Factors influencing the life-cycle GHG emissions of Brazilian office buildings

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ABSTRACT

Effective mitigation of greenhouse gas (GHG) emissions in the buildings sector requires a full understanding of the factors influencing emissions over the life-cycle of buildings, particularly in places where large additions to the building stock are expected. Currently, little is known about what affects the GHG emissions of buildings located in warmer climates, a typical situation for many emerging economies. This paper presents a study of emissions from Brazilian office buildings using building archetypes. A sensitivity analysis explores possible parameter ranges, various contributions to life-cycle impacts and their key drivers. For each of the 1000 building variations in the sample, the emissions were calculated using a life-cycle assessment. Multivariate regression analysis enabled the study of the results' sensitivity to 10 parameters, influencing building operation, design and others. The emissions ranged from 20 to 106 kg CO₂-eq/m² gross floor area and year. Electricity mix, climate and cooling efficiency were the most impactful parameters, but building component service time was also significant.

POLICY RELEVANCE

Emerging economies are expected to rapidly increase their building stock and energy use, particularly for cooling in the coming decades. The findings show the key factors influencing the GHG emissions of office buildings in warm climates, typical for many emerging economies, such as Brazil. For effective mitigation, priority should be placed on reducing the carbon intensity of electricity and encouraging highly efficient heating, ventilation and air-conditioning systems. Policymakers may want to offer incentives for office buildings with a combination of natural ventilation and mechanical cooling, because they were less emission-intensive in every investigated city. The benefits are the biggest for buildings in which a high proportion of windows can be opened for natural ventilation.

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1. INTRODUCTION

Office buildings are among the most important types of commercial buildings. In 2012, offices represented 18% of floor space and 20% of energy consumption of commercial buildings in the US, and this building stock keeps growing (EIA 2012). It is a relatively uniform building type, characterised by high energy use due to artificial lighting, information and communication technology (ICT) equipment and air-conditioning (AC) (Pérez-Lombard et al. 2008). The increasing need for office floorspace is generally coupled with service sector growth (Deetman et al. 2020), observed in most important emerging economies (UN 2021). Consequently, this building type is responsible for a significant share of building-related greenhouse gas (GHG) emissions.

Life-cycle assessment (LCA) is a method used to assess the potential environmental impacts of a product from the extraction of raw materials through manufacturing and use to the eventual disposal of the product (ISO 2006). The method is widely applied to study the environmental performance of buildings, including the assessment of GHG emissions over the life-cycle stages, also known as the carbon footprint (Pandey et al. 2011). Numerous studies have been conducted on life-cycle energy use (Cole & Kernan 1996; Dimoudi & Tompa 2008; Junnila et al. 2006; Kofoworola & Gheewala 2009; Wang et al. 2018; Yohanis & Norton 2002) and GHG emissions (Airaksinen & Matilainen 2011; Asdrubali et al. 2013; Chau et al. 2012; Dimoudi & Tompa 2008; Eberhardt et al. 2019; Frischknecht et al. 2019; Junnila et al. 2006; Kofoworola & Gheewala 2008; Kumanyake et al. 2018; Lessard et al. 2018; Suzuki & Oka 1998; Wallhagen et al. 2011; Yan et al. 2010; Ylmén et al. 2019) of office buildings, with some focused on material-related impacts (Chau et al. 2012; Dimoudi & Tompa 2008; Eberhardt et al. 2019; Yan et al. 2010). The available estimates of life-cycle emissions of office buildings vary significantly, as shown in Table S1 in the supplemental data online.

Previous research shows that operational energy use and production of materials are the two most important life-cycle stages for energy consumption (Cabeza et al. 2014; Chau et al. 2015; Karimpour et al. 2014; Ramesh et al. 2010; Sartori & Hestnes 2007) and GHG emissions (Chau et al. 2015; Fenner et al. 2018; Sea & Hwang 2001) of buildings. Operational energy use in offices was found to be influenced by ventilation rate (Heiselberg et al. 2009), cooling set point (Lam & Hui 1996a), cooling efficiency (Lam & Hui 1996a), window-to-wall ratio (WWR) (Wang et al. 2019), shading (Carvalho et al. 2010) and solar heat gain coefficient (SHGC) (Carvalho et al. 2010). Material-related emissions are strongly impacted by the lifetime of the building (Häfliger et al. 2017) and the service life of the components of which it is made (Chau et al. 2012; Häfliger et al. 2017; Hoxha et al. 2014; Morales et al. 2020; Ruuska & Häkkinen 2015). A comprehensive sensitivity analysis of residential buildings in Switzerland found that electricity mix, ventilation rate and heating system type were the most important parameters influencing life-cycle GHG emissions (Heeren et al. 2015). Pannier et al. (2018) investigated sensitivity analysis methods by modelling life-cycle emissions of a single-family house in France. Each method showed that Intergovernmental Panel on Climate Change (IPCC) time horizon, electricity mix and building lifetime were the three most influential factors.

One way to decrease the operational energy use of office buildings is to implement passive cooling strategies. Mixed-mode ventilation (MMV) is a combination of natural ventilation and mechanical cooling. It allows one to maintain acceptable thermal conditions with reduced energy consumption compared with conventional mechanical cooling systems (Arnold 1996). Implementation of MMV strategies in office buildings offers some energy savings in all climate zones, a literature review for the period 1996–2016 by Salcido et al. (2016) suggested. Later research, meanwhile, indicates that hot and humid climates have negligible natural ventilation potential, while desert and semi-arid climates exhibit a higher potential if one assumes occupants’ ability to adapt to thermal conditions (Chen et al. 2017). Some recent studies investigated the influence of building design parameters on the energy use of MMV buildings (Gokarakonda et al. 2019; Neves et al. 2019). Among parameters specific to naturally ventilated spaces, the important ones turned out to be zone depth (Gokarakonda et al. 2019) and window opening effective area (Neves et al. 2019), the latter being the most influential when external shading is low (Neves et al. 2019).
To the authors’ knowledge, a systematic parametric variability analysis for life-cycle GHG emissions of office buildings in developing countries has not yet been conducted. Addressing this research gap is particularly important considering that emerging economies are expected to rapidly increase their building stock (IEA 2017) and energy use for cooling (IEA 2018) in the coming decades. These countries likely represent the majority of future office building stock additions. With hot climates being typical for many emerging economies, it also appears relevant to investigate the potential of MMV strategies for GHG emissions reduction.

Brazil was chosen for this study because it is one of the biggest emerging economies and represents a whole range of hot climates. Alves et al. (2017) performed a comprehensive analysis of office building stock in Belo Horizonte, Brazil, and found that typical office buildings built before the 2000s had a cellular floor layout with an ‘E’, ‘H’ or ‘U’-shaped floor plan; they also usually relied on MMV systems. Newer buildings showed an increase in open office spaces and in the use of central AC cooling systems (with no natural ventilation available), which caused higher energy use intensity (Alves et al. 2017). Recent work on Brazilian office buildings improved the understanding of their energy performance (Alves et al. 2017; Borgstein & Lamberts 2014; Lamberts et al. 2015; Wong et al. 2019) and possible energy savings (Alves et al. 2018; Carvalho et al. 2010; Neves et al. 2019). In Brazil, whole-building LCA studies are limited to university buildings (Gomes et al. 2018) and residential housing (Evangelista et al. 2018; Morales et al. 2019; Paulsen & Spoto 2013). A material flow analysis performed by Condeixa et al. (2017) shows that national standards (ABNT 2006; Sinduscon-MG 2007) and industry averages (PINI 2010) may be used to model the material requirements of representative buildings.

The present paper uses archetypes for office buildings in hot climates. Archetypes are often used in the literature to describe subdivisions of building stocks, e.g. to model energy or material demand of regional or national building stocks (Heeren et al. 2013; Heeren & Hellweg 2019; Swan & Ugursal 2009). Office building archetypes were used (1) to estimate their life-cycle GHG emissions; (2) to find key drivers of these impacts in both mixed-mode (MM) and fully AC buildings; and (3) to identify strategies to reduce the impacts.

2. METHODS

The framework involves defining office building archetypes, selecting a sample of 1000 building variations, modelling building energy use, material demand and GHG emissions, and performing a sensitivity analysis. The system boundaries include life-cycle stages associated with production and the construction process, replacement, operational energy use and end-of-life (see Section 2.5).

2.1 OFFICE BUILDING ARCHETYPE DEFINITION

Three building archetypes were created, representative of Brazilian office buildings. The design and operational parameters are listed in Table 1. The material data and main design features (such as building size and floor layout) were based on commercial building types described in national standard NBR 12721 (ABNT 2006), further specified by the Syndicate of Construction Industry (Sinduscon-MG 2007). Buildings denoted in NBR 12721 (ABNT 2006) as CSL-8, CSL-16 and CAL-8 correspond to archetypes I, II and III, respectively. These archetypes were defined by considering the current real estate market and they serve as a tool to estimate construction costs (Sinduscon-MG 2007). The structural elements were modelled according to typical construction practices in Brazil (Morishita et al. 2011). The area of internal walls was determined based on the amount of brick per 1 m² according to NBR 12721 (ABNT 2006), reduced by the amount of brick needed for external walls. Other data in Table 1 were chosen based on national standards, technical reports and other studies on Brazilian office buildings (ABNT 2008; Alves et al. 2017; ANVISA 2003; CB3E et al. 2015; CIBSE 2004).
Among the parameters significantly affecting the emission performance of buildings in hot climates, 10 parameters were selected based on findings of prior research (Borgstein & Lamberts 2014; Carvalho et al. 2010; Häfliger et al. 2017; Heeren et al. 2015; Hoxha et al. 2014; Lam & Hui 1996a; Lamberts et al. 2015; Morales et al. 2020; Neves et al. 2019; Ruuska & Häkkinen 2015; Wong et al. 2019). Each parameter was assigned a list of possible input values (Table 2). For example, a city was selected from among 12 Brazilian cities reflecting a whole range of climatic conditions, as represented by cooling degree-hours (CDH). The electricity mix is dependent on the region (see Figure S1 and Table S8 in the supplemental data online). Shading was modelled as a window overhang, and its values ranged from 0 (no shading) to 1 (overhang depth equal to window height). Window opening effective area represents the share of windows that can be opened for natural ventilation; when this share is zero, the building is fully AC.

### Table 1: Design and operational parameters of the office building archetypes.

| Parameter                                      | ARCHETYPE I | ARCHETYPE II | ARCHETYPE III |
|-------------------------------------------------|-------------|--------------|---------------|
| Number of floors                                | 8           | 16           | 8             |
| Floor layout                                    | Cellular    | Cellular     | Open          |
| Building footprint (m)                          | 20 × 30     | 20 × 30      | 20 × 30       |
| Gross floor area (m²)                           | 4,800       | 9,600        | 4,800         |
| Floor height (m)                                | 2.8         | 2.8          | 2.8           |
| Number of elevators                             | 2           | 3            | 2             |
| External wall structure                         | 2.5 cm plaster + 9 cm brick + 2.5 cm plaster | 2.5 cm plaster + 13.5 cm brick + 2.5 cm plaster | 2.5 cm plaster + 9 cm brick + 2.5 cm plaster |
| Internal wall structure                         | 2.5 cm plaster + 9 cm brick + 2.5 cm plaster |
| Roof structure                                  | 10 cm concrete + 6 cm air + 0.6 cm fibre cement roof tile |
| Floor structure                                 | Internal: 1.25 cm acoustic ceiling + 10 cm concrete + 0.5 cm carpet | External: 20 cm concrete + 0.5 cm carpet |
| Internal wall area per floor (m²)               | 179.9       | 144.6        | 40.2          |
| Glazing thickness (mm)                          | 6           | 6            | 6             |
| Glazing thermal transmittance (W/(m².K))        | 5.782       | 5.782        | 5.782         |
| Internal loads schedule                         | 0600–1800 hours on weekdays | 0600–1800 hours on weekdays | 0600–1800 hours on weekdays |
| Occupant density (people/100 m²)                | 11          | 11           | 11            |
| Lighting use intensity (W/m²)                   | 10.5        | 10.5         | 10.5          |
| Equipment use density (W/m²)                    | 14          | 14           | 14            |
| Mechanical ventilation: fresh air intake (L/s/person) | 7.5          | 7.5          | 7.5          |

2.2 SAMPLE SELECTION

The parameters were sampled using Latin hypercube sampling (LHS), a method widely used in building energy research (Tian et al. 2018). It uses stratified sampling to ensure that the chosen sample uniformly covers the parameter space (McKay et al. 1979). The components of the different variables are matched at random, making this a quasi-random method. A sample of 1000 building variations was selected out of the 3,732,480 possible combinations. The chosen sample size (1000 iterations) leads to model convergence for GHG emissions of all life-cycle stages, with the approximate relative error at < 5% (see Section 4 in the supplemental data online).
2.3 ENERGY MODELING

Building energy simulations were performed in EnergyPlus 9.2.0 (US Department of Energy 2019). The climate of the chosen Brazilian cities was simulated using weather files with a typical meteorological year (Climate.OneBuilding 2021), based on data collected from weather stations of the National Meteorological Institute of Brazil (INMET) (Roriz 2012). EnergyPlus input files were created with the help of open-source code developed by Santesso (2018). Thermal properties of materials were based on national-specific data (Morishita et al. 2011) and built-in EnergyPlus material datasets (ASHRAE 2005). Heating and cooling systems were modelled as ideal systems that meet the loads but consume no energy. MMV was modelled according to Neves et al. (2019), where the cooling regime is a function of office occupancy, thermal satisfaction of the occupants, and indoor and outdoor temperature. The sensor ‘Zone Thermal Comfort ASHRAE 55 Adaptive Model 90% Acceptability Status’ is used to check if the indoor climate is within comfortable limits. The mechanical cooling (heating, ventilation and air-conditioning—HVAC) system is activated if the

| PARAMETER | POSSIBLE INPUT VALUES | EXPLANATION OF THE CHOSEN VALUES |
|-----------|-----------------------|----------------------------------|
| CITY      | CDH                  | ELECTRICITY MIX (kg CO-eq/kWh)   |
| São Paulo | 14,172               | 0.233                            |
| Rio de Janeiro | 45,016             | 0.233                            |
| Brasilia  | 16,624               | 0.154                            |
| Salvador  | 67,930               | 0.402                            |
| Fortaleza | 71,394               | 0.402                            |
| Belo Horizonte | 23,883         | 0.233                            |
| Manaus    | 82,005               | 0.206                            |
| Curitiba  | 9,397                | 0.143                            |
| Recife    | 63,550               | 0.402                            |
| Goiânia   | 31,081               | 0.154                            |
| Belém     | 81,393               | 0.206                            |
| Porto Alegre | 23,954           | 0.143                            |

Table 2: Parameters and their possible input values.

Note: a City determines the climate and electricity mix. Climate is represented by cooling degree-hours (CDH), measured using a wet-bulb temperature of 15°C (Versage et al. n.d.). Electricity mix scores were sourced from the ecoinvent v3.7.1 database (allocation cut-off), measured using GWP100 metrics, Intergovernmental Panel on Climate Change (IPCC) (2013) method.

b A window opening effective area of 0.0 represents a building with no natural ventilation (fully air-conditioned—AC).

c COP was decreased by 0.5 to account for distribution losses.
zone is occupied and fewer than 90% of occupants are satisfied with the thermal conditions. The natural ventilation mode is activated (i.e. windows are opened) when all three conditions are met: the zone is occupied, the indoor operative temperature is higher than the outdoor temperature, and more than 90% of occupants are satisfied with the thermal conditions. In any other case—e.g. when the zone is unoccupied—the HVAC system is off, and the windows are closed.

2.4 MATERIAL MODELLING

The model included material demand for construction and replacement. The material intensity data are available in Section 3.1 in the supplemental data online. The replacement factor \( r_i \) was determined for each building component \( i \):

\[
\begin{align*}
    r_i &= \frac{BL}{CL_i \cdot m} - 1 \quad \text{if } CL_i = BL \\
    r_i &= 0 \quad \text{otherwise}
\end{align*}
\]

where \( BL \) is the building lifetime; \( CL_i \) is the service life of component \( i \) (see Section 3.2 in the supplemental data online); and \( m \) is the component service life multiplier. When the service life of a component is equal to the building’s lifetime, there are no replacements. The component service life multiplier can be 75%, 100% or 125%, representing faster, typical or slower replacement cycles, respectively.

The energy simulation included aspects aimed at reflecting the material intensity. The focus was on materials that could significantly influence the building’s thermal response, i.e. by being a part of the building envelope or influencing thermal inertia (for the effect of thermal inertia on GHG emissions, see Heeren et al. 2015). Floor covering and acoustic ceiling were modelled as construction layers in the energy simulation. As WWR varied, the material intensity of glass and brick was adjusted (see Table S3 in the supplemental data online). Finally, the simulation included thermal mass in the form of internal walls, calculated based on the amount of brick per 1 m\(^2\) according to NBR 12721 (ABNT 2006), reduced by the amount of brick needed for external walls.

2.5 EMISSION MODELING

GHG emissions were modelled using LCA methodology, according to European Standard EN 15978 (European Standards, 2011). This work covered modules A1–A5 (production and construction process), B4 (replacement), B6 (operational energy use), and C1–C4 (end of life). The system boundary was in line with the boundaries for each considered module, as defined by EN 15978 (for the list of building components, see Table S3 in the supplemental data online). The functional unit was defined as ‘1 m\(^2\) of the gross floor area (GFA) of a building during one year of its operation’. GHG emissions were calculated using GWP100 metrics, as given by the IPCC (2013) method. Life-cycle inventory (LCI) data were sourced from the ecoinvent v3.7.1 database (allocation cut-off) (Weidema et al. 2013), except for the acoustic ceiling for which industry data were used (Knauf A/S 2016). Material emissions were calculated based on material intensity (see Table S3 in the supplemental data online). For the replacement stage, the material intensity was multiplied by the replacement factor (equation 1). The system processes selected for this study are of the market type, so they include transportation (Weidema et al. 2013), thus covering module A4—Transport to the building site. Process requirements for construction and demolition were limited to energy use and machinery wear, as documented in Section 3.3 in the supplemental data online. It is assumed that the material intensities include on-site material losses; the underlying data serve as a tool to estimate construction costs (Sinduscon-MG 2007), which likely include the cost of wasted material. Operating energy use emissions were calculated based on EnergyPlus simulation results (see Section 3.4 in the supplemental data online). It was assumed that all waste is transported by lorry to a waste-processing facility located 11 km from the construction site (Condeixa et al. 2014). For waste processes of the market type, the transportation distance was changed to 11 km. For LCI datasets, see Section 3.5 in the supplemental data online.
2.6 SENSITIVITY ANALYSIS

A multivariate regression analysis was used to quantify the sensitivity of the impact to each parameter. Before the regression analysis, all the variables were standardised according to formulas from Bring (1994):

\[ x_i^* = \frac{x_i - \bar{x}_i}{s_i} \]  
\[ y^* = \frac{y - \bar{y}}{s_y} \]

where \( x_i^* \) and \( y^* \) are standardised variables; \( x_i \) is the value of parameter \( i \); \( y \) is the dependent variable (such as the total life-cycle GHG emissions); \( \bar{x}_i \) and \( \bar{y} \) are the means of each variable in the sample; and \( s_i \) and \( s_y \) are standard deviations. The analysis was based on a standardised version of a linear regression equation (Bring 1994; Hygh et al. 2012):

\[ y^*(x_1, x_2, \ldots, x_{10}) = \sum_{i=1}^{10} B_i x_i^* \]

where \( B_i \) is the standardised regression coefficient (SRC) for parameter \( i \). The bigger the absolute value of coefficient \( B_i \), the more sensitive \( y \) is to the changes in parameter \( i \). Numeric data were used to represent categorial variables. Two variables substituted the variable city: climate represented by CDH, and electricity mix represented by emission intensity (kg CO\(_2\)-eq/kWh). Variable building type was redefined by two binary variables: Archetype II and Archetype III. Each of these binary variables had a value of 1 if a given sample item was of the given building type, and 0 otherwise. Consequently, SRCs for variables Archetype II and Archetype III reflected the change in the dependent variable \( y \) associated with switching the building type from archetype I to archetypes II or III, respectively. The regression analysis calculated 95% confidence intervals (CIs) for the standardised coefficients.

3. RESULTS

The archetype modelling approach was used to estimate life-cycle GHG emissions of office buildings located in Brazil. The median impact was approximately 39 kg CO\(_2\)-eq/m\(^2\) GFA/year, with an interquartile range of 26 (31–57) kg CO\(_2\)-eq/m\(^2\) GFA/year (Table 3). Operational energy use (B6) contributed most to GHG emissions of all simulated buildings, with a median 67% contribution. Consequently, this module was also the main source of variation in the total impact. The median contribution of material production and transport to the construction site (A1–A4) was 15%, corresponding to 448 kg CO\(_2\)-eq/m\(^2\) GFA and with a 95% CI of [363, 500]. Building component replacement (B4) constituted a median of 13% of the total impacts, with emissions of 391 kg CO\(_2\)-eq/m\(^2\) GFA and 95% CI [140, 938]. The emissions of other considered life-cycle modules were negligible.

| GHG EMISSIONS (kg CO\(_2\)-eq/m\(^2\) GFA/year) | A1–A4 | A5 | B4 | B6 | C1 | C2–C4 | TOTAL |
|------------------------------------------------|-------|----|----|----|----|-------|-------|
| Minimum                                        | 3.63  | 0.02| 2.79| 11.87| 0.29| 0.16  | 20.22 |
| 25th percentile                                | 4.86  | 0.04| 3.95| 17.73| 0.39| 0.21  | 30.74 |
| Median                                         | 5.96  | 0.05| 5.18| 26.04| 0.41| 0.25  | 38.61 |
| 75th percentile                                | 7.36  | 0.08| 6.92| 43.79| 0.58| 0.33  | 57.00 |
| Maximum                                        | 10.01 | 0.19| 9.45| 95.77| 0.81| 0.43  | 106.39|

Table 3: Median with quartiles, minimum and maximum greenhouse gas (GHG) emissions by life-cycle module. Some modules were grouped for convenience.

Note: A1 = raw material extraction and processing; 
A2 = transport to the manufacturer; 
A3 = manufacturing; 
A4 = transport to the building site; A5 = installation in the building; B4 = replacement; B6 = operational energy use; C1 = deconstruction, demolition; C2 = transport to waste processing; C3 = waste processing for reuse, recovery and/or recycling; and C4 = disposal.
To better understand the composition of life-cycle GHG emissions, the components of the most impactful modules were investigated (Figure 1). Material production and transport to the site (A1–A4) showed the biggest contribution of steel, concrete, aluminium, lime and plywood, with these five materials responsible for around three-quarters of GHG emissions of this life-cycle stage. Material replacement emissions (B4) were the highest for paint, responsible for median 37% of this module’s GHG emissions. Paint, followed by five other items (AC devices, floor covering, aluminium, doors and ceramic tiles), made up a median of 96% of GHG emissions associated with material replacement. Operational energy use (B6) was composed of medians of 17% cooling, 13% equipment and 17% lighting. In a great majority of cases, emissions from heating were negligible. Cooling was the energy end use causing the most significant variations in GHG emissions. As this module was the most impactful, cooling demand represented the main factor determining the differences in GHG emissions of the buildings. For further details on the composition of the emissions, see the supplemental data online.

How can cooling strategies influence GHG emissions? Addressing this matter required a comparison of the emissions of fully AC and MM buildings (Figure 2). In all cities except Goiânia, buildings with a MM cooling strategy were associated with lower emissions. In some cases, possible emission savings were significant (e.g. Rio de Janeiro, Recife). Goiânia was an exception to this trend, likely due to a sampling error—closer inspection of the results revealed a bias in cooling efficiencies, making the AC buildings relatively less polluting. Nonetheless, MM office buildings seemed to be an effective alternative to buildings relying solely on mechanical cooling, reducing median emissions by 10%.

Figure 1: Greenhouse gas (GHG) emissions by life-cycle modules: (a) material production and transport; (b) material replacement; and (c) operational energy use. Only materials of at least 5% contribution to impacts are included.

Figure 2: Greenhouse gas (GHG) emissions as a function of the city. The buildings are divided into fully air-conditioned (AC) and mixed mode (MM). The cities are ordered according to their cooling degree-hours (CDH).
A multivariate regression analysis was performed for MM and AC buildings (Table 4) to identify the key drivers of life-cycle GHG emissions. The linear models explained > 96% of the variance in total emissions (adjusted $R^2 > 0.96$). The SRCs were lower for AC buildings, and the 95% CI was wider. The electricity mix was the most important parameter, with a strong correlation for both cooling strategies. Climate ranked second in importance for MM buildings and third for AC buildings. Cooling efficiency proved to be another influential factor, its effect being stronger for AC buildings. MM buildings showed a stronger correlation with material-related factors (building lifetime and component service life) due to their lower operational energy use, making material-related emissions relatively more impactful. On the other hand, the impact of AC buildings was more sensitive to parameters closely related to operational energy use (WWR, SHGC, shading). Window-opening effective area ranked fifth for buildings with an MMV system and was an architectural design feature of the greatest importance to their GHG emissions.

| INDEPENDENT VARIABLE | MIXED-MODE BUILDINGS | FULLY AIR-CONDITIONED BUILDINGS |
|-----------------------|----------------------|-------------------------------|
|                       | ADJUSTED $R^2 = 0.966$ | ADJUSTED $R^2 = 0.963$ |
|                       | STANDARDISED COEFFICIENTS | 95% CI | STANDARDISED COEFFICIENTS | 95% CI |
| Electricity mix       | 0.79                  | (0.77, 0.80)                 | 0.79                  | (0.75, 0.82) |
| Climate (CDH)         | 0.23                  | (0.21, 0.25)                 | 0.22                  | (0.19, 0.26) |
| Archetype II (versus Archetype I) | 0.09                  | (0.08, 0.11)                 | 0.06                  | (0.02, 0.10) |
| Archetype III (versus Archetype I) | 0.07                  | (0.06, 0.08)                 | 0.02                  | (-0.02, 0.05) |
| Window-to-wall ratio (WWR) | 0.02                  | (0.00, 0.03)                 | 0.03                  | (0.00, 0.06) |
| Solar heat gain coefficient (SHGC) | 0.06                  | (0.05, 0.07)                 | 0.07                  | (0.04, 0.10) |
| Window opening effective area | -0.09                 | (-0.11, -0.08)               | -                     | -         |
| Shading               | -0.04                 | (-0.05, -0.02)               | -0.05                 | (-0.08, -0.02) |
| Cooling set point     | -0.07                 | (-0.08, -0.05)               | -0.07                 | (-0.10, -0.04) |
| Cooling efficiency    | -0.17                 | (-0.19, -0.16)               | -0.23                 | (-0.26, -0.20) |
| Building lifetime     | -0.08                 | (-0.09, -0.07)               | -0.06                 | (-0.10, -0.03) |
| Component service life multiplier | -0.10                 | (-0.11, -0.08)               | -0.08                 | (-0.11, -0.05) |

The eight-floor archetype with cellular floor layout, denoted as archetype I, turned out to be the least emission intensive—the change to any other building type was associated with an increase in GHG emissions (Table 4). The taller archetype had slightly lower operational energy use, but its emissions were still higher due to higher requirements for materials such as steel, concrete and paint. The archetype with an open floor layout (archetype III) had higher life-cycle emissions than archetype I, mainly due to its higher aluminium demand.

The sensitivity of the total life-cycle GHG emissions shown in Table 4 is mostly determined by module B6 (operational energy use) due to its high importance for overall emissions (Table 3). For the results by the life-cycle stage, Section 5.3 in the supplemental data online.

How does the effectiveness of the MM cooling strategy change under different climatic conditions? To answer, SRCs were calculated for MM buildings in each city. The importance of various parameters changed with increasing CDH. For a few parameters, these changes could be approximated by a linear relationship (Figure 3). Buildings in milder climates (with a low CDH) showed more dependence on building lifetime, showing the major role of material emissions for buildings with small cooling needs. As the climate gets hotter, the need for cooling increases, so the relative importance of the cooling set point and the cooling efficiency also increases. The cooling efficiency gained significance at a much faster rate, suggesting that MM office buildings in hotter climates may share some similarities with AC buildings (cf. Table 4).
4. DISCUSSION

4.1 IMPACTS BY LIFE-CYCLE STAGE

The obtained range of GHG emissions for Brazilian office buildings is in line with values found in the literature for office buildings, generally ranging from just above 20 to over 100 kg CO$_2$-eq/m$^2$/year (Airaksinen & Matilainen 2011; Asdrubali et al. 2013; Frischknecht et al. 2019; Junnila et al. 2006; Kofoworola & Gheewala 2008; Kumanayake et al. 2018; Lessard et al. 2018; Suzuki & Oka 1998; Wallhagen et al. 2011; Ylmén et al. 2019). As expected, operational energy use was the single most important module for GHG emissions, also associated with the biggest variations.

The GHG emissions associated with modules A1–A4 (the material production and transport to the construction site) were generally similar to the values found in previous studies (Airaksinen & Matilainen 2011; Asdrubali et al. 2013; Frischknecht et al. 2019; Junnila et al. 2006; Kofoworola & Gheewala 2008; Kumanayake et al. 2018; Lessard et al. 2018; Ylmén et al. 2019). The only significantly higher values were those of more massive structures, due to either height (Yan et al. 2010) or national regulations for earthquake-resistant structures (Suzuki & Oka 1998). Lower values were observed in cases with wooden walls (Wallhagen et al. 2011), improved material use options (Chau et al. 2015) or different modelling assumptions about the reinforcing steel (Dimoudi & Tompa 2008; Eberhardt et al. 2019). The studies assume different building lifetimes, so their construction impacts were compared considering the entire building lifetime, and not on a per year basis (see Section 1 in the supplemental data online).

This study confirms that the main contributors to GHG emissions of the material production stage are steel and concrete, often followed by brick and limestone (a constituent of cement plaster and cement mortar) (Dimoudi & Tompa 2008; Fenner et al. 2018; Junnila et al. 2006; Kofoworola & Gheewala 2008; Kumanayake et al. 2018; Morales et al. 2019; Seo & Hwang 2001; Ylmén et al. 2019). High levels of aluminium-related GHG emissions associated with window frames or curtain wall systems were also found elsewhere (Meneghelli 2018; Morales et al. 2019; Najjar et al. 2019; Taborianski & Prado 2012). Another hotspot of material production emissions was plywood. Although few whole-building LCA studies consider this material, their results confirm its significant environmental impact (Kyllili et al. 2017; Sinha et al. 2016).

The material replacement emissions were statistically smaller than initial material emissions (a median 48% contribution to embodied emissions). Research shows that material replacement impacts often dominate over initial material impacts in buildings with a lifetime of over 50 years (Cole & Kernan 1996; Ding 2007; Häfliger et al. 2017; Yohanis & Norton 2002), although this is not always the case (Opher et al. 2021; Wiik et al. 2018; Williams et al. 2012). However, frequent fit-outs in office buildings represent a potentially significant contribution to the total impacts (Forsythe & Wilkinson 2015). Therefore, the model may underestimate replacement-related impacts. What may be considered surprising, replacement material emissions were dominated by paint (Figure 1),

![Figure 3: Standardised regression coefficients (SRCs) resulting from a multivariate regression analysis of greenhouse gas (GHG) emissions of mixed-mode (MM) buildings, plotted as a function of cooling degree-hours (CDH). Only parameters with $R^2_{adj} > 0.50$ are shown. Negative values are shown on the y-axis.](image-url)
a material whose contribution to initial emissions was < 5%. However, the importance of paint increases due to the high frequency of replacement, shown also by other researchers (Eberhardt et al. 2019; Morales et al. 2020; Rauf & Crawford 2015).

4.2 SENSITIVITY OF GHG EMISSIONS

The largest variations in GHG emissions could be observed for the operational energy stage (module B6), which is partly a consequence of the parameter choice (see Section 5.3 in the supplemental data online). As shown by the sensitivity analysis (Table 4), the emission intensity of electricity is the key driver for GHG emissions. Climate was the second most important because it influences the amount of cooling needed in the office space.

Cooling efficiency was notably less important for GHG emissions of buildings with MMV (Table 4), which is a consequence of their decreased reliance on the HVAC system. However, the importance of cooling efficiency in MM buildings strongly increased with increasing CDH (Figure 3), suggesting that MM office buildings in hotter climates show increasing dependence on AC cooling. Additional investigation of building energy simulation results confirmed that the HVAC system was more active in MM buildings located in climates with a higher demand for cooling.

MM office buildings were more sensitive to parameters associated with material emissions (building lifetime and component service life multiplier) and less sensitive to those related to operational energy use (WWR, SHGC, shading) (Table 4). This pattern emerges because the MMV buildings generally had lower operational energy use, making material-related emissions relatively more impactful.

According to the sensitivity analysis, the eight-floor archetype with a cellular layout (archetype I) was the least polluting. The eight-floor archetype with an open floor layout (archetype III) showed different performance depending on the cooling strategy—the AC buildings were less emission intensive because the increase of material-related emissions was countered by decreased operational energy use, possibly caused by thermal inertia effects.

The findings of the sensitivity analysis are generally consistent with the literature. The remarkably high importance of electricity mix for life-cycle GHG emissions was shown by others (Blom et al. 2011; Frischknecht et al. 2019; Heeren et al. 2015; Obrecht et al. 2021; Pannier et al. 2018; Rossi et al. 2012). Heeren et al. (2015) reported a relatively small influence of climate on GHG emissions of Swiss buildings, but this discrepancy could be attributed to a smaller range in the analysed climate parameters. Lam & Hui (1996b) also noted the high importance of cooling set point and cooling efficiency for operational energy use in offices. The results confirm that window-opening effective area is the most important parameter influencing the cooling loads of MM office buildings, followed by SHGC, shading and, eventually, WWR (Neves et al. 2019).

4.3 THE BENEFITS OF MM BUILDINGS

MM office buildings offered an average 14% emission reduction compared with fully AC buildings. The potential savings differed among cities, but there was no pattern, possibly due to insufficient sample size and associated sampling errors. MM buildings in hotter climates showed an increasing dependence on AC cooling systems, so the relative benefits of introducing the MMV system seem to be smaller. In milder climates, energy demand for cooling is comparatively lower, so the savings potential is limited. Consequently, the implementation of MM buildings in moderate climates offers the highest energy savings, which had been noted by other researchers as well (Chen et al. 2017; Ward et al. 2012). Switching to MM buildings in cities with a high carbon intensity of electricity could also offer more significant GHG emission savings.

4.4 APPLICABILITY

The findings are mainly applicable to office buildings located in warm and hot climates, ranging from around 10,000 to 80,000 CDH. Applying the results to other regions should be done with caution because the emission intensity of energy carriers and construction materials may substantially differ among countries (Frischknecht et al. 2019), leading to vastly different GHG
emissions even if the building’s lifetime is accounted for (Frischknecht et al. 2020). Despite these differences, the collected data suggest that many regions could benefit from replacing fully AC office buildings with MM ones.

4.5 LIMITATIONS

Non-negligible sampling errors could be observed, e.g. in the case of AC buildings in Goiânia whose emissions were similar to those of MM buildings, but likely underestimated (Figure 2). LHS has the advantage of covering the parameter space uniformly, making it better than conventional sampling methods such as Monte Carlo (Saltelli 2008). However, the chosen sample size (1000 building variations) did not sufficiently cover the parameter space, especially for AC buildings (a subset of 167 buildings). The small sample size was also why AC buildings had a wider range of 95% CI for their standardised coefficients.

The results of the sensitivity analysis (Table 4) were influenced by the chosen range of parameter values (Table 2) because the standardisation of regression coefficients depends directly on standard deviations of parameters. Some parameters had a full span of physically possible values, but others could have had more significance if a wider range were used. For example, component service life ranged from 75% to 125% of the standard values defined in Table S4 in the supplemental data online, but allowing for a broader range could make the component service life multiplier more important. Additionally, a wide range of possible CDHs made climate a more significant parameter.

LCI was not fully adapted to Brazilian reality and included global data for some essential processes, e.g. aluminium production. Material-related impacts could be overestimated, as environmental impacts in the Brazilian context are often smaller than the global average (Frischknecht et al. 2019; Morales et al. 2019, 2020).

Other aspects not included in this work include the thermal comfort of office occupants, indoor air quality, occupant behaviour, design differences between the AC and MM buildings (with the associated material demand differences), and the influence of building shape. Humidity plays a vital role in the natural ventilation potential (Chen et al. 2017), but it was not considered. Some material–energy interactions were not accounted for, e.g. demand for aluminium associated with window size (WWR) or with the existence of shading devices, sometimes made of aluminium. Finally, this study did not include all the constituents of the life-cycle GHG emissions of a building. A simplified system boundary can potentially lead to underestimating emissions by up to 10% (Zhang et al. 2019). Drains, ventilation ducts and fire protection equipment were omitted.

4.6 RECOMMENDATIONS

The efforts to mitigate the climate change impacts of Brazilian office buildings should focus on the carbon intensity of the electricity mix. Although 65% of Brazilian electricity is based on hydropower, the share of natural gas has been steadily growing in the past decades (Ministry of Mines and Energy 2019). Development of wind and solar energy and electricity demand reduction are some actions that could reduce the CO₂ emissions of electricity generation. Close to half of the country’s office space is located in two federal states (São Paulo and Rio de Janeiro) (IBGE 2019). Improvement of the electricity mix in such areas could yield the most considerable benefits for the life-cycle GHG emissions of Brazilian office buildings. Electricity demand could be reduced in office buildings themselves with the use of energy-efficiency strategies. This way, any parameter correlated with operational energy use could potentially be a part of the solution to increasing emissions from electricity generation in Brazil. Additionally, the efficiency of lighting and equipment could be improved, which would have yet another advantage: reduction of cooling needs by lowering internal heat gains. An implicit conclusion is that office buildings can profit greatly from on-site electricity production through photovoltaics because it improves electricity’s carbon intensity.

Among parameters influencing GHG emissions of office buildings, cooling efficiency was the most crucial design parameter. Highly efficient HVAC systems should be prioritised, especially in hotter climates. Decreased frequency of office fit-outs could also significantly decrease the GHG emissions, particularly for materials such as paint. Longer building lifetime is another option.
for a reduction in GHG emissions, given our assumptions that building lifetime does not impact initial material intensities. Building life extension would be relatively more effective in a milder climate. Brazilian policymakers may want to offer incentives for MM office buildings, because they were less emission intensive in every investigated city. The benefits are the biggest for high values of window-opening effective area. Better emission performance of archetype II suggests that reduction of aluminium use could yield additional emission savings, whose exact magnitude depends on modelling assumptions (Meneghelli 2018).

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COMPETING INTERESTS

The authors have no competing interests to declare.

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SUPPLEMENTAL DATA

The two supplemental data for this article can be accessed at:

- File 1: Additional information and results. Review of the literature on greenhouse gas emissions of office buildings (Section 1); Brazilian geography (Section 2); life-cycle inventory (Section 3); model convergence evaluation (Section 4); and additional results (Section 5). DOI: https://doi.org/10.5334/bc.136.s1
- File 2: Parameter values and greenhouse gas (GHG) emissions by sample item; underlying data for figures. DOI: https://doi.org/10.5334/bc.136.s2

REFERENCES

ABNT. (2006). NBR 12721-2006. Avaliação de custos de construção para incorporação imobiliária e outras disposições para condomínios edilícios. Associação Brasileira de Normas Técnicas (ABNT). https://www.abntcatalogo.com.br/norma.aspx?ID=62882

ABNT. (2008). NBR 16401-3. Instalações de ar-condicionado—Sistemas centrais e unitários. Parte 3: Qualidade do ar interior. Associação Brasileira de Normas Técnicas (ABNT). https://www.abntcatalogo.com.br/norma.aspx?ID=572
Matilainen, P., Ng, W. Y., INMETRO, Castell, A., Boer, D., Powell, G., Boer, D., Malkawi, A., Fthenakis, V., Lamberts, R., de Wilde, P., 2018. Assessing the energy saving potential of an existing high-rise office building stock. Energy and Buildings, 143, 100–113. DOI: https://doi.org/10.1016/j.enbuild.2017.03.017

Alves, T., Machado, L., de Souza, R. G., & de Wilde, P. (2017). A methodology for estimating office building energy use baselines by means of land use legislation and reference buildings. Energy and Buildings, 143, 100–113. DOI: https://doi.org/10.1016/j.enbuild.2017.03.017

Alves, T., Machado, L., de Souza, R. G., & de Wilde, P. (2018). Assessing the energy saving potential of an existing high-rise office building stock. Energy and Buildings, 173, 547–561. DOI: https://https://doi.org/10.1016/j.enbuild.2018.05.044

ANVISA. (2003). Resolução-RE Nº 09, de 16 de janeiro de 2003. Agência Nacional de Vigilância Sanitária (ANVISA). https://www.saude.mg.gov.br/index.php?option=com_gmg&controller=document&id=899

Arnold, D. (1996). Mixed-mode HVAC—An alternative philosophy. ASHRAE Transactions: Symposia, article CONF-960254. Winter meeting of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). https://www.osti.gov/biblio/392497-mixed-mode-hvac-alternative-philosophy

Asdrubali, F., Baldassarri, C., & Fthenakis, V. (2013). Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. Energy and Buildings, 64, 73–89. DOI: https://doi.org/10.1016/j.enbuild.2013.04.018

ASHRAE. (2005). 2005 ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

Blom, I., Itard, L., & Meijer, A. (2011). Environmental impact of building-related and user-related energy consumption in dwellings. Building and Environment, 46(8), 1657–1669. DOI: https://doi.org/10.1016/j.buildenv.2011.02.002

Borgstein, E. H., & Lamberts, R. (2014). Developing energy consumption benchmarks for buildings: Bank branches in Brazil. Energy and Buildings, 82, 82–91. DOI: https://doi.org/10.1016/j.enbuild.2014.07.028

Bring, J. (1994). How to standardize regression coefficients. American Statistician, 48(3), 209–213. DOI: https://https://doi.org/10.2307/2684719

Cabeza, L. F., Rincón, L., Vilarinho, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews, 29, 394–416. DOI: https://doi.org/10.1016/j.rser.2013.08.037

Carvalho, M. M. Q., La Rovere, E. L., & Gonçalves, A. C. M. (2010). Analysis of variables that influence electric energy consumption in commercial buildings in Brazil. Renewable and Sustainable Energy Reviews, 14(9), 3199–3205. DOI: https://doi.org/10.1016/j.rser.2010.07.009

CB3E, Eletrobras, PROCEL, & INMETRO. (2015). Catálogo de propriedades térmicas e óticas de vidros comercializados no Brasil. Universidade Federal de Santa Catarina. https://cb3e.ufsc.br/sites/default/files/projetos/etiquetagem/catalogo-propriedades-vidros-comercializados-brasil-13032015_v2.pdf

Chau, C. K., Hui, W. K., Ng, W. Y., & Powell, G. (2012). Assessment of CO₂ emissions reduction in high-rise concrete office buildings using different material use options. Resources, Conservation and Recycling, 61, 22–34. DOI: https://https://doi.org/10.1016/j.resconrec.2012.01.001

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy, 143, 395–413. DOI: https://doi.org/10.1016/j.apenergy.2015.01.023

Chen, Y., Tong, Z., & Malkawi, A. (2017). Investigating natural ventilation potentials across the globe: Regional and climatic variations. Building and Environment, 122, 386–396. DOI: https://doi.org/10.1016/j.buildenv.2017.06.026

CIBSE. (2004). Guide F—Energy Efficiency in Buildings. Chartered Institute of Building Services Engineers (CIBSE). https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000Hy6hcQAB

Climate.OneBuilding. (2021). Climate.OneBuilding.Org. http://climate.onebuilding.org/

Cole, R. J., & Kernan, P. C. (1996). Life-cycle energy use in office buildings. Building and Environment, 31(4), 307–317. DOI: https://https://doi.org/10.1016/0360-1323(96)00017-0

Condeixa, K., Haddad, A., & Boer, D. (2014). Life cycle impact assessment of masonry system as inner walls: A case study in Brazil. Construction and Building Materials, 70, 141–147. DOI: https://doi.org/10.1016/j.conbuildmat.2014.07.113

Condeixa, K., Haddad, A., & Boer, D. (2017). Material flow analysis of the residential building stock at the city of Rio de Janeiro. Journal of Cleaner Production, 149, 1249–1267. DOI: https://doi.org/10.1016/j.jclepro.2017.02.080

Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. Journal of Cleaner Production, 245, 118658. DOI: https://https://doi.org/10.1016/j.jclepro.2019.118658

Krych et al. Buildings and Cities DOI: 10.5334/bc.136
Dimoudi, A., & Tompa, C. (2008). Energy and environmental indicators related to construction of office buildings. Resources, Conservation and Recycling, 53(1), 86–95. DOI: https://doi.org/10.1016/j.resconrec.2008.09.008

Ding, G. K. C. (2007). Life cycle energy assessment of Australian secondary schools. Building Research & Information, 35(5), 487–500. DOI: https://doi.org/10.1080/0961321060116408

Eberhardt, L. C. M., Birgisdottir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. Building Research & Information, 47(6), 666–680. DOI: https://doi.org/10.1080/09613218.2018.1517458

EIA. (2012). Commercial Buildings Energy Consumption Survey (CBECS). US Department of Energy, Energy Information Administration (EIA).

European Standards. (2011). EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method (Pub. L. No. EN 15978, 2011). European Standards. https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

Evangelista, P. P. A., Kiperstok, A., Torres, E. A., & Gonçalves, J. P. (2018). Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA). Construction and Building Materials, 169, 748–761. DOI: https://doi.org/10.1016/j.conbuildmat.2018.02.045

Fenner, A. E., Kibert, C. J., Woo, J., Morque, S., Razkenari, M., Hakim, H., & Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. Renewable and Sustainable Energy Reviews, 94, 1142–1152. DOI: https://doi.org/10.1016/j.rser.2018.07.012

Forsythe, P., & Wilkinson, S. (2015). Measuring office fit-out changes to determine recurring embodied energy in building life cycle assessment. Facilities. DOI: https://doi.org/10.1108/F-08-2013-0065

Frischknecht, R., Birgisdottir, H., Choe, C.-U., Lützkendorf, T., Passer, A., Alsema, E., Balouktsi, M., Berg, B., Dowdell, D., Martínez, A. G., Habert, G., Hollberg, A., König, H., Lasvaux, S., Llatas, C., Rasmussen, F. N., Peupotier, B., Ramseier, L., Röck, M., ... Yang, W. (2019). Comparison of the environmental assessment of an identical office building with national methods. IOP Conference Series: Earth and Environmental Science, 323, 012037. DOI: https://doi.org/10.1088/1755-1315/323/1/012037

Frischknecht, R., Ramseier, L., Yang, W., Birgisdottir, H., Choe, C. U., Lützkendorf, T., Passer, A., Balouktsi, M., Berg, B., Bragança, L., Butler, J., Cellura, M., Dixit, M., Dowdell, D., Francart, N., Martínez, A. G., Gomes, V., Silva, M. G. D., Guimaraes, G., ... Zara, O. (2020). Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches—IEA EBC Annex 72. IOP Conference Series: Earth and Environmental Science, 588, 022029. DOI: https://doi.org/10.1088/1755-1315/588/2/022029

Gokarakonda, S., van Treeck, C., & Rawal, R. (2019). Influence of building design and control parameters on the potential of mixed-mode buildings in India. Building and Environment, 148, 157–172. DOI: https://doi.org/10.1016/j.buildenv.2018.10.043

Gomes, V., Saade, M., Lima, B., & Silva, M. (2018). Exploring lifecycle energy and greenhouse gas emissions of a case study with ambitious energy compensation goals in a cooling-dominated climate. Energy and Buildings, 173, 302–314. DOI: https://doi.org/10.1016/j.enbuild.2018.04.063

Häfliger, I.-F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M. R. M., & Habert, G. (2017). Buildings environmental impacts’ sensitivity related to LCA modelling choices of construction materials. Journal of Cleaner Production, 156, 805–816. DOI: https://doi.org/10.1016/j.jclepro.2017.04.052

Heeren, N., & Hellweg, S. (2019). Tracking construction material over space and time: Prospective and georeferenced modeling of building stocks and construction material flows. Journal of Industrial Ecology, 23(1), 253–267. DOI: https://doi.org/10.1111/jiec.12739

Heeren, N., Jakob, M., Martius, G., Gross, N., & Wallbaum, H. (2013). A component based bottom-up building stock model for comprehensive environmental impact assessment and target control. Renewable and Sustainable Energy Reviews, 20, 45–56. DOI: https://doi.org/10.1016/j.rser.2012.11.064

Heeren, N., Mutel, C. L., Steubing, B., Ostermeyer, Y., Wallbaum, H., & Hellweg, S. (2015). Environmental impact of buildings—What matters? Environmental Science & Technology, 49(16), 9832–9841. DOI: https://doi.org/10.1021/acs.est.5b01735

Heiselberg, P., Brohus, H., Hesselholt, A., Rasmussen, H., Seinre, E., & Thomas, S. (2009). Application of sensitivity analysis in design of sustainable buildings. Renewable Energy, 34(9), 2030–2036. DOI: https://doi.org/10.1016/j.renene.2009.02.016

Hoxha, E., Habert, G., Chevalier, J., Bazzana, M., & Le Roy, R. (2014). Method to analyse the contribution of material’s sensitivity in buildings’ environmental impact. Journal of Cleaner Production, 66, 54–64. DOI: https://doi.org/10.1016/j.jclepro.2013.10.056

Hygh, J. S., DeCarolis, J. F., Hill, D. B., & Ranji Ranjithan, S. (2012). Multivariate regression as an energy assessment tool in early building design. Building and Environment, 57, 165–175. DOI: https://doi.org/10.1016/j.buildenv.2012.04.021
Morishita, C., Sorgato, M. J., Versage, R., Triana, M. A., Marinossi, D. L., & Lamberts, R. (2011). Catálogo de propriedades térmicas de paredes e coberturas. Laboratório de Eficiência Energética em Edificações (LABEEE). https://www.academia.edu/14978441/Cat%C3%A9logo_de_propriedades_t%C3%A9rmicas_de_paredes_e_coberturas

Najjar, M. K., Figueiredo, K., Evangelista, A. C. J., Hammad, A. W. A., Tam, V. W. Y., & Haddad, A. (2019). Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. International Journal of Construction Management. DOI: https://doi.org/10.1080/15623599.2019.1637098

Neves, L. O., Melo, A. P., & Rodrigues, L. L. (2019). Energy performance of mixed-mode office buildings: Assessing typical construction design practices. Journal of Cleaner Production, 234, 451–466. DOI: https://doi.org/10.1016/j.jclepro.2019.06.216

Obrecht, T. P., Jordan, S., Legat, A., & Passer, A. (2021). The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures. International Journal of Life Cycle Assessment, 26(5), 839–851. DOI: https://doi.org/10.1007/s11367-021-01920-2

Opher, T., Duhamel, M., Posen, I. D., Panesar, D. K., Brugmann, R., Roy, A., Zizzo, R., Sequeira, L., Anvari, A., & MacLean, H. L. (2021). Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada. Journal of Cleaner Production, 279, 123819. DOI: https://doi.org/10.1016/j.jclepro.2020.123819

Pandey, D., Agrawal, M., & Pandey, J. S. (2011). Carbon footprint: Current methods of estimation. Environmental Monitoring and Assessment, 178(1–4), 135–160. DOI: https://doi.org/10.1007/s10661-010-1678-y

Pannier, M.-L., Schalbart, P., & Peuportier, B. (2018). Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment. Journal of Cleaner Production, 199, 466–480. DOI: https://doi.org/10.1016/j.jclepro.2018.07.070

Paulsen, J. S., & Sposto, R. M. (2013). A life cycle energy analysis of social housing in Brazil: Case study for the program ‘MY HOUSE MY LIFE’. Energy and Buildings, 57, 95–102. DOI: https://doi.org/10.1016/j.enbuild.2012.11.016

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. Energy and Buildings, 40(3), 394–398. DOI: https://doi.org/10.1016/j.enbuild.2007.03.007

PINI. (2010). TCPO: Tabelas de Composições de Preços para Orçamentos (13th ed.). PINI.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings, 42(10), 1592–1600. DOI: https://doi.org/10.1016/j.enbuild.2010.05.007

Rauf, A., & Crawford, R. H. (2015). Building service life and its effect on the life cycle embodied energy of buildings. Energy, 79, 140–148. DOI: https://doi.org/10.1016/j.energy.2014.10.093

Roriz, M. (2012). Arquivos Climáticos de Municípios Brasileiros. Associação Nacional de Tecnologia do Ambiente Construído. https://labeee.ufsc.br/downloads/arquivos-climaticos/formato-epw

Rossi, B., Marique, A.-F., & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, case study. Building and Environment, 51, 402–407. DOI: https://doi.org/10.1016/j.buildenv.2011.11.002

Ruuska, A. P., & Häkkinnen, T. M. (2015). The significance of various factors for GHG emissions of buildings. International Journal of Sustainable Engineering, 8(4–5), 317–330. DOI: https://doi.org/10.1080/19397038.2014.934931

Salcido, J. C., Raheem, A. A., & Issa, R. R. A. (2016). From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review. Energy and Buildings, 127, 1008–1018. DOI: https://doi.org/10.1016/j.enbuild.2016.06.054

Saltelli, A. (Ed.). (2008). Global sensitivity analysis: The primer. Wiley. DOI: https://doi.org/10.1002/9780470725184

Santesso, C. A. (2018). ParIDF: Python open source code developed to perform parametric simulations through EnergyPlus Building Energy Simulation (BES) software (Source code). Universidade de São Paulo. https://www.iau.usp.br/laboratorios/lca/index.php/trabalhos-conforto/

Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy and Buildings, 39(3), 249–257. DOI: https://doi.org/10.1016/j.enbuild.2006.07.001

Seo, S., & Hwang, Y. (2001). Estimation of CO₂ emissions in life cycle of residential buildings. Journal of Construction Engineering and Management, 127(5), 414–418. DOI: https://doi.org/10.1061/(ASCE)0733-9364(2001)127:5(414)
Sinduscon-MG. (2007). Costo unitário básico (CUB/m²): Principais aspectos. Sinduscon-MG. http://www.cub.org.br/cartilha-cub-m2

Sinha, R., Lennartsson, M., & Frostell, B. (2016). Environmental footprint assessment of building structures: A comparative study. Building and Environment, 104, 162–171. DOI: https://doi.org/10.1016/j.buildenv.2016.05.012

Suzuki, M., & Oka, T. (1998). Estimation of life cycle energy consumption and CO₂ emission of office buildings in Japan. Energy and Buildings, 28(1), 33–41. DOI: https://doi.org/10.1016/S0378-7788(98)00010-3

Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 13(8), 1819–1835. DOI: https://doi.org/10.1016/j.rser.2008.09.033

Taborianski, V. M., & Prado, R. T. A. (2012). Methodology of CO₂ emission evaluation in the life cycle of office building façades. Environmental Impact Assessment Review, 33(1), 41–47. DOI: https://doi.org/10.1016/j.eiarc.2011.10.004

Tian, W., Heo, Y., de Wilde, P., Li, Z., Yan, D., Park, C. S., Feng, X., & Augenbroe, G. (2018). A review of uncertainty analysis in building energy assessment. Renewable and Sustainable Energy Reviews, 93, 285–301. DOI: https://doi.org/10.1016/j.rser.2018.05.029

UN. (2021). GVA by kind of economic activity. National accounts. UNData. http://data.un.org/

US Department of Energy. (2019). EnergyPlus version 9.2.0 documentation. Engineering reference. US Department of Energy. https://bigladdersoftware.com/epx/docs/9-2/engineering-reference/

Versage, R., Borgstein, E., & Lamberts, R. (n.d.). Grau-horas de resfriamento GHR. Conselho Brasileiro de Construção Sustentável (CBCS). http://cbcs2.hospedagemdesites.ws/_5dotSystem/userFiles/CTEnergia-benchmark/CBCS_GHrs_v1%20(1).pdf

Wallhagen, M., Glaumann, M., & Malmqvist, T. (2011). Basic building life cycle calculations to decrease contribution to climate change—Case study on an office building in Sweden. Building and Environment, 46(10), 1863–1871. DOI: https://doi.org/10.1016/j.buildenv.2011.02.003

Wang, J., Yu, C., & Pan, W. (2018). Life cycle energy of high-rise office buildings in Hong Kong. Energy and Buildings, 167, 152–164. DOI: https://doi.org/10.1016/j.enbuild.2018.02.038

Ward, J. K., Wall, J., & Perfumo, C. (2012). Environmentally active buildings: The controls challenge. Architectural Science Review, 55(1), 26–34. DOI: https://doi.org/10.1080/00038628.2011.641735

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., & Wernet, G. (2013). Overview and methodology. Data quality guideline for the ecoinvent database version 3 (Ecoinvent Report No. 1 (v3)). The ecoinvent Centre. https://lca-net.com/publications/show/overview-methodology-data-quality-guideline-ecoinvent-database-version-3/

Wilk, M. K., Fufa, S. M., Kristjandsdottir, T., & Andresen, I. (2018). Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre. Energy and Buildings, 165, 25–34. DOI: https://doi.org/10.1016/j.enbuild.2018.01.025

Williams, D., Elgholi, L., Wheeler, R., & France, C. (2012). Climate change influence on building lifecycle greenhouse gas emissions: Case study of a UK mixed-use development. Energy and Buildings, 48, 112–126. DOI: https://doi.org/10.1016/j.enbuild.2012.01.016

Wong, I. L., Krüger, E., Loper, A. C. M., & Mori, F. K. (2019). Classification and energy analysis of bank building stock: A case study in Curitiba, Brazil. Journal of Building Engineering, 23, 259–269. DOI: https://doi.org/10.1016/j.jobe.2019.02.003

Yan, H., Shen, Q., Fan, L. C. H., Wang, Y., & Zhang, L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. Building and Environment, 45(4), 949–955. DOI: https://doi.org/10.1016/j.buildenv.2009.09.014

Ylmén, P., Peñaloza, D., & Mjörnell, K. (2019). Life cycle assessment of an office building based on site-specific data. Energies, 12(13), 2588. DOI: https://doi.org/10.3390/en12132588

Yohanis, Y. G., & Norton, B. (2002). Life-cycle operational and embodied energy for a generic single-storey office building in the UK. Energy, 27(1), 77–92. DOI: https://doi.org/10.1016/S0360-5442(01)00061-5

Zhang, X., Zheng, R., & Wang, F. (2019). Uncertainty in the life cycle assessment of building emissions: A comparative case study of stochastic approaches. Building and Environment, 147, 121–131. DOI: https://doi.org/10.1016/j.buildenv.2018.10.016

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