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Abstract	A tool for modeling the thermal performance of the Uruguayan residential building stock was developed. EnergyPlus simulations were performed for typical buildings, and the results were extrapolated for the whole residential sector according to the prevalence of these typical buildings among the whole housing stock. Python functions and its Eppy library were used to generate and simulate the large quantity of EnergyPlus models required to represent the Uruguayan housing stock as accurately as possible. Results of thermal performances were obtained for the residential sector, and also the impact of energy efficiency strategies was analyzed.	
Keywords (separated by '-')	Energy Efficiency - Residential Sector - Thermal Modeling	

Chapter 91
Modeling Thermal Performance in the Uruguayan Residential Sector

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91.1 Introduction

Residential buildings contribute to the world's total final energy demand in a relevant proportion. As a consequence, in recent years different building energy models have been developed with the purpose of effectively understanding, assessing, and managing energy consumption in the residential building sector (Aydinalp et al. 2002; Cerezo-Davila et al. 2016 and Wilson et al. 2017).

When aiming at characterizing building energy requirements for whole cities or countries, two main modeling approaches are distinguished. The top-down approach utilizes the estimate of total building sector energy consumption and relates it with major drivers such as gross domestic product (GDP), energy price, population, weather conditions, etc. (Li et al. 2017). On the contrary, the bottom-up approach is based on determining the energy consumption of individual buildings and then extrapolating these results to represent a region or nation (Swan and Ugursal 2009). Each technique thus requires different levels of detail for the input data and produces results with a different applicability.

Unlike in top-down models, the bottom-up technique is used to assess the contribution of each end-use toward the aggregate demand of the building sector. Most of these models rely on the definition of archetypes, which consist of building definitions that are used to represent a group of buildings with similar properties. The strengths of the bottom-up approach are that the resulting models allow identifying areas of improvement by analyzing the demand of each end-use and also to evaluate

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M. Z. Sogut et al. (eds.), *Proceedings of the 2022 International Symposium on Energy Management and Sustainability*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-031-30171-1_91

the impact of technology or design changes. However, models of this type require a large set of input information and great effort is required to develop and maintain them.

In Uruguay, though an important consumer, there are yet no developments that model the energy requirements of the residential sector in detail, nor for thermal requirements for space conditioning in particular. In this regard, the objective of this work is to develop a bottom-up model to analyze thermal performance of the Uruguayan residential sector disaggregated according to relevant characteristics of the buildings and their local climate. The model is focused on modeling thermal energy requirements as they are the most complicated to characterize due to the high level of interdependence they have on many variables (local weather, construction materials, building design, occupants' behavior, etc.). The analysis includes the study of the residential sector as it is and also the evaluation of the impact of different energy efficiency strategies.

91.2 Methodology

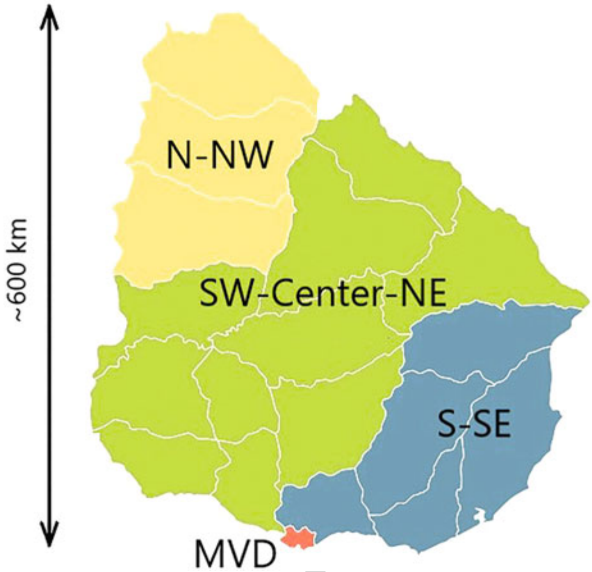
A physics-based bottom-up approach was followed based on buildings identified as representative of the residential sector. Being a physics-based model, the thermal performances of the representative buildings (or archetypes) were obtained by simulations performed focusing on their physical characteristics and the thermodynamic principles that govern the interaction between a building and its surroundings. Then, the results obtained for these archetypes were extrapolated for the whole residential sector based on their prevalence among the housing stock.

The development of this bottom-up model is based on the Uruguayan housing stock characterization performed in Curto-Risso and Picción (2017), where the archetypes were defined as well as their prevalence in the residential sector. Then, important parameters for the simulations were defined such as the weather information to use, the occupation schedules in the archetypes, the behavior of the occupants regarding ventilation and use of solar protections, the thermal comfort criteria, etc. Finally, there was the process automation stage, in which a tool was developed to automatically generate and simulate each archetype model and also process its results.

During the housing stock characterization, the attributes of the residential buildings that are closely related to their thermal performances were identified and divided into categories. Those are as follows:

- Geographic location: the country was divided into four regions according to their climatic characteristics (MVD, N-NW, SW-Ctr, NE, and S-SE; see Fig. 91.1). The city of Montevideo defined a region on its own (MVD) as it holds 41% of the total residential buildings.
- Household type: house or apartment.
- Size: less than 40 m^2, between 40 and 70 m^2, or more than 70 m^2.

Fig. 91.1 Regions considered



- Socioeconomic status: income deciles 1–4, 5–7, or 8–10.
- Vintage: less than 10 years, between 10 and 30 years, and more than 30 years.

Each possible combination of type, size, socioeconomic status, and vintage defined an archetype to which a typical geometry, construction materials, and a number of occupants were assigned. Then, the weight of each archetype along the four geographic regions was determined for the whole housing stock.

During the next stage, weather files based on the Typical Meteorological Year (Alonso-Suárez et al. 2016) were selected for the simulations as they proved to be the most representative or Uruguayan weather. The occupation schedules as well as internal gains due to occupancy, lighting, and equipment were defined as established in NBR15575 technical rule (Associação Brasileira de Normas Técnicas 2013). The thermal comfort model considered was the ASHRAE55 adaptive model (ANSI/ ASHRAE Standard 2017), which relates indoor acceptable temperature ranges to outside meteorological parameters based on the idea that humans can adapt to different conditions during different times of the year. The thermal performances of the archetypes were measured as the quantity of thermal energy required to maintain comfortable conditions during the occupied hours. Occupants were defined to use natural ventilation and operate solar protections in order to reduce thermal requirements when they are at home, and windows remained closed and protections inactive (open) during unoccupied hours.

Besides, each archetype represents a large quantity of different households with similar characteristics in terms of typology and construction materials. However, these households may be located in different geographic regions and have different orientations and surroundings, all of which will affect the thermal performance of the buildings. Therefore, for the results to be representative, every archetype in every geographic region should be simulated as many times as possible considering these variations, so as to obtain averaged results for each. This led to automation as the final stage of the model development.

A tool developed based on Python scripts (and in particular its Eppy library) enables the user to perform a large number of simulations as it automates the whole process by generating several models for each archetype varying its orientation and surroundings. It then performs the EnergyPlus simulations for every model and processes the results. Then, results for each archetype are extrapolated according to the housing stock characterization in order to represent the whole residential sector.

EnergyPlus v.8.7 is the simulation engine in which the energy calculation method for each archetype relies on. Regarding the surface heat balances, EnergyPlus default models were used for the convection coefficients calculations: TARP for inside and DOE-2 for outside coefficients. For the case of walls and roofs, the ConductionTransferFunction was used as the algorithm for solving the conduction heat fluxes. For the ground, the model selected was GroundDomain:Slab combined with the KusudaAchenbach model for the undisturbed ground temperatures. Heat transfer through the windows was solved by the layer-by-layer approach, whereas infiltration and ventilation loads were calculated by means of the AirflowNetwork model. The IdealLoads HVAC system was used to calculate thermal energy requirements for achieving thermal comfort. Details regarding all these models can be found in U.S. Department of Energy (2021).

91.3 Results and Discussion

Results for a simulation of 500 models show that, as expected, when distinguishing between the type of household, apartments have better performances than houses on average (see Table 91.1).

Apartments performing better than houses is mainly due to the difference in the percentage of the exposed area. Whereas in houses it is 87% on average, in apartments it is 32%. Besides, and based on the impact socioeconomic status have on the construction qualities, the income decile prevalence in each type of household also contributes to apartments requiring less thermal energy than houses (45% of houses correspond to income deciles 1–4 while 66% of apartments correspond to income deciles 8–10).

Energy requirements obtained when disaggregating the results by the geographic regions are shown in Fig. 91.2. MVD and S-SE total demand is less than 60 kWh/m^2,

Table 91.1 Annual thermal requirements

Type	Cooling	Heating
	kWh/m^2	kWh/m^2
House	32.6	33.4
Apartment	20.5	14.2

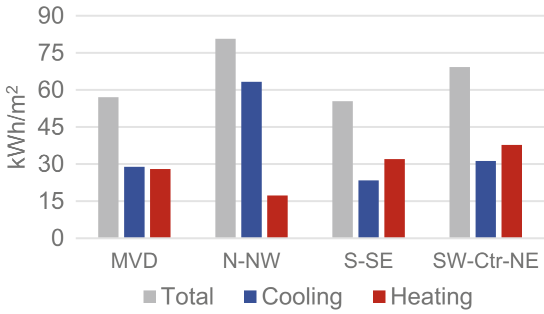


Fig. 91.2 Thermal energy requirements in regions

Table 91.2 Regions' mean temperatures

	MVD (°C)	N-NW (°C)	S-SE (°C)	SW-Ctr-NE (°C)
Cooling period	21.7	25.4	21.5	23.1
Heating period	10.8	13.7	11.0	10.7

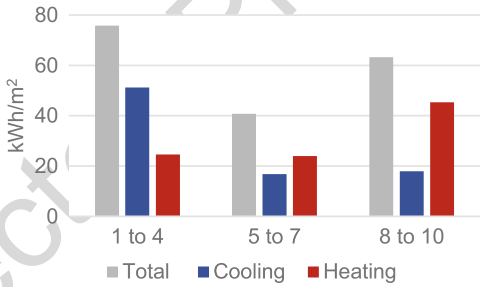


Fig. 91.3 Thermal energy requirements in income deciles

whereas N-NW is around 80 kWh/m^2 and SW-Center-NE is nearly 70 kWh/m^2. For the case of N-NW, the difference is due to the cooling requirements, which are double of those in the other regions. SW-Center-NE, on the other hand, has both higher cooling and heating requirements than MVD and S-SE; yet, the differences are less evident than those for N-NW.

Heating and cooling loads of Fig. 91.2 are in accordance with the differences in mean temperatures for each region shown in Table 91.2 and also with Uruguayan solar and wind maps (Alonso-Suárez et al. 2016; MIEM et al. 2009). The N-NW's higher irradiance and temperatures and lower wind speeds result in higher heat gains and lower losses than in the rest of the regions.

When distinguishing between income decile ranks, the differences between energy requirements are related to different construction materials, number of occupants, and household area. While deciles 1–4 have the highest demands, deciles 5–7 have the lowest. Moreover, when distinguishing between cooling and heating, it remains clear that the reason for deciles 1–4's high requirements are the cooling loads, whereas the opposite is true for deciles 8–10 (see Fig. 91.3).

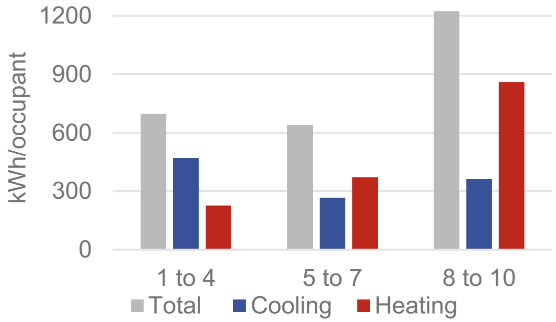


Fig. 91.4 Thermal energy requirements in income deciles per occupant

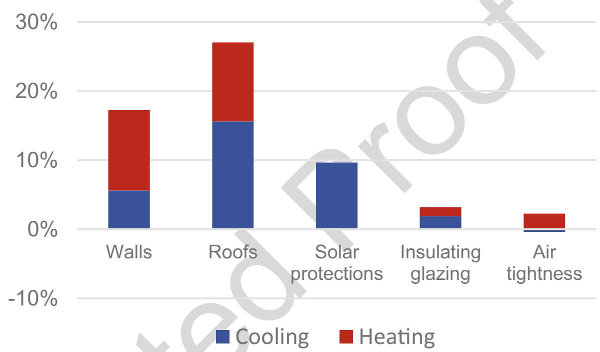


Fig. 91.5 Energy savings per efficiency strategy

However, if energy requirements for the different socioeconomic categories are analyzed relative to the number of occupants in the households rather than relative to their areas, the results are different (see Fig. 91.4). A person in the highest income category thus requires, on average, 1200 kWh each year so as to maintain thermal comfort whereas a person in deciles 1–4 requires 700 kWh, and this is despite the higher deciles living in houses with better quality constructions. These results are very different than those from Fig.91.3, where deciles 1–4 have the highest requirements. Hence, the basis on which the results are expressed should be conscientiously selected, as the best alternative would depend on the aim of the analysis.

Five energy efficiency measures were proposed and modeled with the aim of analyzing their impact on the residential sector's thermal performance. Those measures are the improvement of construction materials in the exterior walls and in the roof, the incorporation of solar protections in every window, changing the windows constructions to insulating glazing, and improving the buildings' air tightness. Five new simulations (of 500 models each) were performed, incorporating one efficiency measure in each.

Results show that the strategy with the highest impact on thermal performance when applying it to the whole residential sector is improving the construction materials of the roofs (see Fig. 91.5). The annual benefits of this strategy are 27% of thermal energy requirements and are both for cooling and heating loads in similar proportions.

Table 91.3 Strategy cost relative to energy savings

Walls	Roofs	Solar protections	Insulating glazing
$/kWh	$/kWh	$/kWh	$/kWh
962.4	205.2	97.0	764.9

Apart from the energy saved, the efficiency measures were also analyzed in terms of their cost-effectiveness. In order to do so, the extra cost associated with each measure is estimated based on INCA (2019) and is expressed relative to the energy savings. This was not done for the improvement of the air tightness given that it would be very difficult to estimate its cost and it has a very low impact on energy requirements.

Results show that although improving the roofs' construction is the strategy with the highest annual savings, the most cost-effective is the incorporation of solar protections in every window of the households (see Table 91.3). However, the energy savings obtained when incorporating solar protections—and consequently its cost-effectiveness—will be highly dependent on how they are operated by the occupants.

91.4 Conclusions

A physics-based bottom-up model was developed to characterize the thermal performance of the Uruguayan residential sector. Efforts in making the model as accurate as possible led to automation as the strategy to generate and simulate a large number of buildings models. A platform was thus developed based on Python scripts and Eppy library, as well as on the outcomes of a housing stock characterization process performed in Curto-Risso and Picción (2017). This platform relies on EnergyPlus as the simulation engine, and it is capable of carrying out the whole simulation process, including the characterization, generation, and simulation of the models as well as the results processing.

As it is, the tool developed is capable of quantifying annual or seasonal energy requirements for thermal comfort in the Uruguayan housing stock as it was characterized in Curto-Risso and Picción (2017). Also, evaluating the impact of energy efficiency retrofits in the enclosures of the buildings or the usage patterns. Besides, the effect climate change could produce in the energy required for heating and cooling could also be determined. All of these studies could be performed either for the whole residential sector or disaggregated according to certain relevant characteristics of the buildings modeled. Analyzing the results distinguishing among different building categories allows identifying major areas of improvement, which might in turn lead to the design of targeted energy policies and of cost-effective retrofit measures.

Nevertheless, the tool developed has its limitations, and further work should be devoted to improving the model. Given the high impact they have on results, housing stock characterization and the hypotheses considered (such as the definition of the usage patterns) should be improved. Also, considering the EnergyPlus models used, latent heat ought to be accounted for in the energy balance equations and pressure coefficients might be more accurately determined when solving infiltration and ventilation loads.

Future work will incorporate the remaining end-uses apart from space conditioning and the transformation of energy requirements into final energy demand. By doing so, it would be possible to develop a forecasting model, which can be used to obtain projections of energy demand in the residential sector. Moreover, further development could produce results on an hourly scale, hence providing power demand curves.

Acknowledgments We thank the Comisión Académica de Posgrado of Universidad de la República for the economic support throughout this work.

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