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Towards benchmarking of HVAC energy in commercial buildings in warm climates

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Abstract:
Mechanical cooling and ventilating of buildings is responsible for a significant proportion of their energy consumption. In any benchmarking strategy or operational performance assessment for energy efficiency, it is important to consider calculations or correction factors to account for the impacts of external conditions on the cooling load.
Many emerging economies have stocks of commercial buildings of which some operate in fully air-conditioned modes and others in mixed-mode, using air conditioning for a significant proportion of the year. In warm climates, these buildings may interact with the external climate in different ways.
In detailed analyses of energy consumption in 32 office buildings across Brazil, buildings are categorised according to HVAC system type and energy consumption is calculated end-use. For each building, the statistical relationship between climate and energy consumption is measured, using cooling degree hours.
Buildings which are fully air conditioned show large variations in energy consumption, indicating that although they are conditioned to standard temperatures, they face operational challenges. The buildings with mixed-mode operation are shown to have a more even correlation with external conditions even at high temperatures.
This result has implications for steady-state building energy models, benchmark development and climate correction calculations for monitoring and verification.

Keywords: Benchmarking, Cooling energy consumption, Climate correction, Energy audit

Introduction

International efforts to improve energy efficiency in buildings repeatedly emphasise the importance of benchmarking performance. Benchmarks can be used to rate and evaluate energy performance, to identify improvement potential or to track performance through time. A benchmark performance level can be based on top-down methodologies including statistical evaluations of building stocks or bottom-up models developed through building physics (Burman et al. 2013; Hong et al. 2013; Borgstein et al. 2016). Current work in performance benchmarking aims to reconcile the difference between these types of models to produce building performance evaluations where physical characteristics can be used to interpret statistical performance data.

For the purposes of energy performance evaluations, the factors affecting energy consumption in buildings can generally be separated into:

- External factors – principally climate but also local factors such as shading;

- Building efficiency – including both the envelope and the building systems;
- Operational efficiency – most buildings do not operate at their optimal control point;
- Service provision – indoor environmental conditions and usage intensity.

Cooling and HVAC energy in warm climates

In tropical and sub-tropical climates, especially in emerging economies, commercial buildings generally have no space heating systems but space conditioning often remains the largest energy consumer. As external temperatures will often be within comfortable ranges, a building can aim to provide adequate thermal conditions for its occupants through a fully conditioned (AC) approach, a Naturally Ventilated (NV) approach or a Mixed-Mode (MM) approach. These will require distinct design strategies in order to produce efficient, comfortable buildings (CIBSE 2017).

Many bottom-up models for energy performance evaluation will assume constant internal temperatures during operating hours; this is unlikely to be the case in NV or MM buildings. ASHRAE Standard 55-2013 (ANSI/ASHRAE 2013) includes an adaptive comfort model which can be applied to buildings in which the thermal conditions are regulated by the users primarily through the opening and closing of windows. There are models available to evaluate the performance of NV buildings. For example, Rackes et al have carried out extensive modelling to evaluate the impact of building characteristics on energy consumption of NV buildings, specifically identifying the discomfort hours likely in low-rise buildings, principally schools (Rackes et al. 2016). However, there is a challenge in applying the same tools to mixed-mode buildings, which may use both operable windows and air conditioning during the same day, or sometimes simultaneously.

Methodology

Building data

Simple building information, such as energy bills, typology and floor area, are often used to carry out simple benchmarking exercises or performance evaluations in homogenous building typologies (Borgstein & Lamberts 2014). However, this simplified information does not provide enough detail to be able to carry out effective performance analyses comparing mixed-mode and fully conditioned buildings.

For this evaluation, detailed building information have been collected on 32 commercial buildings in Brazil. These were primarily office buildings, with a wide range of sizes and building characteristics, distributed in 14 cities across the country. Each building provided preliminary information, including basic building characteristics and energy bills for at least 12 consecutive months. Following this, each building was subjected to a full energy audit, following ASHRAE Procedures for Commercial Building Energy Audits levels one or two (ASHRAE 2011). During these energy audits, the principal building systems and envelope were catalogued and evaluated, a full end-use breakdown was calculated and calibrated against measured consumption using CIBSE's TM22 methodology (CIBSE 2006), significant operational performance issues were identified and opportunities for energy saving measures were listed. Building information was gathered through on-site surveys, interviews, spot measurements and the installation of remote monitoring, sub-metering or data-logging energy meters in some cases. Each of the 32 buildings evaluated operates as a complex system and exhibits unique characteristics related to its occupation, physical infrastructure and operational efficiency. Data collection is difficult and requires repeated site visits as much of the reported data is unreliable. Several different definitions of area are used (useful area, built area, conditioned area, let area) and often these are not clearly defined. Buildings have occupancy rates which vary significantly throughout the year and record-keeping is not always accurate. Metered data reported by some buildings was found to refer to a campus including a group of buildings, while some energy meters only referred to a part of the building. Often building managers supplied incomplete or erroneous information, requiring detailed investigation and checking.

Levels of service provision

The buildings evaluated have different levels of operational and systems efficiency. Fully quantifying and disaggregating these levels of efficiency will be the subject of future work. However, a few key issues can be raised. Firstly, several buildings do not meet full requirements for occupant satisfaction, either through underperforming air conditioning systems or low lighting levels (in one case, a building had insufficient installed electrical capacity, meaning the users had to choose between lighting and air conditioning). Secondly, there were major differences in building floor area ratios; some had air conditioning installed in less than 50% of the area, others were only partially occupied whilst others were fully occupied and conditioned. Finally, although the hours of use tended to be similar for the majority of buildings, there were differences in the intensity of use: one building was dominated by a cultural centre, another by a major data centre, others had varying densities of occupation (m^2 per person). These factors all have major impacts on the total energy consumption.

Climate data

Energy consumption in buildings can be impacted by factors like air temperature, humidity, wind speed, direct solar radiation and cloud cover. These will have different impacts, depending on the type of building, but a meta-model developed by Rackes et al shows that for the commercial buildings studied in warm climates (principally low-rise buildings), the number of cooling degree hours is the single characteristic with the greatest impact on energy consumption of simulated buildings, (Rackes et al. 2016).

The Brazilian Institute of Metrology (INMET) has provided historical climate data for several hundred cities in Brazil, which has been used to produce weather years that are provided online for building performance simulation (LABEEE, n.d.). In addition, some recent data is made freely available by INMET, including air temperature and relative humidity. As dry-bulb air temperature is the dominant climate impact on building energy consumption, cooling degree hours (CDHs) are calculated and used to map climate intensity and evaluate performance. Based on the authors' experience in modelling balance temperatures for buildings in warm climates, 22°C is selected as the base temperature for calculating CDH according to Equation 1.

$$CDH = \sum_{hours} (T - T_{base})^+$$

Equation 1.

T = mean hourly temperature; T_{base} = base temperature, 22°C

CDHs can be easily calculated for both the weather years used for simulation in Brazil, and the real recent weather conditions in selected cities. In order to use them for performance evaluations, they are calculated and tabulated on a monthly basis.

In general, the term climate normalisation or climate correction is used for comparing energy consumption by buildings in different climatic regions (spatial adjustment), while weather normalisation is used to compare building performance over time in the same region (time adjustment). As described in Table 1 and illustrated in Figure 1, there is a significant difference between the historical weather data provided for some major cities in Brazil, and the actual recent climatic conditions. Although some months are colder than historical data would indicate, the greatest differences appear to be in peak temperatures during hot months. This is likely to be due to a combination of climate change and urban heat islands, leading to more intense climatic events such as heat-waves in the summer. This would seem to clearly indicate the importance of using weather normalisation for building performance evaluation, especially when monthly data are considered. The three year average CDH is close to the INMET level for Brasília and Belo Horizonte (within 10%), but is 43% and 67% above the INMET level for Rio de Janeiro and São Paulo respectively.

Table 1 – Monthly means of cooling degree hours in selected Brazilian cities

Mean monthly CDH	**Rio de Janeiro**	**São Paulo**	**Belo Horizonte**	**Brasília**
2014-2016 (3 years)	2427	980	1355	1097
INMET	1694	588	1228	1152

Climate-related energy consumption

In order to carry out evaluations of energy performance related to weather in different building types, it was necessary to clean the data. Firstly, monthly energy consumption was calculated and normalised by the useful floor area. The major end-uses which are not classed as normal building services for offices (usually data centres) were subtracted from total energy consumption, using the mean annual percentage of the energy consumed by these systems. A correction factor was applied for the number of working days per month, to account for some months containing more weekends and national public holidays. Finally, buildings which could not be classified as principally office spaces were removed from the dataset.

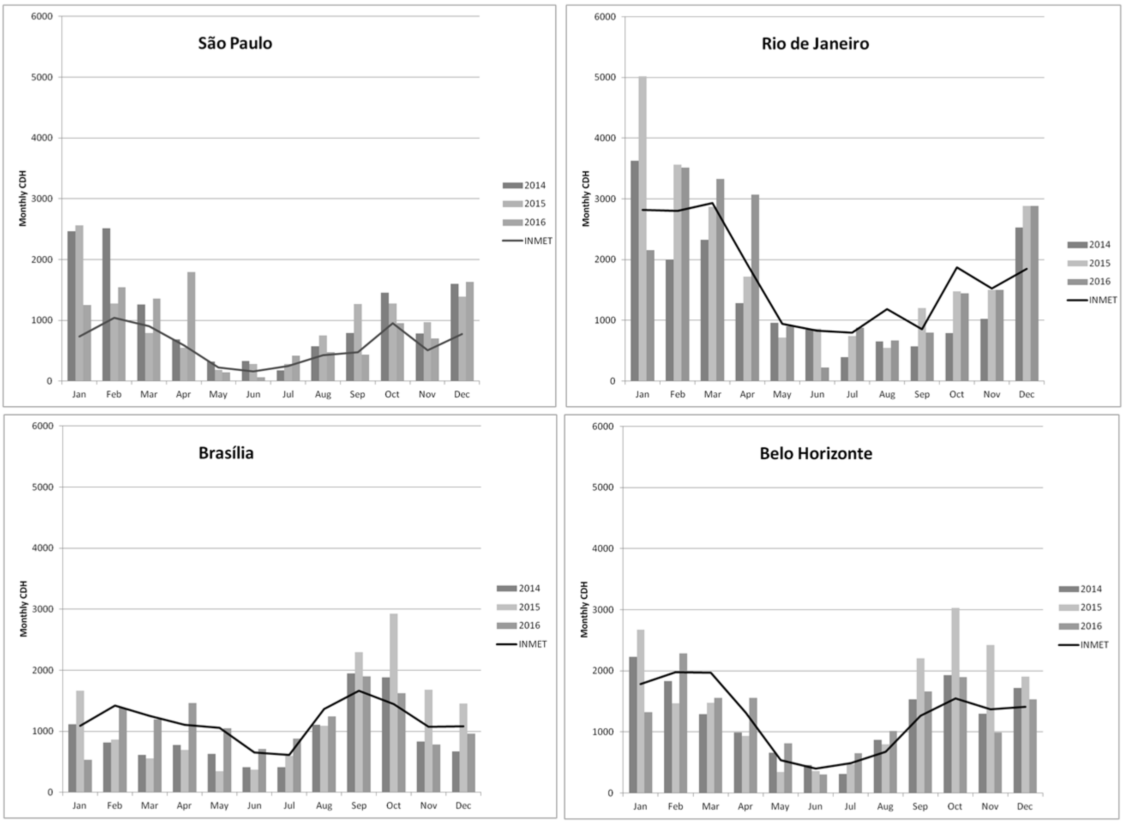

Figure 1. Comparisons of cooling degree hours calculated from historical weather data (INMET) and measured temperature for recent years

The building HVAC systems were described and their primary cooling technology tabulated. In larger buildings, centralised HVAC systems are used to condition a whole building and are generally chilled water systems, although some may be variable refrigerant flow (VRF). Generally, in buildings with centralised systems over 80% of the area is conditioned (stairwells and corridors are usually not conditioned) and these buildings almost always have central control and operation. Distributed HVAC systems nearly always use direct expansion (DX) units, primarily split air conditioners. They may be fully conditioned or may only have air conditioning installed in a small proportion of the building, but the air conditioning is operated locally and does not have a central control system. Separately, the buildings were evaluated according to their window operation. By noting whether the majority of windows were operable, the number of windows open during the visits and the use of windows cited in interviews with building managers, buildings were classified as having fixed or operable windows.

With few exceptions, smaller buildings had operable windows and distributed HVAC systems and were considered Mixed-Mode (MM), while larger buildings had fixed windows and centralised HVAC systems and were considered Fully Conditioned (AC). One smaller building had a DX system but did not have operable windows, so was classified AC, while one large building classed as MM – it did not have a central air conditioning system because it was built before such systems were available.
Table 2 shows the building characteristics and identification as MM or AC.

Table 2. Building characteristics and cooling systems

ID	Primary use	Occupied area (m²)	Window use	Cooling system	HVAC category	Notes
1	Office	754	Yes	DX	MM	
2	Office	1,502	Yes	DX	MM	
3	Office	1,862	Yes	DX	MM	
4	Data centre	678	No	DX	MM	**Excluded:** primarily data centre
5	Cultural centre	926	Yes	VRF	MM	
6	Office	1,947	Partial	DX	MM	Building only partially conditioned

7	Office	1,745	No	DX	AC	
8	Office	1,638	Yes	DX	MM	
9	Office	4,046	Yes	DX	MM	
10	Office	6,370	Yes	DX	MM	
11	Office	3,331	No	VRF/chilled water	AC	
12	Office	749	No	DX	MM	
13	Office	9,208	Partial	DX	MM	
14	Office	5,637	Partial	DX	MM	
15	Cultural centre	2,046	Partial	Chilled water	MM	
16	Office	12,970	No	Chilled water	AC	Poor thermal comfort
17	Office	28,332	No	VRF/chilled water	AC	
18	Office	15,738	No	Chilled water	AC	
19	Office	12,214	No	Chilled water	AC	HVAC operational problems
20	Office	19,128	Partial	Chilled water	AC	
21	Office	102,180	No	VRF	AC	
22	Office	27,625	No	Chilled water	AC	
23	Office	54,555	No	Chilled water	AC	Excluded due to poor quality data
24	Office	35,364	No	Chilled water	AC	
25	Office	12,325	No	Chilled water	AC	
26	Office	35,325	No	Chilled water	AC	Includes shops and commercial areas
27	Office	39,844	No	Chilled water	AC	Includes large laboratory
28	Office	15,829	No	VRF	AC	Data for common parts only
29	Office	36,221	Yes	DX	MM	Building is not conditioned
30	Office	4,583	No	Chilled water	AC	
31	Office	52,361	No	Chilled water	AC	
32	Office	31,614	No	Chilled water	AC	

Results

The energy consumption for the 32 buildings in the dataset was broken down five end-use groups: HVAC, lighting, plug loads, data centres and other. The division of the energy consumption according to these categories is shown in Figure 2 for the MM buildings in the dataset (14 buildings) and in Figure 3 for the AC buildings (18 buildings). This data is not normalised for occupancy density or for climate, but it is clear that AC buildings generally have a larger consumption for HVAC, while data centres can cause significant distortions of the results.

The energy disaggregation provided for the buildings during the energy audits is based on estimated or calculated data, generally using a few spot measurements to calibrate estimates. As such, the end-use data was not deemed accurate enough to completely separate cooling energy consumption for a separate analysis. Instead, the removal of major distortions from data centres and non-standard energy uses left a more uniform basis for comparison, based on standard building services (cooling, ventilation, heating, plug loads, lighting, elevators and UPS systems). Although no correction was made for occupant density, the vacancy rates were considered in the calculation (consumption was normalised by occupied area), and operational hours were found to be similar in all of the buildings.

The corrected monthly energy consumption for each building was then paired with the monthly degree days calculated for the month in which the energy consumption took place. Buildings 4 and 23 were excluded and there were between 12 and 24 energy bills available for each building, producing a total of 617 data points

(292 in MM buildings and 325 in AC buildings).

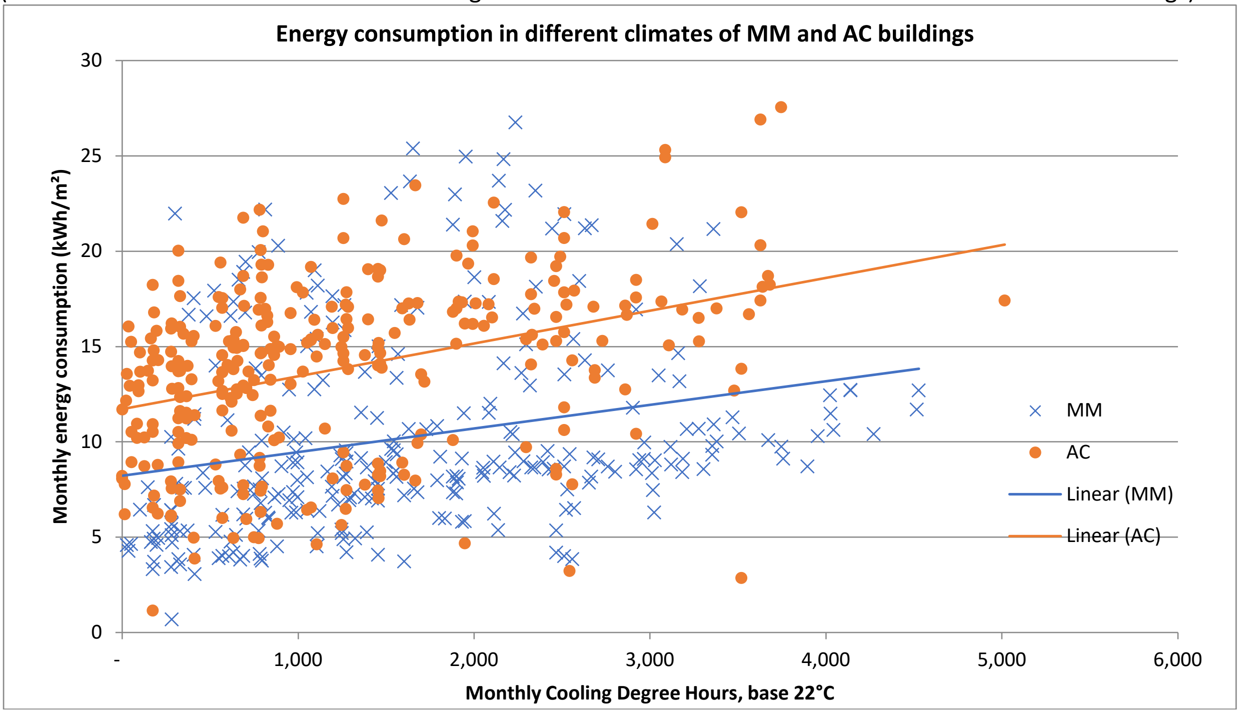

Figure 4 shows the energy consumption of mixed-mode and air conditioned buildings, plotted against the energy consumption of the relevant month. A linear, least-squares regression between degree days and energy consumption gave a positive correlation for each building individually, with one exception (this AC building was undergoing retro-commissioning at the time when the data were collected). However, there is clearly a large variation between buildings and the statistical relationships were generally weak. Overall, the AC buildings demonstrate higher energy consumption and greater variability, as well as a slightly higher energy consumption increase in higher temperatures. A further evaluation was carried out on the MM buildings, removing the buildings which had in which the conditioned area was below 50% of the total useful area, as these buildings would be expected to show different relationships with temperature. The scatter-plot in

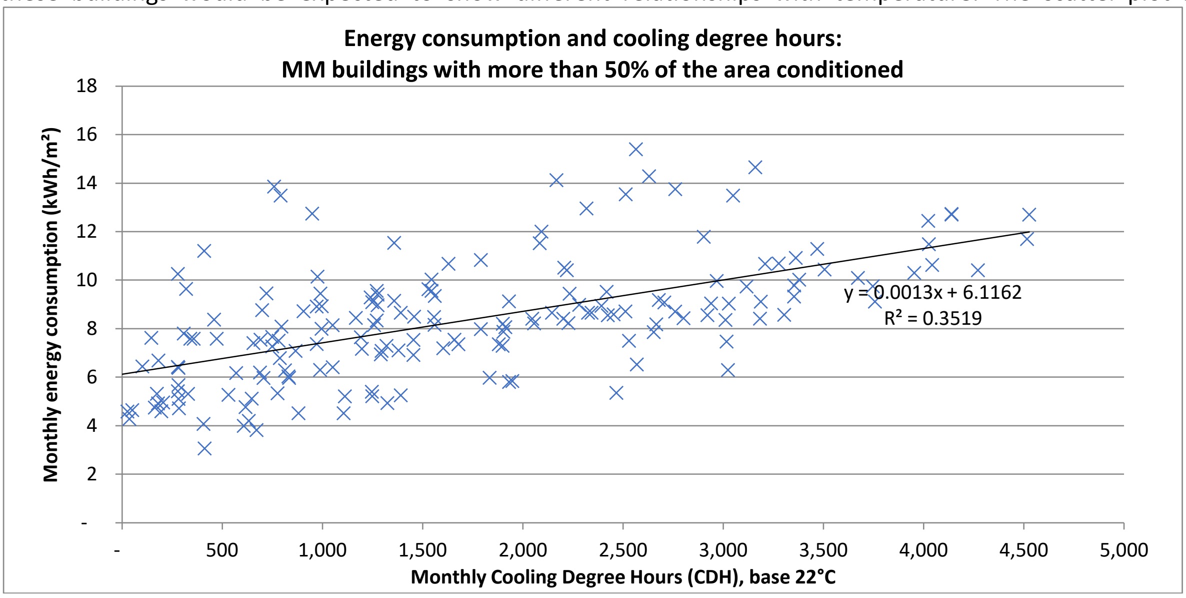

Figure 5 shows the results in the ten remaining buildings, with a linear least-squares regression. Although the R^2 value is still only 35%, this plot shows a clearer statistical relationship between energy and temperature.

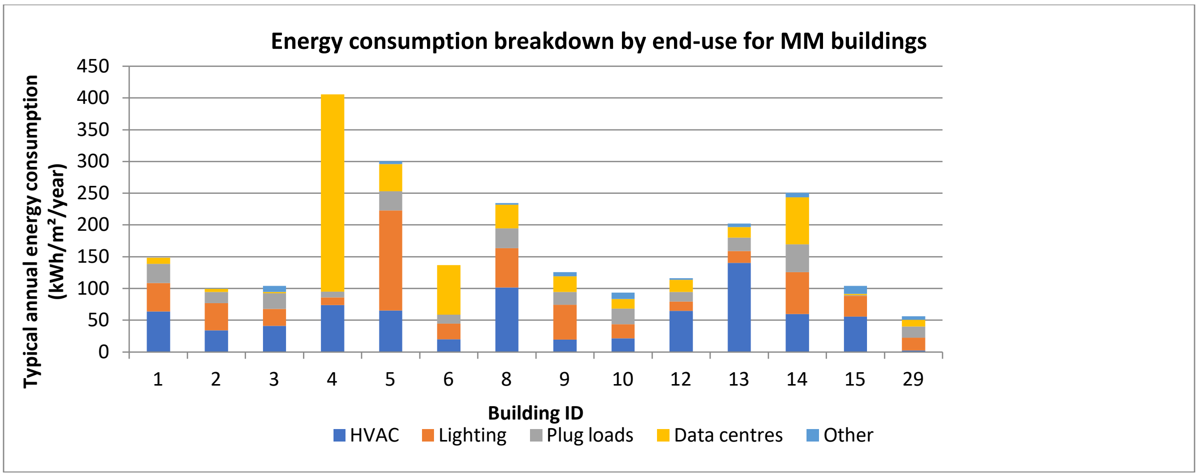

Figure 2. Energy consumption in five major end-use categories, calculated for mixed-mode buildings

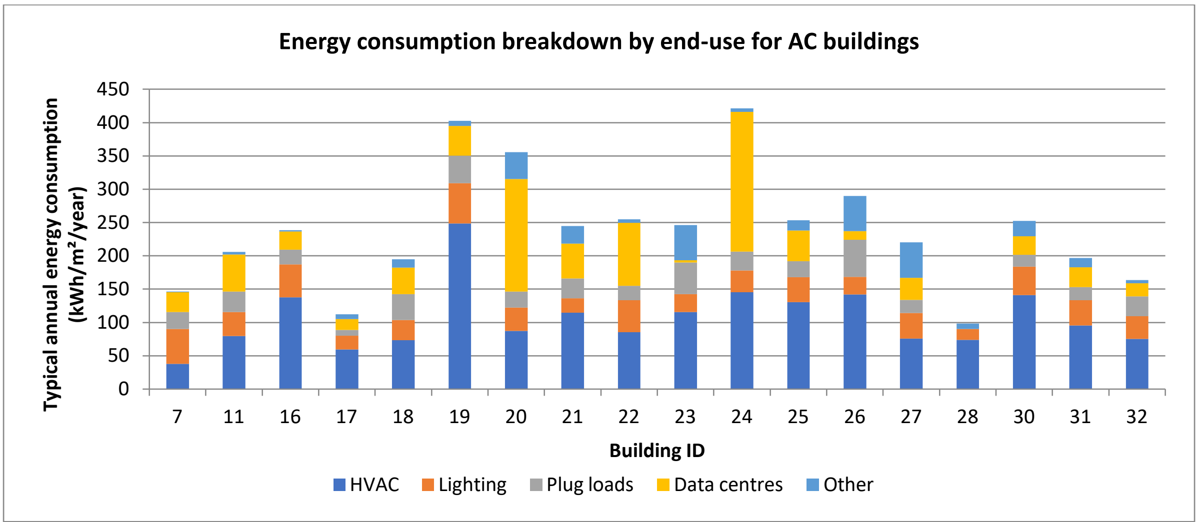

Figure 3. Energy consumption in five major end-use categories, calculated for fully conditioned buildings

The higher energy consumption of AC buildings is to be expected, as fully conditioned buildings are generally expected to provide a higher level of service: constant year-round temperatures, air filtration, barriers to noise pollution and low air speeds, for example. Several of the buildings in this study were considered AAA-level corporate offices, which may also have higher equipment densities due to the use of UPSs and tasks which are more computer-intensive. Several of the AC buildings had undergone sustainability certifications at the time of construction, which requires the inclusion of high-efficiency equipment to meet international certification parameters (Brazilian legislation does not currently include any energy efficiency requirements for commercial buildings). Although these buildings showed less variation than other buildings in the AC dataset, they still demonstrate higher energy consumption than MM buildings. In general, the high variation and low predictability of performance amongst the AC buildings is likely to be related to their use of larger, more complex equipment for building conditioning. Although this equipment can be designed and operated in a highly efficient fashion, the data from the energy audits showed that HVAC equipment was never operating under optimal conditions and in some cases was responsible for sharply increased energy consumption because of incorrect operational parameters. The lack of professional commissioning, poor maintenance, the low level of expertise of building managers and a lack of strategic oversight or energy management are responsible for this variation.

In MM buildings, there was also a significant variation in energy performance, with some buildings showing characteristics that were far from typical. However, there was a greater degree of standardisation of equipment and operation: air conditioning was provided through split or window units and building occupants could operate windows as and when required. Four of these buildings were only partially conditioned, and once these were removed from the dataset, there was a high degree of correlation between energy consumption and climate.

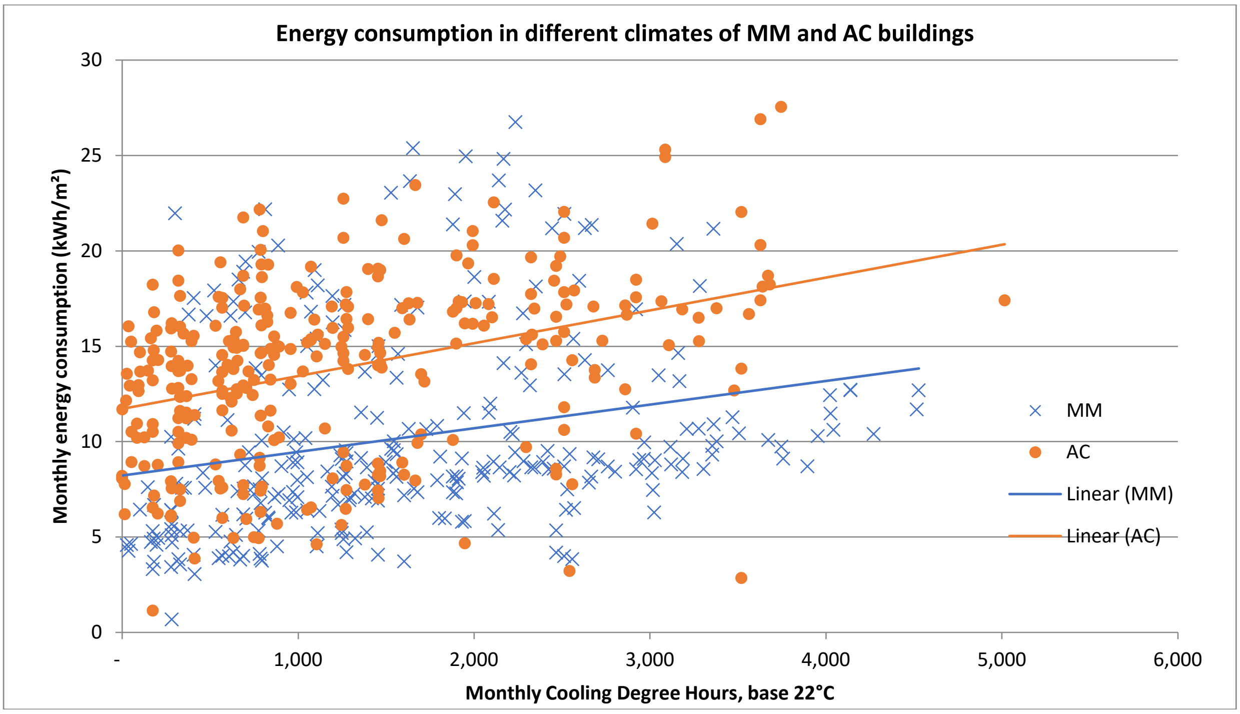

Figure 4. Energy consumption versus CDH in mixed-mode and fully conditioned buildings (30 buildings, data centre energy consumption excluded)

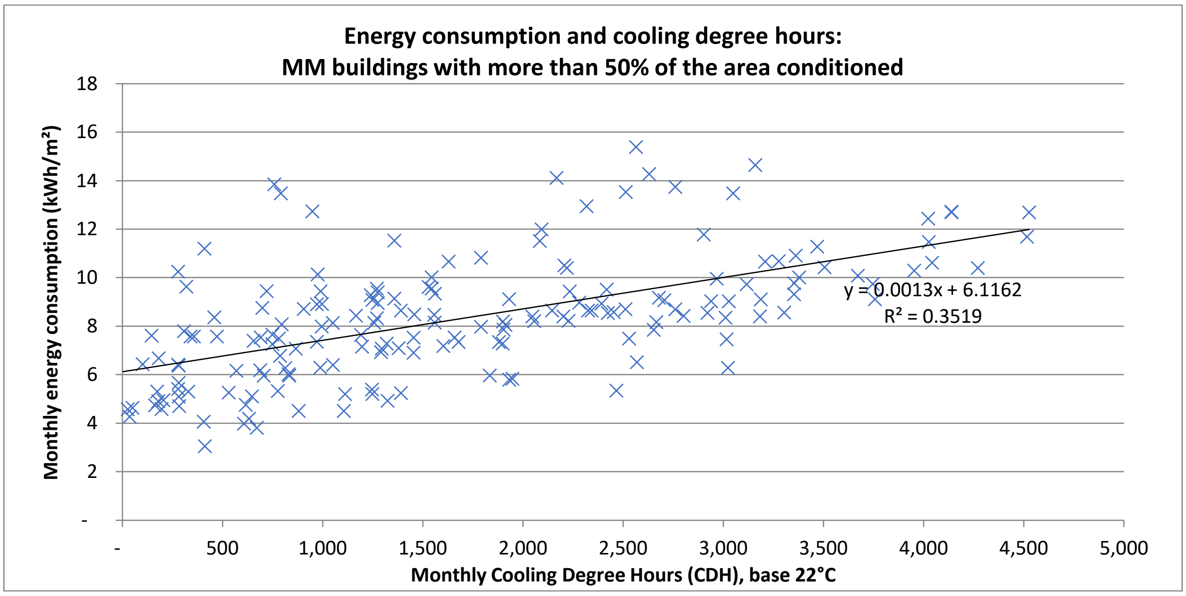

Figure 5 - Energy consumption versus temperature for mixed-mode (MM) buildings in which the majority of the area is conditioned (8 buildings, data centre energy consumption excluded)

Discussion

Although some AC buildings show performance levels equivalent to MM buildings, the majority have significantly higher energy consumption. Excluding data centres, the mean annual energy consumption of MM buildings was 124 kWh/m²/year and only three of the 18 AC buildings had energy consumption below this level; the mean for MM buildings was 188 kWh/m²/year. As AC buildings tend to have more highly designed and complex systems, with efficient chillers or VRF units, they might be expected to demonstrate better levels of efficiency at higher temperatures, where their systems would be fully utilised. Following this logic, the small DX units in MM buildings would have higher energy consumption at high temperatures due to their low efficiency, while external temperatures would almost always be too high to allow windows to be opened. However, this is not demonstrated in the results, which instead show that the energy consumption of AC buildings increases with temperature at a faster rate than that of MM buildings. This result should be explored in more detail; reasons are likely to involve poor operational practice, lack of optimisation in AC buildings, higher internal loads and some levels of discomfort at high temperatures in MM buildings.

The adaptive comfort model from ASHRAE 55-2013 would indicate that MM buildings can operate in a wider range of temperatures; the results of this paper seem to indicate that the impacts on energy consumption of the wider comfort range are measurable and significant. Clearly, there are several other factors with significant impact on energy consumption that were not considered here. Amongst external factors, levels of wind speed, solar radiation, humidity and external shading were not considered. The simple normalisation carried out made no attempt to correct for levels of occupant density, systems efficiency and operational efficiency; these three factors are likely to account for a significant proportion of the remaining variation in building energy consumption.

These results indicate several areas for further research. Additional weather variables (beyond CDH) should be tested to find out which, if any, will be required for benchmarking climate-related energy consumption. With a weather correction factor applied, further development of analytical tools to separate the energy consumption due to operational inefficiency and systems efficiency should be carried out, to show the performance improvement potential for an individual building.

List of abbreviations

CDH – Cooling Degree Hours, considering dry-bulb temperatures with base 22°C unless otherwise specified
MM – Mixed-mode building, which can operate using air conditioning and/or operable windows
AC – Fully air conditioned building, which does not typically operate using operable windows in the majority of the usable area
NV – Naturally ventilated building, which has little or no air conditioning.
INMET – Brazilian Institute for Metrology, which publishes weather data from across the country.
DX – Direct expansion air conditioning system (typically includes split and window systems)
UPS – Uninterruptible Power Supply

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