Environmental Performance of a Social Housing Type Characteristic of South-Eastern Mexico

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Abstract. National indicators point that 85% of Mexico’s energy production come from fossil fuels. Quintana Roo is the state with the most significant increase on energy consumption with almost 20% from 2010 to 2017. This project carries out a holistic energy analysis approach in three case studies in typical dwellings built with average materials and construction systems under tropical climate conditions. Two validation levels were performed, one with an historical weather data file, and the second one with a costumed weather file corresponding to February 2019. The obtained values of mean bias error on an hourly-based analysis in interior conditions varied with the following ranges: level 1, from 1.57% to 2.11%; in level 2, from 1.17% to 1.74%. On the other hand, it was also found that the first level of simulation predicted the electricity consumption slightly closer to actual values reported for February 2019, with values ranging from 7.56% to 16.63%. However, further analysis with more detailed input data and monitoring of daily consumption is recommended in order to reduce the variation ranges.

1. Introduction

According to national indicators, in Mexico 85% of primary energy production in 2017 came from hydrocarbons. However, final energy consumption is concentrated in three groups: the transport sector with 43%, the industrial sector with 34% (including cement manufacturing and construction with 3.14% and 0.93%, respectively) and the residential sector with 14% [1]. Consumption of the residential sector, corresponding to the occupancy stage of the dwellings, has been widely supported by studies focused on the life cycle analysis of buildings, concluding that the operational stage represents between 80% and 85% of the total impacts generated, with CO2 being the main compound released during these processes [2]. On the other hand, energy consumption in Quintana Roo during 2017 was estimated at 4500 GWh, being the highest growth rate in Mexico with 19.44% increase from 2010 to 2017 [1], which in turn is related to the immigration rate and tourism, the main economic activity of the state.

The ease for the acquisition of credits has generated a higher demand for housing, which has grown from 367,569 to 440,663 dwellings (which translates into an increase of 16.59%) [3]. This has brought the construction of houses in series, promoting the replication of designs in different climatic zones of
the country, ignoring that each house will have a different environmental behavior and energy consumption. The increase in electricity and fuels prices, together with the policies aimed at improving energy efficiency in the residential sector, has led to studies devoted to evaluating the results of these improvements applied to thermal insulation and equipment for energy saving [4] [5], which rely in most cases on theoretical simulation models and to a lesser extent on periodic monitoring records.

Building energy performance simulation (BEPS) is a tool used since the early 90's, being an alternative applied in industrialized countries, mainly in office buildings and educational centers that have complex heating and cooling systems [6]. In recent years, they have been widely accepted as a guide for decision making, due to the improvement in the interface of software systems (the main component of this kind of tools). Simulation models are popularly used at the design stage and before construction, assuming that the simulated results correspond to the actual ones. In general, BEPS, and its validation or calibration, is an area with little exploitation in developing countries with tropical climates, as is the case in Latin America, due to its climates with little differentiated seasons, as well as its less complex construction systems.

Regarding simulation models with validation or calibration, Mustafaraj et al. [7] conducted an energy and comfort analysis in a 2-story research center building in Ireland, using two levels of validation. The first one by means of a complete description of the building that included the nominal ranges of the equipment, the envelope and the occupants, using a meteorological file with historical data for the site. The second one consisted of reviewing the actual consumption of the heating systems, the measurement of the hot water temperature, interviews with the occupants and the records of indoor temperatures. They estimated errors at the hourly and monthly level with a range of -6.5% and 11.4% and -1.5 and 6.1%.

Royapoor and Roskilly [8] used the same process to calibrate a 3-story office building with a glass curtain facade. In order to reduce errors in the calibration, they integrated a meteorological file with data obtained from a station located on the roof of the building. As a result, the validation showed a deviation of 1.08% less in the simulated annual electricity consumption compared to the real measured and 3.8%, while the interior temperature had results of ± 1 °C in 93.2% of the cases, indicating that the software has a remarkable tendency to predict lower temperatures for the inside. Likewise, in Spain, a calibration alternative was carried out consisting of the personalization of a climatological data file by interpolating 6 meteorological variables, annual records of 70 meteorological stations surrounding the study area [9]. The creation of the meteorological file for environmental simulation reduced the coefficient of variation from 0.74 to 0.26.

In Mexico, a study using BEPS for the evaluation of energy efficiency was conducted in the city of Salamanca, under a temperate sub-humid climate [10]. The project consisted in a first stage of energy validation resulting in 5% in electricity and gas in 1% in 5 representative dwellings that do not use cooling or mechanical heating systems, to then run another period of optimization simulations focused on identifying the combinations of materials and insulators in the envelope that guarantee the annual decrease in energy consumption, while assessing the interior comfort.

The previous studies were conducted in temperate, continental climates or elevations above sea level of up to 1720 m, whose conditions are different from those of humid and tropical climates. For this type of climate, there is a study carried out in 2015 in Malaysia [11], in which a series of simulations were developed replacing the material of each element of the building (floors, walls, windows, ceiling and roof) to evaluate the influence of the materials that can generate savings in the loads of the refrigeration equipment in a residential house of 676 m2. As a result, in addition to identifying the roof as the element with the greatest impact on load consumption for cooling, they
found that the internal air temperature setpoint raises the load obtained by simulation up to 240%, considering air temperatures between 20°C and 26°C. In Colombia, in the city of Bucaramanga, a validation of a 2-story prototype house with an area of 45.9m² was carried out [12]. In this case, the validation was carried out during a periodical monitoring of several areas of the house during one month, evaluating two variables without air conditioning: with and without air circulation. Once contrasting the simulated and real data of both study variables, they selected the spaces that showed the least error bias (1.98 to 3.30% for relative humidity and 0.21 to 0.82°C for temperature) to evaluate the performance during daily and annual periods to predict the behavior of other houses when changing the orientation.

The present work had the objective of calibrating the simulation models of three dwellings that correspond to the most extensive social housing typology built in the Mexican state of Quintana Roo under real occupation conditions, based on the physical characterization of the dwellings, usage patterns of home appliances by the dwellers (including air conditioning) and comparison against electricity bills.

2. Methods and data

“Whole building simulation approach”, also known as "detailed simulation" gives results closer to real conditions [6]. Its evaluation consists of using one of the most used energy simulation software [13] to recreate the geometric composition and thermal properties of materials and rely on the annual monitoring of electricity, gas and water consumption, among other parameters, as the temperature differences between the inside and the outside. Using this approach, the methodology used in this research is summarized below:

- Detailed description of each of dwellings, which includes: orientation, dimensions, materials of the envelope, glazing, shadow elements, among others.
- Inventory of electrical equipment used in each area of the dwellings, based on the routines of operation reported by the dwellers, for the creation of frequency tables of use of each electrical element [14], including air conditioning type, daily periods of use, temperature setpoints, lighting type in each area of the dwelling and operation period, through interviews with dwellers.
- Processing of the collected data led to the creation of the simulation models through DesignBuilder and EnergyPlus analysis engine.
- Analysis of the models was done through a historical meteorological file of the city of Chetumal obtained through Meteonorm.

The second level of validation consisted of:

- Monitoring of temperature and relative humidity in the rooms with cooling equipment through onset HOBO MX1101 data acquisition devices, arranged on a wall at a height of 1.50 m above the floor level [15].
- Record of environmental parameters (dry bulb, dew point, relative humidity, atmospheric pressure, wind speed, wind direction and solar radiation) with a Davis Vantage Pro2 meteorological station, whose data were stored at time intervals and sub-schedules.
- Report of the electric consumption bill corresponding to the analyzed month.
- Creation of a climate file with meteorological data corresponding to the evaluation period.
- Interviews and reports on the operation of dwelling during the period analyzed.

In this second level, another simulation period was performed with the operation data reported by the dwellers and by replacing the meteorological data obtained with the station during February 2019. Then, a comparison was made between the real data obtained in the second stage (indoor
environmental and electricity consumption bill) against the models created in the other level of simulation, using statistical indicators [16] such as the maximum error resulting (mean average deviation, MAD) and the bias or measurement error (MBE) (Equation 1), as well as the estimate of carbon dioxide emissions produced by monthly electricity consumption, according to the official emission factor for Mexico of 0.527 CO2-eq/MWh [17].

$$MBE = \frac{\sum_{i=1}^{Np} (M_i - S_i)}{\sum_{i=1}^{Np} M_i}$$  \hspace{1cm} (1)

Where, $M_i$ and $S_i$ are the measured and simulated data, respectively; $Np$ is the number of values per interval (in this case, 480 hr).

3. Results

3.1 Model development

The physical characterization of the dwellings can be seen in Tables 1 and 2. They describe their characteristics of design and habitability, volumetry, as well as the materials that make up each constructive element. Figure 1 shows the model created following the characteristics of the actual dwellings.

![Figure 1. On the left, a photograph of Case 3. On the right, virtual model made in DesignBuilder](image)

| Orientation       | Case 1 | Case 2 | Case 3 |
|-------------------|--------|--------|--------|
| Total Occupancy   | 2      | 2      | 4      |
| Area (m²)         | 35.45  | 42.5   | 48.9   |

| Zones             | Case 1       | Case 2       | Case 3       |
|-------------------|--------------|--------------|--------------|
| Living room/dinner| Kitchen      | Kitchen      | Kitchen      |
| Bathroom          | Bathroom     | Bathroom     | Bathroom     |
| Bedroom           | Bedroom(storage) | Children's room | Main bedroom |
| Monitored zone    | Bedroom      |              | Main bedroom |
| Area (m²)         | 10.2         | 8.62         | 9.4          |

Table 1. Design configuration of each dwelling
Table 2. Envelope model configuration

|                     | Case 1 U-value (W/m²K) | Case 2 U-value (W/m²K) | Case 3 U-value (W/m²K) |
|---------------------|-------------------------|-------------------------|-------------------------|
| **Floor**           | 100 mm concrete slab    | 4.73                    | 100 mm concrete slab    | 4.73                    | 100 mm concrete slab | 4.73 |
| **External/Internal walls** | 15mm exterior mortar, 150mm concrete block, 15mm interior mortar | 2.66 | 15mm exterior mortar, 150mm concrete block, 15mm interior mortar | 2.66 | 15mm exterior mortar, 150mm concrete block, 15mm interior mortar | 2.66 |
| **Roof**            | 30mm concrete slab, 150mm joist and concrete hollow brick, 15mm mortar interior | 3.377 | 30mm concrete slab, 150mm joist and concrete hollow brick, 15mm mortar interior | 3.377 | 15mm mortar, 30mm concrete slab, 150mm joist and concrete hollow brick, 15mm mortar interior | 3.288 |
| **Glazing**         | Absorbent green 6mm     | 5.808                   | Absorbent grey 6mm      | 5.812                   | Absorbent green 6mm    | 5.808 |
| **Window awning**   | 1.5mm galvanized steel sheet | 60 | N/A | N/A | N/A | N/A |

Table 3 shows the classification made for the household appliances inventory. To streamline the operation of the electrical equipment in the models, a compact programming divided by days between week and weekends was used, taking the total power by dwelling zone and their fraction of use according to the schedules of the dwellers activities.

Table 3. Example of equipment inventory and schedule and plug loads for each component zone

| Building zone       | Equipment name  | Quantity | Volts | Power factor | Week hr/dy | Weekend hr/day |
|---------------------|-----------------|----------|-------|--------------|------------|---------------|
| Living room/dinner  | Floor fan       | 1        | 110   | 70           | 0.5        | 0             |
|                     | Refrigerator 9" | 1        | 110   | 235          | 18         | 18            |
|                     | T.V 38"         | 1        | 110   | 55           | 5          | 8             |
|                     | Floor fan       | 1        | 110   | 70           | 5          | 8             |
|                     | Laptop Computer | 1        | 110   | 60           | 2          | 3             |
|                     | Iron            | 1        | 110   | 1000         | 0.25       | 0             |
|                     | Dryer           | 1        | 110   | 1860         | 0.167      | 0             |
|                     | Mobile phone    | 2        | 110   | 5            | 6          | 6             |

In terms of lighting, the three dwellings had compact energy saving lamps, so in all spaces the lighting was standardized to 5 W/m². The inventory and characteristics of the cooling systems are listed in Table 4. Although the three houses have minisplit equipment of 1 Ton capacity, Case 3 has an equipment of more than 4 years, so the estimated power for old equipment was used [18]. For its part, the energy efficiency ratio (EER) was taken from the supplier's specifications, while the dwellers reported the setpoint temperature with which they use the equipment.
Table 4. HVAC configuration in each bedroom

|                      | Case 1 | Case 2 | Case 3 |
|----------------------|--------|--------|--------|
| HVAC load (kW)       | 1.3    | 1.3    | 1.8    |
| EER                  | 3.5216 |        |        |
| Temperature Setpoint (°C) | 20     | 23     | 22     |

3.2 Simulation results

Figure 2 shows the relative humidity behavior registered in the two simulation stages corresponding to Case 1. Figures 3 to 5 present the resulting data for the environmental temperature parameter in the three dwellings.
The comparison of the environmental data is simplified in Table 5. Those values with negative data represent that the values produced by the validations were greater than those from the monitoring.

Table 5. Statistical analysis of data recorded and output data from simulations in level 1 and level 2

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| EnergyPlus Level 1 | EnergyPlus Level 2 | EnergyPlus Level 1 | EnergyPlus Level 2 | EnergyPlus Level 1 | EnergyPlus Level 2 |
| RH | Temp. | RH | Temp. | RH | Temp. | RH | Temp. | RH | Temp. |
| MAD | 1.25 | 6.19 | 0.48 | 2.98 | -12.53 | -0.57 | -11.28 | -3.59 | -4.05 | 3.26 | -9.99 | -1.61 |
| MBE | 9.75 | 2.11 | 9.76 | 1.73 | 12.24 | 1.57 | 12.07 | 1.74 | 9.41 | 1.72 | 14.11 | 1.17 |

Regarding electricity consumption, in Table 6 the consumptions obtained in both levels of simulation are broken down, to conclude with the average deviation between the registered demand and that obtained with EnergyPlus. Table 7 shows electricity consumption and CO2-eq broken down into two categories: by dweller and by dwelling built area.
Table 6. Total and specific loads in each level of performance against actual electricity consumption

| Simulation         | Miscellaneous kWh | Lighting kWh | HVAC kWh | Total simulated kWh | Electric bill kWh | MAD % |
|--------------------|-------------------|--------------|----------|---------------------|-------------------|--------|
| **Case 1**         |                   |              |          |                     |                   |        |
| EnergyPlus Level 1 | 143.63            | 27.14        | 60.15    | 230.93              | 198               | -16.63 |
| EnergyPlus Level 2 | 143.63            | 27.14        | 64.14    | 234.91              | -                 | -18.64 |
| **Case 2**         |                   |              |          |                     |                   |        |
| EnergyPlus Level 1 | 115.37            | 16.56        | 40.98    | 172.91              | 141.00            | -22.63 |
| EnergyPlus Level 2 | 115.37            | 16.56        | 47.29    | 179.22              | -                 | -27.10 |
| **Case 3**         |                   |              |          |                     |                   |        |
| EnergyPlus Level 1 | 181.19            | 35.33        | 26.56    | 243.08              | 226               | -7.56  |
| EnergyPlus Level 2 | 181.19            | 35.33        | 28.87    | 245.39              | -                 | -8.58  |

Table 7. CO₂ comparison between occupancy and dwelling built area

|                    | Case 1 | Case 2 | Case 3 |
|--------------------|--------|--------|--------|
|                    | Level 1 | Level 2 | Actual | Level 1 | Level 2 | Actual | Level 1 | Level 2 | Actual |
| kWh/Occupancy      | 115.5  | 117.5  | 99     | 86.46   | 89.61   | 70.50  | 60.77   | 61.35   | 56.50  |
| CO₂eq/occupancy    | 0.061  | 0.062  | 0.052  | 0.046   | 0.047   | 0.037  | 0.032   | 0.032   | 0.030  |
| kWh/m²             | 6.51   | 6.63   | 5.59   | 4.07    | 4.22    | 3.32   | 4.97    | 5.02    | 4.62   |
| CO₂eq/m²           | 0.0034 | 0.0035 | 0.0029 | 0.0021  | 0.0022  | 0.0017 | 0.0026  | 0.0026  | 0.0024 |

4. Conclusions

The results obtained from the simulations present variations with respect to the actual measured data and this may be due to a series of factors that the literature contemplates in which the modeler has no control, mainly those related to the dwellers activities [19]. Using the temperature and relative humidity curves, some discontinuity patterns may be observed due to dwellers absences or interruptions caused by unscheduled activities.

Another factor to mention is the greater difference existing between the second stage of calibration and the real data, unlike the first stage. Therefore, it will be convenient to carry out a sensitivity analysis to determine which parameters have the greatest influence on the variation of the results and to what degree the input data affect the results of the validations.

To conclude, from the observation of the detailed models, it can be stated that they offer an overview of energy and environmental performance, but they also evidence the complexity of predicting the behaviour of a social dwelling under real occupation conditions, compared to other types of buildings. Also, it should be noted that the one month analyzed period is not representative of the periods with the greatest energy consumption. This monitored period provides the basis to continue with a prolonged measurement in which daily consumption records should be taken in conjunction with routine reports from the dwellers, in order to reduce the margin of uncertainty.

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