied by two inhabitants; meanwhile four inhabitants were the majority occupancy for three-bedroom dwellings. The daily time duration of each user activity was 8 h for sleeping, 8 h for working, 2 h for cooking and eating, 2 h for cleaning and personal care and 4 h for entertainment.

The users adapted their clothing according to seasonal variations, being tropical for summer (clo = 0.3), intermediate for spring and autumn (clo = 0.5) and light coated for winter (clo = 1.0).

Bathrooms, kitchen and common circulation areas were spaces where ventilation was the main strategy for thermal conditioning, meanwhile bedrooms and the living room used air conditioning equipment (if any). The HVAC systems on dwellings are air-to-air heat pump splits, fans and radiators. During summer, 100% of inhabitants used fans to reach thermal comfort at any time during the day, meanwhile 63% of the population use the split heat pump. However, 63% opened the window every time they wanted to ventilate the dwelling. Only 16% of the users maintained closed windows. During spring and autumn, 46% used fans, 9% used the split and 4% needed to use electric radiators. In these seasons there was a great portion (37%) which did not use any mechanical space conditioning system, and 24% kept their windows closed. During winter, those occupants with split systems used them (63%), 22% had and used electric radiators and 20% of the population did not use any heating equipment or did not have it. In this season, 54% of the inhabitants kept their windows closed.

The dwellings are equipped with a fridge (24 h functioning), two PCs and two TVs that are utilized for 2 h each, and the shower is used for 1 h. Daylight is the main lighting source from 8:00 h to 18:00 h and there is a fluorescent lamp in each space which functions from 18:00 h to 22:00 h.

Surveys verified that inhabitants used adaptive comfort practices. The operation hypothesis, thus, has been assembled bearing in mind the strategies and actions that are allowed per adaptive comfort model, that is, the changes of clothing for inhabitants and the operation of windows in order to get the dwelling ventilated, shown in Table 4 and Figure 9.

Table 4. Operation hypothesis.

	Main Bedroom	Bedroom	Living Room	Kitchen	Bathroom
People	2	1	2	1	1
Hours	8	8	4	2	2
Activity	Sleep	Sleep	Read/eat	Cook	Shower
Metabolism (W/pers)	72	72	110	230	180
Clothing (clo)	Summer = 0.3 | Winter = 1,0 | Spring-Autumn = 0.5				
Thermal zone	Conditioned			Ventilated	
Tª setpoint	Minimum = 18 °C | Maximum = 27 °C			-	
Air change rate	2				

Figure 9. Occupancy hypothesis.

The environmental temperature range for comfort and HVAC was taken from the adapted Givoni's chart, with a minimum value of 18 °C and a maximum of 27 °C.

The air change rate was set to 2 ac/h due to the ventilation strategy of the users and the bad quality of permeability of the window frames. This value is in accordance with the suggested values of the standard IRAM 11.604/01 [37].

2.2.3. Present Environmental Conditions

In order to get the present environmental conditions of the building for the purpose of calibrating the energy model, seven dwellings were monitored. Dry bulb air temperature (inside–outside), relative humidity (inside–outside) and global exterior solar radiation were recorded for a time-step of 30 min from the 14th to 22th in January and from 10th to 18th in July, representing winter and summer conditions, both in 2016.

Inside thermal conditions were recorded by two HOBO UX100-003 data loggers per dwelling (in the main bedroom and living room), located 150 cm from the floor and protected from direct solar radiation, shown in Figure 10. The external temperature, relative humidity and global radiation were recorded with another HOBO data logger. The sensors were protected from direct solar radiation and precipitation.

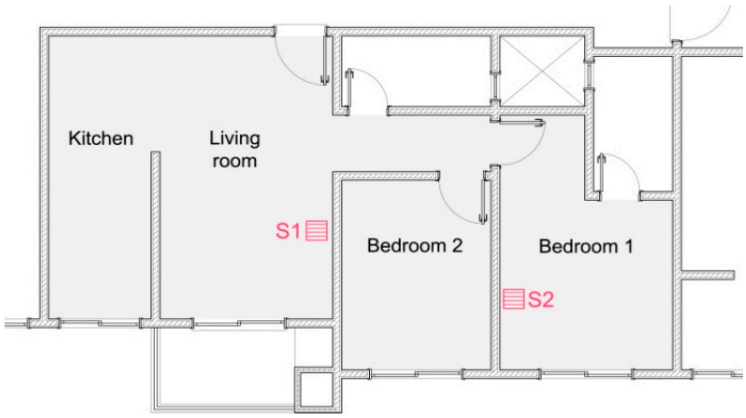

Figure 10. Location of the sensors in ground plan: Apartment 303.

The measured values were drawn in the adapted Givoni's chart, as it takes into account the adaptability of the user to different temperatures and relative humidity ranges [38]. Although it is designed to include only outdoor air conditions, indoor measured values were drawn in order to confirm the strategies followed by users, as they had reflected on the surveys. The first comfort range (zone E) considers relative humidity values varying from 30% to 50%; the second range (zone F) considers an adaptation to relative humidity values of up to 80%. The temperature for a comfort zone with low humidity varies from 18.5 °C to 27.5 °C but varies from 17 °C to 26 °C if the relative humidity is high, shown in Figure 11.

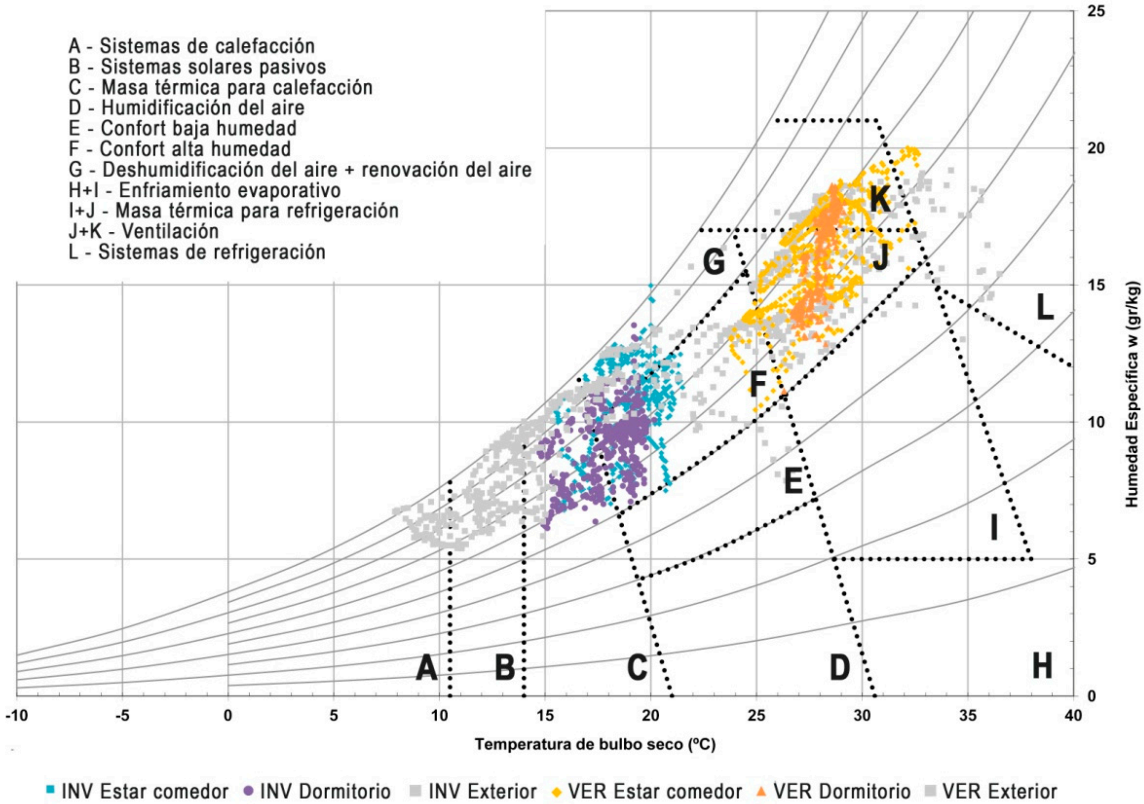

Figure 11. Measured temperature and relative humidity in the adapted Givoni's chart.

It can be observed that during the summer week, 3.24% of the measured hours in the living room were in thermal comfort zone E without any air conditioning strategy. Considering the natural ventilation and adaptation to high humidity, the percentage of hours in comfort increased to 28.70%.

In the main bedroom, those values were 0.46% and 10.19%, respectively. It can be seen that the main bioclimatic strategy followed by users to reach the comfort zone during summer is ventilation, as air movement reduces the perceived temperature.

During the winter week, 6.49% of the measured hours in the living room were in comfort zone E without passive strategies. As users in this period use artificial heating systems, and let solar radiation enter the dwelling but keep the windows closed, the humidity increases but within a certain range, and comfort hours increased this percentage to 49.80%. In the case of the main bedroom, those values were 4.24% and 38.89%, respectively. It can be observed how the users' strategies, obtained from the surveys, during winter have a higher impact on reaching the comfort zone, even with high humidity, than in the summer time.

2.3. Development and Calibration of the Energy Model

An energy model of the case study was created in DesignBuilder (version 5.0.0.137), based on the widely respected EnergyPlus simulation program [39]. The input climate data were the energy plus weather data (epw) [40], modified with the external measured data.

Geometric, constructive, occupancy, equipment, HVAC systems and usage characteristics were created according to the obtained data from the documentation of the building and the user profile created from surveys.

In order to validate the thermal model, a comparison between simulated internal temperature on free running and the measured values from monitoring Figure 12.

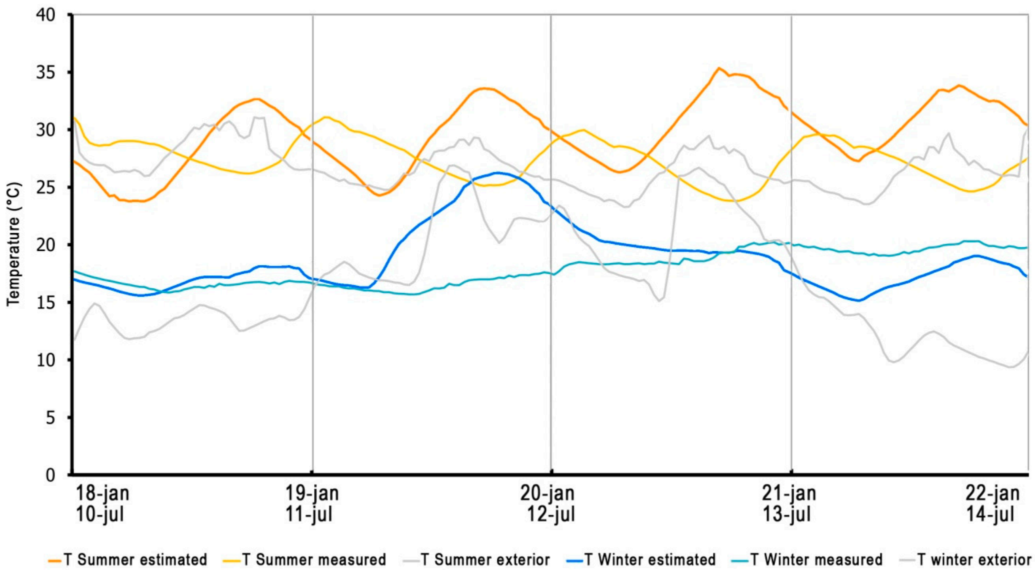

Figure 12. Comparison between measured and estimated interior temperature.

It can be observed that, in summer, the maximum measured temperature was 31.1 °C, meanwhile the maximum estimated temperature was 35.3 °C. In winter, the maximum inside measured temperature was 20.3 °C and the estimated was 26.2 °C with a thermal time lag of 11 h. These values indicate that the energy model overestimates the temperature values, so it was necessary to identify the sources of uncertainty in order to calibrate the model.

Regarding the measured values, it was observed that the heterogeneity of the values was the main uncertain source. The total typical uncertainty of the measured values was 0.15 °C (95% confidence interval, coverage factor k = 2) indicating that the uncertainty is low and that the air stratification during the most critical summer and winter week is negligible.

The geometry of the model was the actual geometry, as it was measured from the case study. The properties of the materials were manually introduced based on the real construction. The weather file is a statistical compilation, so there is a difference between measured data and the data contained in the weather files. Occupancy and internal loads were also a source of uncertainty, as the user profile was created based on the survey, which implies certain subjectivity.

A sensitivity analysis was carried out between three outputs and the parameters of thermo-physical properties of the materials, the general conditions of the building and its surrounding in order to assess the uncertainty of the energy model. The operative temperature was found to be the output which better reflects the modification of the parameters of the model. To adjust the model, the most influential parameters were the air change rate and the thermal conductivity of concrete in roofs and of the brick layer in walls.

The result of the energy balance showed that internal loads and solar heat gains were a significant heat source that provoked the estimated temperatures to be higher than the measured ones. Internal equipment loads and lighting were eliminated from the model and, due to the results from the sensitivity analysis, the air change rate was modified. Thermal properties of the roof and walls were not modified in order to keep the representativeness of the simulation scenarios.

Calibration of the model was performed according to guidelines from ASHRAE Guideline 14 [41]. This guideline states that a model could be considered validated if its mean bias error (MBE) is no larger than 10%, and if the coefficient of variation of the root-mean-square error (CV(RMSE)) is not larger than 30% when the hourly data is used for the validation. The validation was based on the monitored and simulated dry bulb indoor air temperature, which was measured in 30-min intervals.

In each monitoring period, the MBE and CV(RSME) satisfied the 10% and 30% limits respectively for indoor air temperature, as recommended in ASHRAE Guideline 14.

2.4. Simulation Scenarios

In order to build a simplified calculation method and assess the energy consumption difference due to the fulfilment of the minimum requisites of thermal transmittance defined by the Argentinian, Brazilian, Chilean, Mexican and Spanish initiatives, two simulation series were carried out. The first one consists of a simulation of the case study built in different locations with temperate climates. The second one consists of a simulation of the case study in these locations but modifying the thermal transmittance of the opaque elements of the thermal envelope according with the legal requisites of the country.

2.4.1. Locations and U-value Thresholds

In order to establish the locations with temperate climates for the first set of simulations, cities from Argentina, Brazil, Chile, Mexico and Spain with temperate climates and a population higher than 200,000 inhabitants were selected, totaling 307 locations. The information about population was obtained from national censuses.

As energy consumption is highly related to climate rigor, and this is related to degree days [42], cities with heating and cooling degree days higher than 1500 for each regime were selected, resulting in 42 locations, giving priority to those locations with a bigger population, more distance between them and with available weather files.

The selected locations account for 19.05% of the population of Argentina, 2.52% of the population of Brazil, 46.18% of the population of Chile, 13.53% of the population of Mexico and 8.69% of the population of Spain, so the results would cover a significant population from Argentina, Chile and Mexico.

Table 5 shows the selected locations, heating and cooling degree days (HDD and CDD), national climatic zone classification and the minimum thermal transmittance for façades and roofs according to their national requirements for thermal envelopes.

Table 5. Selected locations.

Country	Location	CDD	HDD	Climatic Zone	U Façade	U Roof
Argentina	La Rioja Santiago del Estero	1368 1311	621 450	Ia	0.93	0.45
	Corrientes	1308	192	Ib	1.00	0.45
	Catamarca	1440	531	IIa	0.90	0.45
	Paraná	738	750	IIb	0.99	0.45
	Buenos Aires Córdoba Rosario	732 705 642	771 714 957	IIIa	1.00	0.48
	La Plata	525	1050	IIIb	0.95	0.48
	Mar del Plata	141	1293	IVc	0.85	0.48
Brazil	Curitiba	243	681	1	2.5	2.3
	Ponta Grossa Santa María	408 759	492 462	2	2.5	2.3
	Blumenau Chapecó Criciúma Florianópolis Porto Alegre	975 648 792 942 894	138 387 252 183 372	3	3.7	2.3
Chile	Antofagasta	198	657	1	4	0.84
	Copiacó Valparaíso	453 0	435 1434	2	3	0.60
	Santiago	201	1375	3	1.9	0.47
	Concepción	0	1490	4	1.7	0.38
	Temuco	0	1334	5	1.6	0.33
Mexico	Aguascalientes	589	423	–	0.83	0.83
	Ciudad de Mexico	195	330	–	0.9	0.9
	Guadalajara	717	360	–	0.71	0.71
	Hermosillo	1404	516	–	0.47	0.47
	Juárez	996	1473	–	0.62	0.62
	León	756	189	–	0.71	0.71
	Monterrey	1388	237	–	0.55	0.55
	Puebla	156	429	–	0.83	0.83
	Tijuana	402	657	–	0.71	0.71
Spain	Málaga	864	693	A3	0.94	0.5
	Murcia Palma Valencia	1060 873 864	849 792 756	B3	0.82	0.45
	Alicante Córdoba Seville	861 1080 1173	771 999 741	B4	0.82	0.45
	Barcelona	549	1276	C2	0.73	0.41
	Granada	708	1360	C3	0.73	0.41

2.4.2. Proposals for Walls and Roofs

Five couples of thermal transmittances (façade and roof) were created in order to deal with the requisites of each country. The first couple was established to be the U-values of the case study as the façade and roof materials and configuration are traditionally used in Latin America.

Normative thermal transmittance for the façade and roof for each location were identified Table 5. In Argentina, Brazil, Chile and Spain U-values vary depending on the climatic zone [22,28,36,43]. In Argentina, there is a difference between winter and summer requirements, so the most restricted values were chosen to fulfil both situations. In Mexico, U-values are only defined for certain locations as the normative does not specify a climatic classification [44]; furthermore, there is a change in U-values for buildings of more than three stories high, so the most restricted values were selected.

Finally, the admissible U-values were grouped based on similar ranges, excluding those values corresponding to the case study. Four couples of U-values for the façade and roof were defined in Table 6.

Table 6. Main composition of the five solutions for façade and roof.

Element	Composition	U W/m²K
Wall I	Hollow ceramic brick—15 cm	2.510
Wall II	Double ceramic brick wall—10 cm	1.823
Wall III	Double ceramic brick wall with 1.5 cm of expanded polystyrene 20 kg/m³	1.101
Wall IV	Hollow ceramic brick-15 cm with fiberglass—3.5 cm	0.821
Wall V	Hollow ceramic brick with 5 cm of expanded polystyrene of 30 kg/m³	0.503
Roof I	Concrete slab-15cm with alu-zinc roof tiles	1.960
Roof II	Concrete slab-15 cm with fiberglass—3.5 cm	0.854
Roof III	Concrete slab-15 cm with fiberglass—5 cm	0.680
Roof IV	Concrete slab-15 cm with expanded polystyrene of 30 kg/m³—5 cm	0.526
Roof V	Concrete slab-15 cm with fiberglass—10 cm	0.405

These additional U-values present different materials in the main structure of each element. Excepting Wall II, all additional elements incorporate a thermal insulation layer. Walls are covered on both sides with a plaster layer, the lower side of the roofs are also covered with a plaster layer and the upper side of the slab is a layer of expanded clay.

In order to control the appearance of pathologies, the possibility of condensation risk was analyzed for each wall–roof couple [45]. It was verified that, under normal climatic conditions, there is no superficial or interstitial condensation risk in external walls and roofs.

3. Results

In this chapter, the statistical analysis of the simulation results and the development of the correlational equations are shown. Finally, in order to contrast the results of the equations, they have been compared with the energy consumption resulting from the energy rating schemes of the countries selected.

3.1. Energy Consumption and Linear Regression

The improved energy model was simulated in the 42 locations (scenario R) and also in the 42 locations modifying the U-values of the façade and roof according to national requisites, grouped in five couples (scenario N). The following energy consumption results were obtained, shown in Table 7.

Table 7. Estimated cooling and heating energy consumption (kWh/m^2/year).

Country	Location	Cooling_R	Heating_R	Cooling_N	Heating_N	Ave Cool	Ave Heat
Argentina	La Rioja	152.5	150.3	113.6	114.5	81.21 60.87 71.04	238.77 172.57 205.67
	Santiago del Estero	126.8	111.2	94.7	82.9		
	Corrientes	148.6	74	113.5	48.6		
	Catamarca	132.9	120.7	102.5	86.3		
	Paraná	70.3	209	51.3	150.6		
	Buenos Aires	43.6	339.9	32.9	242.5		
	Córdoba	37.8	258.3	27.9	183.6		
	Rosario	64.6	248.4	47.2	181.3		
	La Plata	30.9	364.8	22.6	263.6		
	Mar del Plata	4.1	511.1	2.5	371.8		
Brazil	Curitiba	17.3	148.4	14.3	139.1	54.64 49.64 52.14	110.14 101.40 105.77
	Ponta Grossa	32.5	112.5	28.1	103.3		
	Santa María	62.2	162.7	56.6	149.7		
	Blumenau	53.9	59.2	49.5	53.4		
	Chapecó	14	149.3	11.8	136.7		
	Criciúma	67.6	115	61.7	104.9		
	Florianópolis	92.9	33	85.6	30.4		
	Porto Alegre	96.7	101	89.5	93.7		
Chile	Antofagasta	2.6	65.6	1.7	63.4	3.28 2.22 2.75	363.15 277.76 306.14
	Concepción	0	507.5	0	392.4		
	Copiacó	1.2	238.9	0.6	200.3		
	Santiago	14.8	432.6	10.7	372.4		
	Temuco	0.9	632.4	0.3	506.8		
	Valparaíso	0.2	301.9	0	259.3		
Mexico	Aguascalientes	42.2	36.6	31.5	25	79.93 58.68 69.31	96.87 67.60 82.23
	Ciudad de Mexico	1.8	68	1	44.1		
	Guadalajara	26.9	63.3	17.3	48.6		
	Hermosillo	306.7	19.6	225.7	12.4		
	Juárez	101.7	359.3	72.8	248.3		
	León	36.5	14.7	27.7	7.9		
	Monterrey	194.3	92.2	147.5	56.7		
	Puebla	2.9	71.7	1.4	50.2		
	Tijuana	6.4	146.4	3.2	115.2		
Spain	Málaga	49.9	213.3	40.1	139.6	56.99 43.24 50.12	327.48 220.60 274.04
	Murcia	42.9	303.9	35.1	204.4		
	Palma	71.8	334.8	52.8	245.1		
	Valencia	72	297.2	53.1	206.8		
	Alicante	56.2	231	45.6	153.3		
	Córdoba	60.3	344.4	46.3	233.1		
	Seville	89.4	243.7	63.7	174.1		
	Barcelona	40.4	437.1	28.5	287		
	Granada	30	541.9	24	342		

Average values: first line scenario R, second line scenario N, third line average between both.

It can be observed that, in general, the modification of the original U-values for the walls and roofs in the requisite values of the national legislation, reduces the energy consumption for cooling and heating.

It also can be observed that, although locations within the same climatic classification generally trend to perform in a similar way (i.e., more heating than cooling consumption), there are cases where different trends can be found in the same climatic zone.

A multiple linear regression study was carried out in order to identify the climatic variables more related to heating and cooling energy consumption. Geographic and climatic data for each location were extracted by means of an analysis of the weather file with the Climate Consultant software including the altitude, latitude, monthly average temperature (Tavg), relative humidity (RH), global radiation (RAD), wind speed (Wsp) and sky cover percentage (SKcv).

Furthermore, degree days (DD) were calculated for each location by using the average temperature (Tavg) of each location considering a base temperature of 18 °C [46]. The minimum and maximum design temperature (Td) were also calculated. The maximum design temperature (Td max) was calculated by adding 3.5 °C to the average maximum temperature (Tmax avg) corresponding to the warmest month, and the minimum design temperature (Td min) was calculated by subtracting 4.5 °C from the average minimum temperature (Tmin avg) corresponding to the coldest month according to indications from IRAM 11.603 [45].

Monthly average temperature, relative humidity, global radiation, wind speed and sky cover percentage values were delimited for two different situations in order to determine the set of data more correlated with the variation of energy consumption. The first one considers the annual average; the second considers the average of the three warmest months (average summer—as) to be correlated to cooling consumption and the three coldest months (average winter—aw) to be correlated to heating consumption, shown in Table 8.

Table 8. Input data for the linear regression analysis.

N °	Variable	Definition
1	Cooling	Cooling energy consumption (kWh/m^2)
2	Heating	Heating energy consumption (kWh/m^2)
3	A	Altitude (°)
4	L	Latitude (°)
5	Tavg	Average temperature—monthly (°C)
6	RH	Relative humidity (%)
7	RAD	Global radiation (W/m^2)
8	Wsp	Wind speed (km/h)
9	SKcv	Covered sky (%)
10	CDD	Cooling degree—days
11	HDD	Heating degree—days
12	TDmax	Maximum design temperature (°C)
13	TDmin	Minimum design temperature (°C)
14	Tmax-avg	Average maximum temperature–hottest month (°C)
15	Tmin-avg	Average minimum temperature–coldest month (°C)
16	RHas	Average relative humidity for the three hottest months%
17	RHaw	Average relative humidity for the three coldest months%
18	RADas	Average global radiation for the three hottest months (W/m^2)
19	RADaw	Average global radiation for the three coldest months (W/m^2)
20	Wspas	Average wind speed for the three hottest months (km/h)
21	Wspaw	Average wind speed for the three coldest months
22	SKcvas	Average of covered sky for the three hottest months (%)
23	SKcvaw	Average of covered sky for the three coldest months (%)
24	CDDs	Average cooling degree-days for the three hottest months
25	HDDw	Average heating degree-days for the three coldest months
26	TDmax-s	Maximum design temperature for the three hottest months (°C)
27	TDmin-w	Minimum design temperature for the three coldest months (°C)

The linear regression analysis was performed by SPSS software (version 15.0). The interpretation of the results was based on the consideration of the values of the determination coefficient. R^2 presents null correlation between their variables if the value is 0; very low correlation if the value is between 0.01 and 0.19; low correlation if the value is between 0.2 and 0.39; moderated correlation if the value is between 0.4 and 0.69; high correlation if the value is between 0.70 and 0.89; very high correlation if the value is between 0.9 and 0.99; and a perfect correlation if the value is 1 [47]. Positive values indicate that dependent the variable increases as the independent variable increases; negative values indicate that the dependent variable decreases as the independent variable increases.

The adjusted determination coefficient ($\overline{R}^2$) was used to assess the reliability of the mathematical model. The relevance of the statistical model and the significance of the variables were verified for each case by means of the null *p*-value hypothesis test in the ANOVA and the probability values. A value ≤0.05 was adopted to test the hypothesis that the analyzed variable is of significance.

The method of multiple linear regression analysis was to add the variables forward, in which the software identifies the variables most correlated with the dependent variable (energy consumption), becoming the main variable. Lately, more variables are progressively added in order to increase the R^2, provided that they are influencers of the dependent variable and improve the statistical model, becoming secondary variables. The latest model corresponds to the highest R^2 between the dependent variable and the main and secondary variables, becoming the optimal statistical model. The independent variables not included are neither significant nor influential on the dependent variable.

Results from the multiple linear regression analysis are shown in Tables 9 and 10.

Table 9. Summary of statistical models considering a principal variable + secondary variables.

Condition	Model	Variables	R	R^2	R^2 Corrected	Typical Error
Summer	1	CDD	0.936	0.877	0.874	16.39443
	2	CDD. L	0.951	0.904	0.899	14.67044
	3	CDD. L. CDDs	0.959	0.920	0.913	13.58502
Winter	1	HDD	0.929	0.863	0.860	59.35259
	2	HDD. RADaw	0.946	0.895	0.889	52.78454
	3	HDD. RADaw. Tmin-avg	0.962	0.925	0.920	44.95103
	4	HDD. RADaw. Tmin-avg. Wspaw	0.968	0.938	0.931	41.58207

Table 10. Coefficients for the statistical models considering a main variable + secondary variables.

Condition	Model	Variables	B	Typical Error	Beta	t	Sig
Summer	1	(Constant)	−17.832	4.553	–	−3.917	0.000
		CDD	0.085	0.005	0.936	16.890	0.000
	2	(Constant)	−22.240	4.286	–	−5.189	0.000
		CDD	0.089	0.005	0.987	19.013	0.000
		L	−0.253	0.076	−0.172	−3.310	0.002
	3	(Constant)	−13.616	5.069	–	−2.686	0.011
		CDD	0.123	0.013	1.353	9.513	0.000
		L	−0.221	0.072	−0.150	−3.078	0.004
		CDDs	−0.207	0.076	−0.394	−2.735	0.009
Winter	1	(Constant)	8.300	16.202	–	0.512	0.611
		HDD	0.282	0.018	0.929	15.887	0.000
	2	(Constant)	192.751	56.100	–	3.436	0.001
		HDD	0.242	0.020	0.799	12.359	0.000
		RADaw	−537.190	157.903	−0.220	−3.402	0.002
	3	(Constant)	464.670	83.480	–	5.566	0.000
		HDD	0.162	0.026	0.533	6.163	0.000
		RADaw	−933.288	167.410	−0.382	−5.575	0.000
		Tmin-avg	−14.385	3.622	−0.277	−3.972	0.000
	4	(Constant)	394.912	81.366	–	4.854	0.000
		HDD	0.164	0.024	0.541	6.759	0.000
		RADaw	−871.390	156.525	−0.357	−5.567	0.000
		Tmin-avg	−12.793	3.401	−0.246	−3.762	0.001
		Wspaw	3.233	1.188	0.116	2.722	0.010

It can be observed that degree days are the main variable for heating and cooling energy consumption. The determination coefficients for both situations are 0.86 for heating energy consumption (winter) and 0.87 for cooling energy consumption (summer), indicating a strong variation of the energy consumption with degree days. The inclusion of secondary variables increased the correlation between energy consumption and climatic variables.

The final statistical model presents R^2 = 0.92 for summer and R^2 = 0.93 for winter (heating energy consumption). These results show that cooling energy consumption depends almost completely (92%) on the variation of cooling degree days, latitude and cooling degree days for the three warmest months. Heating energy consumption depends almost completely (93%) on the variation of heating degree days, global radiation of the three coldest months, average minimum temperature and average wind speed for the three coldest months.

Although heating and cooling degree days are the most influential variables on heating and cooling energy consumption, it is observed that not all of the five selected countries use degree days to define climate rigor, shown in Table 11, this is the case for Argentina and Mexico, which use the maximum design temperature and the average maximum temperature, respectively.

Table 11. List of climatic variables used in the rating systems studied.

Country	System	Condition	Main Climatic Variable	Secondary Climatic Variable
ARG	IRAM 11659 IRAM 11604	Summer Winter	Max design temperature degree days	Solar radiation –
BRA	PBE Edifica	Summer Winter	degree hour degree hour	– –
CHI	– CEV	Summer Winter	– degree days	– Altitude
MEX	NOM-020	Summer	Ave max temperature	Solar radiation
SPA	CEE	Summer Winter	degree days degree days	Solar radiation Solar radiation

ARG = Argentina, BRA = Brazil, CHI = Chile, MEX = Mexico, SPA = Spain.

In Mexico, furthermore, there is no standard for winter conditions, and in Chile there is no regulation on summer conditions. It is observed by analyzing the cooling energy consumption from the Chilean locations, shown in Table 7, that the climate in these cities has been demonstrated to be slightly rigorous during summer, so there is no need for a summer condition standard. However, heating energy consumption in Mexico was shown to be significant so it would be convenient to include any kind of regulation for winter conditions.

3.2. Equations for Energy Consumption Estimation

Once the statistical models were improved, the equations for the energy consumption estimation of multi-family residential buildings in temperate climates were defined (Equations (1) and (2)):

$$\text{HEC} = (0.123 * CDD) - (0.221 * \text{L}) - (0.207 * \text{CDD}_\text{s}) - 13.616 \tag{1}$$

where HEC is the heating energy consumption, CDD is the cooling degree days (base 18 °C), L is latitude (m) and CDD_s is the average cooling degree days for the three warmest months (base 18 °C).

$$\text{CEC} = 394.912 + (0.164 * HDD) - (871.390 * \text{RAD}_\text{aw}) - (12.793 * \text{T}_\text{amin}) + (3.233 * \text{W}_\text{spaw}) \tag{2}$$

where CEC is the cooling energy consumption, HDD is the heating degree days (base 18 °C), RAD_aw is the average global radiation for the three coldest months (W/m^2), T_amin is the average minimum temperature (°C) and W_spaw is the average wind speed for the three coldest months (km/h).

Once the equations are defined, the correlation between the results given by the equations and those obtained by the simulation, shown in Table 7, were compared in order to visualization of their adjustment, shown in Figure 13.

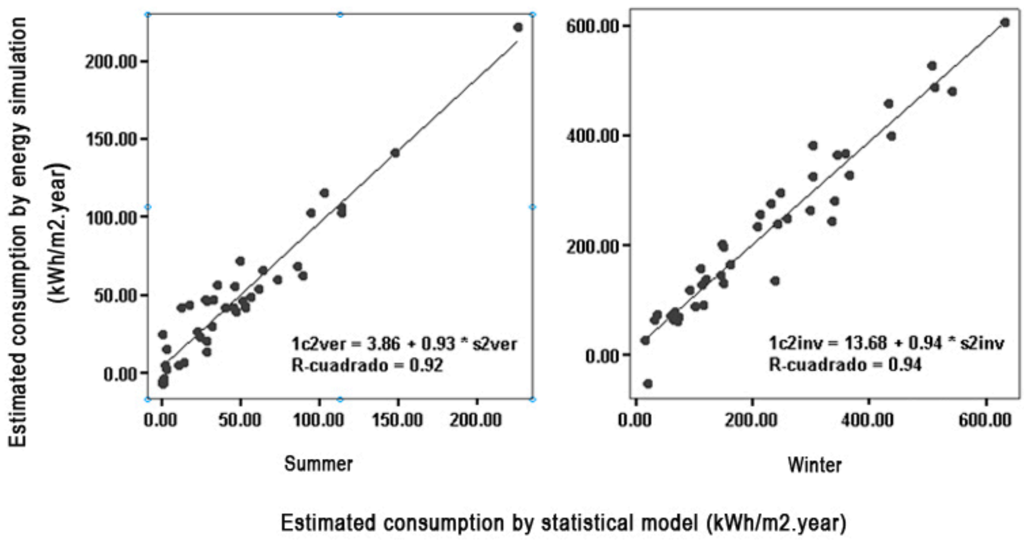

Figure 13. Comparison between energy simulation and statistical model results (kWh/m^2.year).

It can be observed that the R^2 values are 0.92 for cooling and 0.94 for heating, indicating very high reliability in the estimation of energy consumption by the equations.

3.3. Contrasting Predictions from Equations and Established Methods

In order to identify the main similarities and differences between the equations and the existing methods to validate and optimize the model, a comparison between the equations and the Brazilian, Chilean and Spanish existing methods was carried out. The Argentinian and the Mexican method were excluded, as their procedures do not assess thermal loads.

Energy consumption results from equations were compared to the values obtained from the simplified calculation template provided by the PBE Edifica from Brazil and by the CEV from Chile. In the Spanish case, there are some tools, simplified and general methods. For this analysis, the simplified tool CE3X was used.

In the Spanish and Chilean cases, the methods enabled the energy demand to be obtained, so Equation (3) was applied in order to find the energy consumption. The seasonal average performance of the systems has been defined as 1.02 for summer and 1.45 for winter, according to the Institute for the Diversification and Saving of Energy (IDAE), from the Government of Spain [48]:

$$C = D/\eta \quad (3)$$

where C is the final energy consumption (kWh/m^2 year), D is the energy demand (kWh/m^2 year) and η is the seasonal average performance (%)

It was observed that the estimated heating energy consumption by the equation has a difference of 11.2% from CEV results, 21% from CE3x and 210% from PBE Edifica. The estimated cooling energy consumption by the equation has a difference of 43% and 596% from CE3X and PBE Edifica, respectively, shown in Table 12.

Table 12. Comparison between equation results and national calculation tools: PBE for Brazil, CEV for Chile and CE3x for Spain (kWh/m^2 year).

Country	Location	Heating Consumption			Cooling Consumption		
		Equation	Nat. Tool	Δ (%)	Equation	Nat. Tool	Δ (%)
Argentina	Blumenau	12.0	9.1	31.9	68.6	8.3	726.4
	Chapecó	43.6	9.1	379.4	37.9	8.3	357.1
	Criciúma	22.7	9.1	149.1	63.2	8.3	661.7
	Curitiba	77.1	21.5	258.8	2.2	2.6	−17.0
	Florianópolis	6.3	9.1	−30.0	62.4	8.3	651.0
	Ponta Grossa	38.5	10.5	266.9	24.4	4.3	467.4
	Porto Alegre	18.39	9.1	102.0	59.08	8.3	611.8
	Santa Maria	59.53	10.5	466.9	59.26	4.3	1278.2
Chile	Antofagasta	15	43.0	−34.8	–	–	–
	Concepción	227.8	232.0	1.8	–	–	–
	Copiapó	49.3	56.0	12.0	–	–	–
	Santiago	203.5	209.0	2.6	–	–	–
	Temuco	262.8	289.0	9.0	–	–	–
	Valparaíso	155.6	147.5	5.9	–	–	–
Spain	Alicante	124.3	167.5	−25.8	47.1	55.1	−14.5
	Barcelona	178.3	258.75	−31.1	36.5	26.0	40.4
	Córdoba	172.0	167.5	2.7	71.5	46.2	54.8
	Granada	211.5	255	−17.1	43.9	66	−33.5
	Málaga	114.8	123.75	−7.2	52.3	66	−20.8
	Murcia	152.9	167.5	−8.7	51.1	66	−22.6
	Palma	98.3	152	−35.3	57.8	33.1	75.2
	Seville	99.4	167.5	−40.7	102.6	46.2	122.1
	Valencia	113.6	168.75	−32.7	61	66	−7.2

The results indicate that the proposed method is closer to heating energy consumption calculated by the Chilean and Spanish tools and is farther from the cooling energy consumption calculated by the Spanish and Brazilian tools. When comparing the estimated energy consumption results from the equations (Table 7) with the degree days required for the 42 locations (Table 5), it is observed that although there is a very high correlation, for the Brazilian and Spanish cases, the energy consumption calculated by their national tools presents low or very low correlation with degree days, indicating that the proposed method is more consistent with the variation of the local climate rigor (Figure 14).

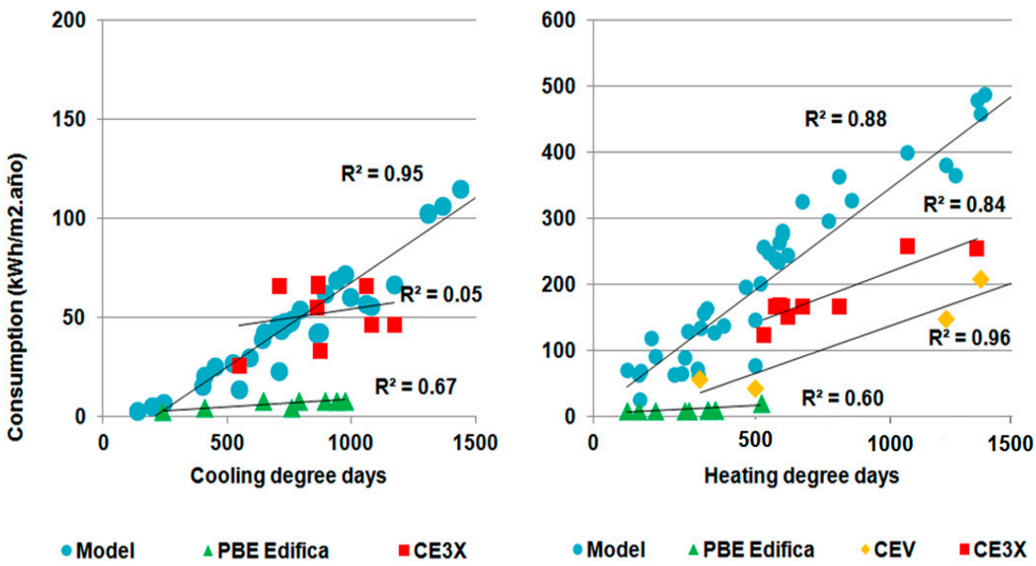

Figure 14. Consumptions estimated by the model and systems of Brazil, Chile and Spain in relation to the degree days of the 42 localities analyzed.

4. Discussion

It is observed that in the Brazilian and Spanish systems, climatic conditions are introduced by means of a selection of the climatic zone (statistically) providing the same energy consumption for different locations within the same climatic zone (i.e., Blumenau, Chapecó, Criciúma, Florianópolis and Porto Alegre in Brazil); the input data in the proposed method are specific climatic data of the location, so it provides further approximation to real conditions. In this regard, the minimum difference to the calculated energy consumption by the Chilean system demonstrates a very high correlation between energy consumption and degree days for each selected Chilean city.

The geometry, building fabric, HVAC systems and user profile characteristics required by the energy rating schemes of the studied countries are similar to the input data of the energy model. However, in the national tools these are input data, while in the proposed method this information is implicit to the equations, so is not possible to modify the building characteristics.

It has to also be highlighted that while this method was built from a user profile developed from a real profile, in the Spanish tool the occupancy and usage profile is predefined for residential buildings with an occupancy thermal load much higher than that of the real profile obtained by surveys. The difference between these profiles is, without doubt, one of the main sources of difference between energy consumption results from the proposed method and the national tools.

The developed methodology is very close to the methods used by Petersdorff, Boermans and Harnisch [14], and Nath and Lamberts [17]. In both cases, an energy model was simulated under different climatic conditions in order to obtain energy consumption data for a statistical analysis. However, the proposed model works with 42 locations when the revised studies worked with three and 18 locations, respectively.

Furthermore, the thermal envelope characteristics in the proposed model is centered in the modification of insulation thickness but Petersdorff, Boermans and Harnisch [14] also vary building typologies, and Nath and Lamberts [17] modified 15 building characteristics without modifying insulation levels. HVAC characteristics are of higher relevance in the model of Nath and Lamberts [17], as it is centered on office buildings.

5. Conclusions

This research describes the methodology developed to create a simplified method to estimate the energy consumption of multi-family housing buildings located in temperate climates, whose input data are just a few climatic variables.

The estimated energy consumptions from the equations present very high values of the determination coefficient (R^2 = 0.92 and R^2 = 0.94), demonstrating the viability of the application of this method as a tool in quantifying energy consumption.

The proposed method is mainly manual, being easier to use than energy simulation software. It can be implemented in other tools as a spread sheet, in order for even easier use. It can be used by professionals during the building design or reconstruction stages helping to make decisions as it predicts the energy consumption for both heating and cooling, by research centered on the energy performance of buildings, allowing an assessment and qualification of the buildings, and by governmental actors to transfer information to populations in a simple manner, generating awareness about energy efficiency in buildings.

In contrast to other schemes that included climatic conditions based on climatic zones, the proposed method requires some specific local climatic variables as input data, so the energy consumption results are more consistent with the local climatic variations. There is a certain difference in the results from those calculated by national schemes based on climatic zones as they output the same energy consumption for different locations within the same climatic zone. In contrast, results from the proposed method and the Chilean one, as they vary with degree days, are very close.

The multiple linear regression analysis demonstrates that, in general, degree days is the most influential variable on energy consumption in residential buildings. In summer conditions, latitude and average degree days for the three warmest months are also influential. In winter conditions, the average global solar radiation for the three coldest months, average minimum temperature and average wind speed for the coldest months have to be taken into account.

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