Impact of implementing air-conditioning systems on the school building stock in Brazil considering climate change effects: a bottom-up benchmarking

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Abstract

This study aimed to investigate future energy benchmarks for the school building stock in Brazil, considering the gradual implementation of air-conditioning systems in those buildings and the influence of future climate conditions. Archetypes were simulated using EnergyPlus for four cities in Brazil, representing predominant weather data in the country. The models were simulated considering air-conditioning implementation in two scenarios: a) administrative and lab environments; b) administrative, labs and all classrooms. Modified weather data considering IPCC scenario A2 was used to include climate change trends for 2050 and 2080. The average and standard deviation of Energy Use Intensity (EUI) were analysed. Results showed an increase of the average EUI of the school building stock in Brazil considering the air-conditioning implementation, raising 88% concerning the actual EUI if the systems were implemented today, 8% in 2050 and 43% in 2080. Conclusions support that upgrading thermal comfort conditions in those buildings require attention towards improving energy efficiency strategies.

Key Innovations

- Stock modelling method through archetypes was employed to estimate future trends of average EUI of a building stock.
- Energy performance benchmarks (in terms of kWh/m²/year) for scenarios of buildings partially and fully air-conditioned were estimated.
- Modified weather files were used to predict stock-level performance under climate change effects.

Practical Implications

Practitioners who deal with stock-level analysis must be aware of the impact that actions taken today will have on future circumstances.

Introduction

The need for improving energy efficiency in buildings is urgent. In Brazil, buildings were responsible for 43% of the electricity consumption in 2019 (Brazil 2020). The amount of energy consumed in this sector tends to increase in the following years if the status quo is maintained.

As extreme climate events become more frequent and the overall global temperature increases, both the effects of Climate Change and the use of HVAC systems in equatorial, tropical and subtropical climates can become health issues (Elnaklah et al. 2021). Additionally, HVAC equipment becomes more socially inclusive (Kigali Project 2019), people of developing countries tend to buy and install more of this equipment (Macrae et al. 2008).

This is especially true in school buildings in Brazil. Air-conditioning systems are responsible for enhancing indoor thermal conditions and increasing the energy use intensity (Saraiwa et al. 2019). Geraldí and Ghisi (2020) performed a top-down analysis of this type of building across the country, showing that HVAC is not frequently installed in all buildings. In fact, it is installed in only about 13.0% of the classrooms, 32.7% of the administrative rooms, and 31.9% of the labs of public schools. In the same study, the performance of schools with and without air-conditioning systems were compared; schools with air-conditioning had an annual EUI 64% higher than schools without air-conditioning. However, this is not a static situation. Schools tend to buy air-conditioning sets over the years, and this gradual implementation will cause an increase in the school building stock energy consumption. For example, the EUI of two schools in which air-conditioning was installed increased from 8.1 to 15.8 kWh/m² and 11.9 kWh/m² to 34.6 kWh/m² (Geraldi and Ghisi 2020b).

Also, as reported in several recent case studies, improving air quality through air-conditioning systems is an urgent task and has been increasing with the outbreak of the coronavirus pandemic.

Since the implementation of air-conditioning in public schools in Brazil is a large-scale action, this issue can be addressed by a stock-level analysis. Modelling the building stock is a useful practice to assess statistical key information of a group of buildings (Geraldi and Ghisi 2020a; Hamilton et al. 2017). Some studies applied this approach to assess the energy performance of buildings and find different insights for energy efficiency, for example, to improve best practices in the United Kingdom (Hong et al. 2014), to model buildings relationships at an urban scale (Reinhart and Davila 2016), and to estimate energy savings potential at national-level (Brøgger and Wittchen 2018).
An example of a stock level analysis application is the development of energy benchmarks, which evaluates the energy efficiency of a building against its pairs (Wilde 2018). Reference buildings (denominated archetypes) are usually adopted to represent the main characteristics of typical buildings of the stock to develop benchmarks. The archetypes are used to simulate a reference building in various conditions that represent the stock reality – i.e., different climate conditions, occupations, materials, and others. Benchmarks are obtained through regressive models of simulation results, according to variables that are important for the type of building (Chung 2011). Advances in benchmarking methods are available in the literature; however, they are usually related to high-granularity data, particular focuses or specific to their countries or regions (Borgstein, Lamberts, and Hensen 2016). In Brazil, a benchmarking approach was developed for bank branches (Borgstein and Lamberts 2014) and high-rise buildings (Alves et al. 2017). Synthesizing the building stock into archetypes is a handy approach to predict trends in the energy use of similar buildings through computer simulation.

Therefore, it is pertinent to measure the carbonisation effect due to the implementation of air-conditioning systems in Brazilian schools to estimate their impact at the stock level.

The objective of this study was to investigate future energy benchmarks for the school building stock in Brazil, considering two scenarios of air-conditioning systems implementation in the building stock and future climate data. To do so, comprehensive building stock data were analysed and used to model seven building archetypes to represent the stock. Those models were simulated considering four cities (that represent the types of weather in Brazil) and calibrated using the actual energy consumption of the stock. Then, the calibrated models were simulated considering air-conditioning implementation in two scenarios: a) administrative and lab environments; b) administrative, labs and classrooms. Three reference years were selected: a baseline year (compound by an TMYx 2020 database file), and two modified-weather data considering IPCC (International Panel for Climate Change) scenario A2 to include climate change trends for 2050 and 2080. Electricity consumption for cooling was analysed in these combinations. The new aspects adopted in the approach proposed herein comprise the combination of interrelated aspects that might have been treated in an isolated manner in previous research. For instance, a comprehensive analysis of the built stock in Brazil enabled to achieve realistic archetypes considering local characteristics; and the consideration of mixed-mode operation in archetypes. Then, exploring future scenarios of the energy performance of the building stock consolidates the need for improving whole-building performance also in developing countries. Also, despite the application of string regionalised data, the method could be adapted for other locations. Nevertheless, this study also serves as a report of the carbonisation of the stock occurring in developing countries – although the causes are locally regionalised, the consequences are global.

**Method**

Figure 1 illustrates the flowchart of the method employed.

**Modelling the school building stock**

In order to build the representative archetype models, a database of 284 educational buildings was analysed. These buildings were provided by the Educational Administrative Organism as the buildings under their jurisdiction. They represent educational buildings in southern Brazil. However, although they belong to a specific region, all public schools in Brazil share similar design guidelines. A well-known method to create archetypes was employed (Attia et al. 2020). Seven building shapes were identified as predominant (Rectangular, H-shape, E-shape, U-shape, O-shape, L-shape and Multiple buildings). The main characteristics used to outline the building stock were: (1) annual energy consumption (kWh/year); (2) gross-floor area (m²); (3) number of students (people), and; (4) building shape. Among the buildings analysed, 35 building designs were assessed, which allowed a detailed investigation in terms of materials properties, fenestration details, window-to-wall ratio (WWR) (%), and number and layout of rooms, classrooms, aisles, office rooms, bathrooms, kitchen and additional spaces. Furthermore, the design analysis also provided information on the lighting power density (LPD) and equipment power density (EPD) in every room. Such information supported the construction of seven models in EnergyPlus Input File (.idf) format, one for each building shape. Average values were adopted from the design analysis. The variability of shapes assists the representation of the variability inherent to the building stock. OpenStudio® was used to support the modelling process. Table 1 shows the average values of gross-floor

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**Figure 1: Flowchart of the method.**
area, and the number of classrooms for all models and the values adopted equally for all models. Adopting average values for building mass and thermal properties may have different outcomes. For building-mass aspects, which had a higher variation throughout the models, average values are a good proxy for the stock characteristics since they may balance the differences found among samples. Additionally, each prototype had its values based on the stock analysis. Considering the thermal properties of the facilities, it is worth mentioning that adopting average values will not hinder the representativeness of results as most buildings share the same constructions and materials used.

Table 1: Summary of the archetype’s parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average gross-floor area</td>
<td>m²</td>
<td>2,547.0</td>
</tr>
<tr>
<td>Average number of classrooms</td>
<td>rooms</td>
<td>14</td>
</tr>
<tr>
<td>Wall thermal transmittance</td>
<td>W/m²K</td>
<td>2.13</td>
</tr>
<tr>
<td>Roof thermal transmittance</td>
<td>W/m²K</td>
<td>1.77</td>
</tr>
<tr>
<td>Slab thermal transmittance</td>
<td>W/m²K</td>
<td>3.30</td>
</tr>
<tr>
<td>Wall thermal capacity</td>
<td>kJ/m²K</td>
<td>151</td>
</tr>
<tr>
<td>Roof thermal capacity</td>
<td>kJ/m²K</td>
<td>230</td>
</tr>
<tr>
<td>Glazing U-value</td>
<td>W/m²K</td>
<td>5.70</td>
</tr>
<tr>
<td>Glazing Solar Heat Gain Coefficient</td>
<td>-</td>
<td>0.87</td>
</tr>
<tr>
<td>Average wall absorptance</td>
<td>-</td>
<td>0.50</td>
</tr>
<tr>
<td>Average roof absorptance</td>
<td>-</td>
<td>0.65</td>
</tr>
<tr>
<td>Administrative room WWR</td>
<td>%</td>
<td>29.00</td>
</tr>
<tr>
<td>Library/Computer lab WWR</td>
<td>%</td>
<td>40.00</td>
</tr>
<tr>
<td>Classrooms WWR</td>
<td>%</td>
<td>35.00</td>
</tr>
<tr>
<td>Average LPD</td>
<td>W/m²</td>
<td>6.57</td>
</tr>
<tr>
<td>Average EPD</td>
<td>W/m²</td>
<td>116.00</td>
</tr>
<tr>
<td>Occupancy in admin. rooms</td>
<td>people</td>
<td>10</td>
</tr>
<tr>
<td>Occupancy Library/Computer lab</td>
<td>people</td>
<td>10</td>
</tr>
<tr>
<td>Occupancy in classrooms</td>
<td>people</td>
<td>25</td>
</tr>
</tbody>
</table>

To ensure that the building models represent the actual stock model, pilot simulations were used to compare actual and simulated building performances. Then, a calibration step was employed to refine the simulation models using International Performance Measure and Verification Protocol guidelines (IPMVP 2001), considering the occupancy schedule during the year in all rooms as the parameters for calibration. Small adjustments in this occupancy provided good calibration considering a comparison of the simulated EUI with the actual EUI of a set of schools. It is important to highlight that the performance gap is a noticeable issue reported in the literature, and in this study, we did not aim to accurately replicate the stock’s actual energy consumption. Instead, we intended only to approximate the simulated and actual energy performances to establish a baseline for comparison – simulation results will be compared with themselves. Figure 2 presents the distribution of the log EUI for (a) the actual building stock analysed and (b) for the calibrated simulated models. Averages and standard deviations for actual EUI are presented as well.

Figure 2: Comparison between (a) actual and (b) simulated EUI of the school building stock in Brazil.

The comprehensive description of the stock analysis to obtain the representative building models and the discussion regarding the representativeness of the archetypes obtained were reported in a research of the Laboratory of Energy Efficiency in Buildings (LabEEE/UFSC) in Brazil. The study is currently being developed, and it aims to investigate the impact of building shape on the energy consumption and to analyse the impact in different Brazilian cities. Figure 3 presents the graphical aspect of each building model.

![Figure 3: Archetype models identified from the stock.](image)

**Simulation for future scenarios**

Three reference years were adopted. The first is a year corresponding to the actual scenario (the baseline year). TMYx data files were used from ClimateOneBuilding website. Then, IPCC scenario A2 for 2050 and 2080 time-slices was used to perform the simulations for future climate. The scenario A2 characterizes the medium emission scenario, which preserves local identity and economic development, with fragmented
Climate Change World, which, air-th. Administrative fb: each r. T tour different orientations for each scenario, 2025 and 2080), the preponderant type, the cooling setpoint was 24°C. As observed in the stock analysis of the cities used in this study. Figure 4 presents the main climatic characteristics (average monthly temperature and relative humidity) for the cities used in this study.

Table 2: Weather data adopted and Correlation between ASHRAE 169 and Brazilian standard NBR 15220-3.

<table>
<thead>
<tr>
<th>Location</th>
<th>ASHRAE 169</th>
<th>NBR 15220-3</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuiabá</td>
<td>0A</td>
<td>ZB 7</td>
<td>Extremely Hot and Humid</td>
</tr>
<tr>
<td>Rio de Janeiro</td>
<td>1A</td>
<td>ZB 8</td>
<td>Very Hot and Humid</td>
</tr>
<tr>
<td>São Paulo</td>
<td>2A</td>
<td>ZB 3</td>
<td>Hot humid</td>
</tr>
<tr>
<td>Curitiba</td>
<td>3A</td>
<td>ZB 1</td>
<td>Warm humid</td>
</tr>
</tbody>
</table>

Figure 4 presents the main climatic characteristics (average monthly temperature and relative humidity) for the cities used in this study.

As observed in the stock analysis of a previous work (Geraldi and Ghisi 2020b), air-conditioning systems in schools are mainly installed in administrative rooms, computer labs and libraries. Retrofits to install air-conditioning systems in classrooms are often observed. When it happens, it is likely that all the classrooms get air-conditioning sets.

In all cases observed in the stock, the preponderant type is mini-split (90%), which means that each room has a single unit. This facilitates the implementation by the Education department, once they can install, replace or maintain the units individually and with no big retrofits. However, the energy efficiency of adopting such an approach is debatable. In this study it was adopted the most frequent case observed in the stock: each room conditioned separately. The system type was cooling with direct expansion. The cooling setpoint was 24°C, and the heating setpoint was 18°C. The average coefficient of performance was 3.6 W/W. The setpoints were assumed according to the Brazilian Centre of Energy Efficiency in Buildings (CB3E 2017), which provides referenced values for energy simulation of buildings considering the Brazilian context. These setpoints are also used in Energy Performance Certification (EPC) in Brazil.

Then, two scenarios of air-conditioning systems implementation in schools were considered:

- Scenario A: air-conditioning in administrative rooms, libraries and computer rooms, and;
- Scenario B: air-conditioning in administrative rooms, libraries, computer rooms and all the classrooms.

EnergyPlus 9.4 engine was chosen to carry out the computer simulations. The use of natural ventilation mixed with air-conditioning is common in Brazil. Then, the control of conditioned and naturally ventilated areas was performed using the Energy Management System (EMS), which is a script programmed to control diverse building systems (Ellis et al. 2007). Sensors of operative temperature and outside air temperature were used to determine the air-conditioning activation or deactivation, considering the setpoints of 26°C and 19°C, respectively. Also, occupancy and operation sensors determine the use of the system, preventing the system from being activated in empty rooms.

Parametric simulation

Finally, four different orientations for each scenario were considered, i.e., each model facing North, South, East and West. With the combination of all seven models, two scenarios of air-conditioning, four orientations, four locations and three weather data (Baseline year, 2025 and 2080), 672 simulations were run. The occupancy schedules were considered according to the standard period of functioning of the school buildings in Brazil: classes from 8:00 am to 12:00 am and from 1:30 pm to 5:00pm. The student year begin in February 15th and finish in December 15th, with a winter-break of two weeks in July. Administrative rooms, libraries and labs have the same occupancy. Lighting and equipment were considered to be on when there is occupancy in the rooms.
Energy performance analysis

The energy performance simulation results were analysed for each weather scenario in terms of each building's total EUI. Using the outcomes from the parametric simulations, an initial description of the results was performed using boxplot-like graphs. Such an approach showed the contrast of both scenarios of air-conditioning implementation according to the current climates and their corresponding projections influenced by climate change trends. Besides that, a general overview of the results shows the expected average of EUI for each year tested, as well as standard deviations for each scenario.

Results and discussions

The results of the parametric simulations are synthesized in Figure 5. The boxplots provide information on each city evaluated (Cuiabá, Rio de Janeiro, São Paulo, and Curitiba) according to both scenarios of air-conditioning implementation and projections of climate change.

Figure 5 shows the important role that local weather plays on the average energy use of the building stock. For instance, even considering the worst-case combination (scenario B in 2080), the energy consumption of schools in Curitiba (below 40 kWh/m²/year) are likely to be lower than those currently observed in Cuiabá if all the classrooms were air-conditioned (generally above the 40 kWh/m²/year threshold).

Such information emphasizes that building stakeholders in large countries like Brazil, which has different climates, should be aware of their current decisions’ implications on the future. Indeed, an important takeaway from this study is that one trend does not fit all the realities in Brazil. Different regions are likely to be impacted by climate changes in varying intensities. Along these lines, the hottest city evaluated, Cuiabá, is likely to require a massive amount of energy to keep the indoor conditions of public schools in comfortable ranges in the future. The median EUI for this city is 63.4 kWh/m²/year, while no school has reached the threshold of 60.0 kWh/m²/year in the other cities. As the state governments are responsible for maintaining such schools, national decision-making should be oriented to guarantee that students across the country will have access to acceptable learning environments.

Figure 5: Energy use intensity for Brazilian schools according to different projections of climate.

A general overview of the stock EUI is shown in Figure 6. It comprises both scenarios of air-conditioning implementation in the school stock. The averages of EUI are highlighted. First, it is important to stress that besides most Brazilian schools that do not have air-conditioning yet, the simulations also included scenario B for the reference year for comparison purpose.

This approach aimed to show a tendency from the baseline year up to 2050, as there is no specific timeline for such a massive air-conditioning implementation across the country. Additionally, a dashed line linking the average for scenario A in the baseline year and the average of scenario B in 2050 is an alternative estimate for continuous air-conditioning implementation throughout these years.
It is evident that if the current condition of schools is maintained (Scenario A), there will be an increase in the energy use of the school stock of about 6% in 2050 and 31% in 2080. Considering the implementation of Scenario B in the buildings today (baseline year), there will be an increase of 88% on the average EUI (from 16.75 to 31.56 kWh/m²/year). Of course, this is a theoretical scenario since it is very unlikely that all schools get air-conditioning today. Thus, a projection from Scenario A in baseline year to Scenario B in 2050 is shown in Figure 6.

Considering the actual scenario without air-conditioning in classrooms (average 16.75 kWh/m²/year), if such systems are implemented up to 2050 – which is probable –, the average increases to 33.94 kWh/m²/year, i.e. a growth of 103%. And this tends to be even higher in 2080 (45.27 kWh/m²/year), resulting in an increase of 170% compared to the baseline year. Of course, this outcome is expected if the status quo is maintained, which means installing poor-efficient air-conditioning systems with no upgrade of the building envelope.

Additionally, scenario B also showed higher standard deviations on the average EUI of schools and an increasing tendency for further years. For instance, the lower limit (average minus the standard deviation) for scenario B in 2080 is greater than the upper limit (average plus the standard deviation) for scenario A in the same year: 31.06 kWh/m²/year and 29.59 kWh/m²/year, respectively.

It is important to highlight the implications of the approach used in this study. Since it is based on stock modelling, there is an uncertainty inherent of the process of simplification that comprehends simulation models. Indeed, standard deviations were maintained to show that the results might vary. Sensitivity analysis performed in other studies (Silva and Ghisi 2014) showed that occupancy schedules, equipment power, and occupants are relevant parameters in energy simulation in general. Thus, a sensitivity analysis could reveal the major aspects that impact stock modelling and energy benchmarking.

Another key point evidenced in Silva and Ghisi (2014) is the possibility of relying on simulation-based results to strategically plan future steps towards decarbonisation (and prevent carbonisation) of the local building stock. Indeed, by combining emerging topics from the literature (stock modelling, energy benchmarking, building performance simulation and climate change), a solid overview of the implications may be captured to aid a country-sized planning building intervention. These outcomes do not support the idea of avoiding the air-conditioning implementation or even installing them only in colder climates to minimize such an increase in energy use. Instead, students’ performance may be negatively affected by suboptimal indoor conditions (Palacios et al. 2020). In fact, this study sheds light on the need to assess the impacts of current decisions on the future comprehensively. Achieving decarbonisation target in buildings is a complex demand, which involves different stakeholders (Hamilton et al. 2017). Therefore, our results support that building designers, researchers, school principals, and policy-makers must be aligned to achieve comfortable yet energy-efficient and climate-change-resilient learning environments in Brazil.

Naturally, achieving such ambitious targets demand high efforts. However, if authorities do not consider this issue from now on, both problems (global warming and thermal comfort) will contribute to aggravate each other. Indeed, without a resilient, energy-efficient transition in Brazilian schools, those buildings will worsen climate change effects with their associated high amount of carbon emissions. As a consequence, the same buildings will be likely to use even more energy to operate.

From a building designers’ perspective, our results support the need to include energy efficiency measures on new buildings constructed throughout the years. As highlighted in the method section, the envelope of current schools in Brazil is not provided with materials able to minimize the energy use (see Table 1). Previous research conducted in Brazil emphasized the major role of incorporating energy efficiency measures to reduce the effect of climate change in the coming decades (Triana et al. 2018). Indeed, preparing the envelopes to such trends on climate change is necessary.

Researchers are also expected to continuously provide new information to other stakeholders about good practices in this field. For instance, understanding acceptable indoor conditions is a key aspect to tailor the building operation to guarantee higher satisfaction and productivity for the students without compromising those buildings’ energy performance. Along these lines, there is evidence that thermal comfort in classrooms in Brazil is highly influenced by airspeed, which provides an opportunity to avoid air-conditioning overuse by relying upon natural ventilation (Buonocore et al. 2018).

As a consequence, both school principals and policy-makers can define their practices according to the best strategies. Policy-makers can implement strict
requirements on the minimal performance of systems installed and the properties of new buildings. In Brazil, energy labeling of buildings is still voluntary, and the transition to a mandatory requirement would facilitate the achievement of an energy-efficient stock in the future.

Conclusion

This paper has shown a study on the EUI of the school building stock in Brazil considering two scenarios of air-conditioning implementation and two scenarios of future climate. The objective was to measure the impact of the implementation of air-conditioning that is occurring in those types of buildings in Brazil, with no other interventions to decrease energy consumption – which causes carbonisation of the building stock. The main conclusions can be outlined as follows:

(a) Considering the scenario of implementing air-conditioning in classrooms (Scenario B) in the baseline year, the average EUI of the school building stock in Brazil might increase about 88%.

(b) If the trend to install air-conditioning without any other energy efficiency measures is kept, the energy consumption tends to increase more 8% in 2050 and 43% in 2080.

(b) To reduce energy consumption in schools and continually provide thermal comfort to students and employees, stakeholders must include energy efficiency programmes for buildings once the actual buildings’ conditions are not prepared to integrate air-conditioning systems.

The detailed reasons for the findings above will be investigated in future studies, for example, specific strategies of energy efficiency and photovoltaic panels implementation to mitigate this carbonisation effect.

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