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

RESEARCH

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KAMILA KRYCH
NIKO HEEREN
EDGAR G. HERTWICH

**Author affiliations can be found in the back matter of this article*

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 CO_2-eq/m^2 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.

CORRESPONDING AUTHOR:
Kamila Krych
Department of Energy and Process Engineering, Norwegian University of Science and Technology, Gløshaugen, Trondheim, Norway
kamila.krych@ntnu.no

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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; Kumanayake *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; Seo & 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) (Wong *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 & Sposto 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 m^2 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).

	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 (m^2)	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 (m^2)	179.9	144.6	40.2
Glazing thickness (mm)	6	6	6
Glazing thermal transmittance ($W/(m^2.K)$)	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 m^2)	11	11	11
Lighting use intensity (W/m^2)	10.5	10.5	10.5
Equipment use density (W/m^2)	14	14	14
Mechanical ventilation: fresh air intake (L/s/person)	7.5	7.5	7.5

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

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.

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).

PARAMETER	POSSIBLE INPUT VALUES			EXPLANATION OF THE CHOSEN VALUES
	CITY	CDH	ELECTRICITY MIX (kg CO-eq/kWh)	
City[a]	São Paulo	14,172	0.233	The 12 largest cities with at least two in each region of Brazil (for a map with the selected cities, see Section 2 in the supplemental data online)
	Rio de Janeiro	45,016	0.233	
	Brasília	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	
Building archetype	I, II, III			Archetypes defined in NBR 12721 (ABNT 2006)
Window-to-wall ratio (WWR)	30%, 50%, 70%, 90%			Full range of possible values
Solar heat gain coefficient (SHGC)	0.2, 0.4, 0.6, 0.8			Full range of possible values
Window opening effective area	0.0[b], 0.1, 0.3, 0.5, 0.7, 0.9			Full range of possible values
Shading	0.0, 0.2, 0.4, 0.6, 0.8, 1.0			Full range of possible values
Cooling set point (°C)	22, 23, 24, 25			Based on Lamberts *et al.* (2015)
Coefficient of performance (COP)[c]	2.0, 2.5, 3.0, 3.5, 4.0			Based on Inmetro (2017) and Lamberts *et al.* (2015)
Building lifetime (years)	50, 75, 100			Recommended minimum of 50 years (ABNT 2013), but 100 years is assumed as a maximum for a concrete structure
Component service time multiplier	75%, 100%, 125%			Assumed based on the literature (see Section 3.2 in the supplemental data online)

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.

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 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:

$$\begin{cases} r_i = \dfrac{BL}{CL_i \cdot m} - 1 & \text{if } CL_i \neq BL \\ r_i = 0 & \text{otherwise} \end{cases} \tag{1}$$

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):

$$x_i^* = \frac{x_i - \overline{x}_i}{s_i} \tag{2}$$

$$y^* = \frac{y - \overline{y}}{s_y} \tag{3}$$

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); $\overline{x}_i$ and $\overline{y}$ 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):

$$y^*\left(x_1, x_2, \ldots, x_{10}\right) = \sum_{i=1}^{10} B_i x_i^* \tag{4}$$

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 categorical 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.

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.

	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

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.

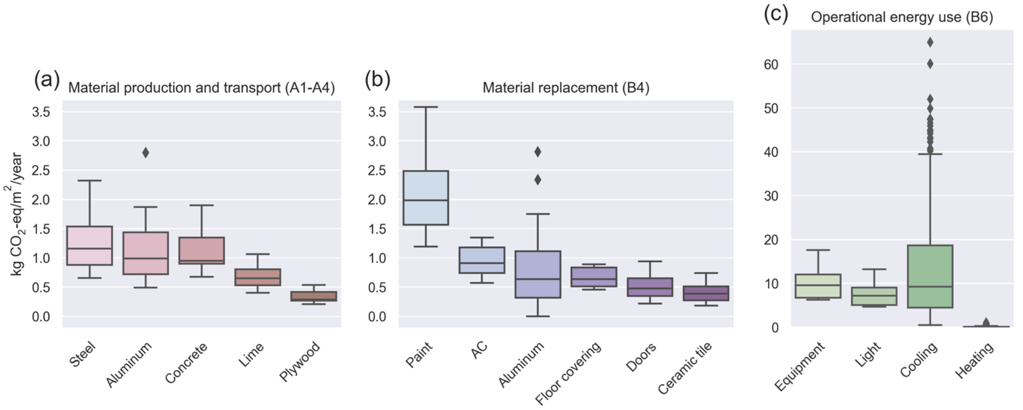

Figure 1: Greenhouse gas (GHG) emissions by life-cycle modules: **(a)** material production and transport; **(b)** material replacement; and **(c)** operational energy use. Only materials of at least 5% contribution to impacts are included.

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%.

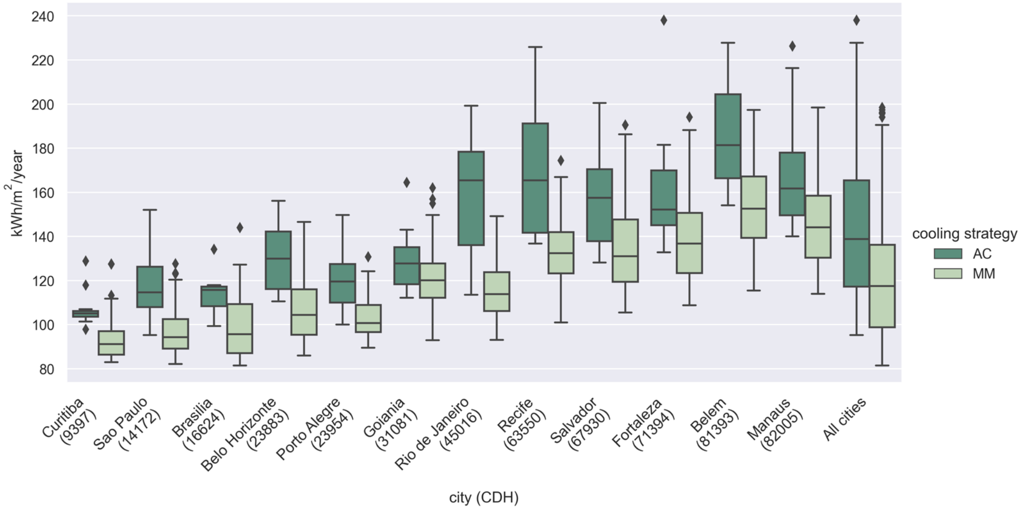

Figure 2: Greenhouse gas (GHG) emissions as a function of the city. The buildings are divided into fully air-conditioned (AC) and mixed mode (MM). The cities are ordered according to their cooling degree-hours (CDH).

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.

Table 4: Results of the multivariate regression analysis of GHG emissions by cooling strategy.

Note: CDH = cooling degree-hours; and CI = confidence interval.

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**).

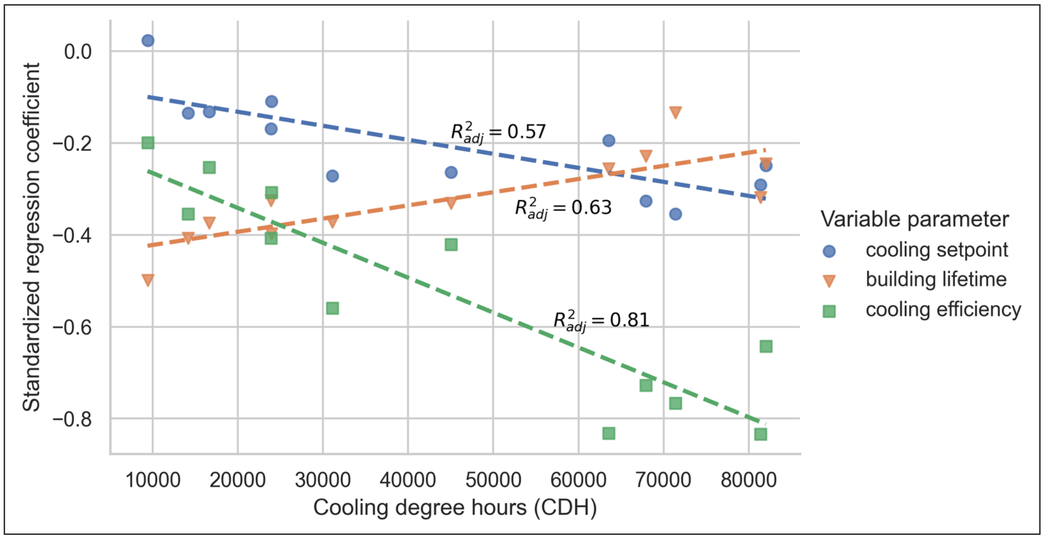

Figure 3: Standardised regression coefficients (SRCs) resulting from a multivariate regression analysis of greenhouse gas (GHG) emissions of mixed-mode (MM) buildings, plotted as a function of cooling degree-hours (CDH). Only parameters with $R^2_{\text{adj}} > 0.50$ are shown. Negative values are shown on the *y*-axis.

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 (Kylili *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***), 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 CO_2 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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AUTHOR AFFILIATIONS

Kamila Krych *orcid.org/0000-0003-4886-1814*
Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
Niko Heeren *orcid.org/0000-0003-4967-6557*
Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
Edgar G. Hertwich *orcid.org/0000-0002-4934-3421*
Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

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*

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