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Sensitivity analysis of parameters influencing the carbon footprint of Brazilian office buildings

Master's thesis in Industrial Ecology

Supervisor: Edgar Hertwich

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Abstract

Energy and material use associated with buildings causes significant environmental impacts which need to be urgently reduced, especially in emerging economies such as Brazil, whose building stock is expected to significantly grow in the following years. Office buildings are typically characterized by higher energy use than residential buildings, yet they have a relatively poor coverage in the research. So far, there has been no comprehensive assessment of the possible range of climate change impacts caused by Brazilian office buildings.

Therefore, the purpose of this study was to investigate the carbon footprint of Brazilian office buildings. Building archetype definition served as a basis for the model, which included 10 variable parameters. To fully explore the possible combinations of these parameters' values, Latin hypercube sampling was performed. The selected buildings were simulated in building energy software in order to estimate their energy performance. The building model that was used during energy simulations was integrated with material composition data to properly reflect energy-material interactions. Further, a life cycle assessment (LCA) study enabled to estimate GWP100 impacts of the sampled buildings. The analysis included the building life cycle stages associated with material production and transport (A1-A4), construction (A5), replacement (B4), operational energy use (B6) and end-of-life stage (C).

The results of the model have shown variations in the total GWP values from 20 to 108 kg CO_2-eq/m^2/year, with the biggest contribution from operational energy use phase. The GWP impacts are also influenced by emissions associated with initial and recurrent material demand, both dominated by aluminum. There was also a significant contribution of paint to the replacement emissions.

The most important parameters for GWP impacts were found to be electricity mix, climate, cooling efficiency and window effective opening area (for mixed-mode buildings). Based on these results, recommendations for mitigation strategies are given.

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List of Abbreviations

AC	Air conditioning
CDH	Cooling degree hours
CL-8	Office building archetype with 8 floors and a cellular layout
CL-16	Office building archetype with 16 floors and a cellular layout
COP	Coefficient of performance
GHG	Greenhouse gas
GWP	Global warming potential
EUI	Energy use intensity
HVAC	Heating, ventilation, and air conditioning
LCA	Life cycle assessment
LCI	Life cycle inventory
LHS	Latin hypercube sampling
MM	Mixed-mode (ventilation or building)
OPL-8	Office building archetype with 8 floors and an open plan layout
NBR	Brazilian Regulatory Standard
SGHC	Solar heat gain coefficient
WWR	Window-to-wall ratio

1 Introduction

1.1 Context

Buildings are an indispensable part of human society, ensuring protection from the outside world and allowing for comfort despite varying weather conditions. At the same time, satifying these needs is associated with flows of materials and energy throughout life cycle stages of a building: construction, operation and demolition. In this system of close interdependencies, flows of material at the construction stage determine the magnitude of future material flows needed to maintain the building, and energy flows needed to provide services to its inhabitants during the operational phase. At the end of the building lifetime, materials are dismantled and disposed of as waste or sent off for recycling. During all of these life cycle stages, greenhouse gas (GHG) emissions are emitted, contributing to climate change impacts.

Buildings are responsible for a significant part of global GHG emissions, both through direct emissions (occurring directly in this sector) and indirect emissions occurring in other sectors due to demand arising from building-related activity. Considering the energy sector, as much as half of global electricity consumption could be attributed to buildings. (IPCC, 2015) Demand from the industry sector includes construction materials such as cement and steel, which are particularly crucial as these materials are emission-intensive. These emissions are inherent to the chemical production processes so they cannot be addressed merely by measures such as energy efficiency or decarbonization of the energy sector. (Material Economics, 2018) Buildings are therefore one of the biggest contributors to anthropogenic climate change but, at the same time, can be seen as the key to mitigation strategies.

Developing countries should be the focus of mitigation strategies in the construction sector, as their floor area is expected to more than double within the next 40 years. (IEA, 2017) The ongoing accumulation of building and infrastructure stock in these countries is associated with significant material emissions. (Müller et al., 2013) Long lifetime of such structures means that potentially inefficient designs create carbon-intensive emission pathways that last for years, which is known as the lock-in effect. (Seto et al., 2016)

Many energy efficiency opportunities in buildings are cost-saving, and additionally, emerging economies could also profit through non-monetary gains such as energy security, reduced pollution, and improved productivity. Delaying the action by another 10 years would lead to significant amounts of additional CO_2 emissions from unnecessary energy demand, associated also with significant additional financial costs. (IEA, 2019a)

Reduction of material use in buildings, besides emission savings, offers co-benefits related to decreased mining activity which often destroys natural ecosystems and impacts livelihoods of local people, such as in case of mining-induced deforestation (Sonter et al., 2017) or illegal sand mining in rivers (Bendixen et al., 2019).

As can be seen, there is an urgent need to develop strategies for creating efficient building stock. These strategies should identify the most beneficial opportunities from the life cycle perspective, which requires in-depth understanding of the existing stock and construction practices. In many developed countries, this need had been identified and have given rise to projects such as TABULA – a European project intended to characterize the residential stock of chosen countries by means of differentiation into building types of various energy standards and energy needs. (Institut Wohnen und Umwelt GmbH, 2017) In developing countries, data availability issues create a challenge for the building stock research, making it difficult to assess possible emission savings and to implement the most efficient designs. This shows the importance of further efforts aimed at improving the understanding of the building stock in emerging economies. However, the stock characterization is faciliated if the scope is restricted to a given building type and a given country.

1.2 Scope restriction: office buildings in Brazil

Building types can be divided into two main categories: residential and non-residential. Non-residential construction is more difficult to address as it is less homogenous, with buildings providing various end-uses and thus possessing different characteristics of material and energy use. Non-residential buildings are often divided into commercial and public services sectors. Offices are the most important group of commercial buildings in developed countries, for example in the U.S. they account for around half of the total number of commercial buildings and half of the total commercial floorspace. (U.S. EIA, 2015) They are also one of the two fastest growing commercial building stock types, the other one being warehouses. (U.S. EIA, 2015) If such trends can be observed in developed countries such as the U.S., the current and expected future increase in office floorspace is likely even more pronounced in emerging economies, where economic growth is often associated with increasing importance of the services sector. Previous studies have shown that office floorspace per capita generally increases with the growth in services value added per capita. (Deetman et al., 2020) Office building stock can be of high energy intensity, especially in places where warm climate in conjuction with internal heat load characteristics of offices create the need for mechanical cooling systems. As it has been pointed out by other authors, there is inferior coverage of non-residential construction in building research. (Deetman et al., 2020; Maslesa et al., 2018) Office buildings, being such a distinct group of non-residential buildings, are therefore an important research area to focus on.

The spatial scope can be restricted to Brazil. It is the third most populous country among major emerging national economies, known as BRICS (Brazil, Russia, India, China, and South Africa). China and India, the two most populous of the BRICS countries, have received relatively more attention in building stock research compared to Brazil, which can be verified by a few simple web search queries using a search engine such as Google Scholar. Brazilian commercial floor space is expected to increase by about 60% between 2000 and 2050. (ICCA, 2012) Together with other developing countries, it forms the key drivers of increasing global demand for materials, such as steel and cement. (IEA, 2019b) Therefore, a valuable contribution can be made by addressing any existent gaps in the current state of Brazilian building stock research.

1.3 Aim of the study

There has been a number of studies concerning office buildings in Brazil, but research investigating their environmental impact is scarce. In particular, the importance of factors influencing the greenhouse gas emissions is not fully understood.

The purpose of this work is therefore to provide an empirical characterization of office buildings, their composition, construction, and energy use. Further, the modeling work should assess the implementation of improvement options, including through improved design. The assessment should take into account the life cycle GHG emissions. A good documentation of empirical observations, modeling assumptions, modeling methods, code and data are required.

This work intends to answer the following questions:

1. What is the possible range of the carbon footprint values for Brazilian office buildings?
2. Which parameters have the most impact on the carbon footprint?
3. What can be done to improve the emission performance of the current office building stock in Brazil?

The study will focus on selected parameters and their influence on the carbon footprint, understood as the total GHG emissions caused by the building during its whole life cycle, from cradle to grave. The selected parameters will be chosen based on available literature. The parameter space will be explored using appropriate sampling methods and the carbon footprint values will be calculated based on life cycle assessment methodology, using GWP100 as metrics.

This research contributes to the current state of knowledge by quantifying the likely range of GHG emissions of Brazilian office buildings and identifying features that have the biggest influence on the emissions from the life cycle perspective. It intends to lay the groundwork for possible future studies on Brazilian office building stock, allowing for scenario modeling, and assisting in deployment of low-emission pathways.

1.4 Thesis overview

The thesis is organized into 6 chapters, including this one, which presented the problem and its context, stated research questions and defined the scope of work.

The following, Chapter 2, provides more detail to the context of the study by describing the current issues related to Brazilian office building stock and the current state of knowledge. The available literature is used to specify which parameters are likely to have a significant contribution to carbon footprint of the buildings.

Chapter 3 explains the methods used to define the office building archetypes, calculate their energy performance and quantify GHG emissions. The chapter includes a description of the sample selection and sensitivity analysis methods.

Chapter 4 presents results of the model, showing the importance of variable parameters on carbon footprint values.

Chapter 5 includes a discussion of the results, particularly comparing them to existent literature on the subject of energy and emission performance research. Limitations of the study are acknowledged at this point.

Chapter 6 concludes the whole work.

2 Background

This chapter intends to put the research goals in a wider context. At first, the background necessary to understand the Brazilian reality is explained: demography, climate, energy sector, construction sector, and environmental issues. Further, Brazilian office buildings are characterized in terms of energy, materials, and emissions, based on available literature. Finally, research on sensitivity analysis in buildings is introduced in order to show the current state of knowledge on parameters influencing energy and emission performance of office buildings.

2.1 Brazilian context

Brazil's population was estimated at around 211 million in 2019, with projections of 229 million in 2050. (The World Bank, 2019) Figure 1 shows the five main regions of Brazil and the twelve most populous cities according to the Brazilian Institute of Geography (IBGE). (IBGE, 2011) The map also shows the division to 27 states – each of the 12 cities is the biggest city in its own state. (IBGE, 2011)

Most of the population resides in the south and south-east of the country. According to IBGE, among all the Brazilian states, just 4 neighboring ones in the south and south-east of the country concentrate half of the working population (São Paulo, Minas Gerais, Rio de Janeiro, and Paraná). (IBGE, 2019a)

Figure 1 Five regions of Brazil with the twelve most populous cities. Adapted from work by Felipe Menegaz, used under CC-BY-SA 3.0.

According to the Köppen classification, the Brazilian climate types range significantly: a very humid rainforest climate in the Amazon region in the northwest, savanna in the center-west, dry semi-arid climate in the northeast, humid subtropical climate in the south. The most populated regions are the ones with humid subtropical climate in the south-east. These climatic conditions create a predominant need for cooling, while heating is mainly required in the southernmost part of the country for a very limited share of the year.

The electricity production in Brazil is based on hydropower, which accounted for 65% of electricity production in 2018. (MME, 2019) The fact that the national electricity production is based on renewable energy has made some people disregard the importance of energy efficiency measures. However, as reported by the Brazilian Ministry of Mines and Energy (MME) (2019), the importance of thermal power plants has been rising in the past decades, with natural gas being their main primary energy source. The emission intensity of Brazilian electricity mix is growing, and such a trend can only be altered by renewable energy development together with efforts to limit the growth of national electricity consumption. Particularly the further development of wind energy can be of help – although its share is still small, it has been steadily increasing in the recent years. (MME, 2019)

Until now, the electricity demand in Brazil has been rising, and some sectors are becoming more energy demanding than others. That is the case for the commercial building sector, whose share of national electricity consumption has grown in the past years. (MME, 2019) There is no official data on the structure of Brazilian commercial building stock, but office buildings are likely the biggest group of commercial buildings, as a similar relation is observed in other countries, such as the U.S. (U.S. EIA, 2015) The increasing energy use in commercial buildings, particularly office buildings, can be attributed to increasing office floor space and increasing need for cooling. These trends are also likely to continue in the future.

Commercial floor space in Brazil is predicted to increase by about 60% between 2000 and 2050. (ICCA, 2012) Increasing office floor space may also be reflected by the apparent recent increasing trend in the amount of people employed in office-related professions such as IT, communication, finance, real estate, professional and administrative activities. (IBGE, 2019a) Interestingly, almost half of the people employed in these professions were based either in Rio de Janeiro or São Paulo state. (IBGE, 2019a) Such statistics suggest that most of the national office floor area is concentrated in just a few cities situated in the south-east of the country, mainly São Paulo and Rio de Janeiro. This can be confirmed by studies such as the energy benchmarking study of corporate office buildings performed by Lamberts et al. (2015), as buildings situated in São Paulo and Rio de Janeiro were 75% of the total sample of 249 buildings; the rest were distributed among other cities, mostly Brasília, Florianópolis, Curitiba, Salvador and Porto Alegre.

As for the need of cooling, there are no national statistics on electricity end-uses of office buildings, but many studies show that cooling is often the single largest electricity end-use in Brazilian office buildings. (Alves et al., 2017; Borgstein and Lamberts, 2014; Carvalho et al., 2010; Lamberts et al., 2015; Pasquali et al., 2011) Some authors note that modern office buildings are often designed with a focus on aesthetics and with little concern for the building's energy performance, giving rise to buildings with high energy consumption. (Lima, 2010; Neves and Marques, 2017; Tamanini Junior and Ghisi, 2015) This elevated energy use in modern office buildings results from several factors: 1) lack of passive cooling strategies such as natural ventilation, replaced by the use of mechanical cooling; 2) high share of window area in building façades, causing higher solar heat gains (fully-glazed façades being the extreme case); 3) lack of external shading, e.g. in the form of brise soleil or overhangs. (Lima, 2010; Minku, 2005; Tamanini Junior and Ghisi, 2015; Veloso et al., 2017) Moreover, temperature increase due to global warming will likely increase the cooling needs even further. In Belém, a city in northern Brazil, the use of passive cooling strategies will become almost completely inviable in the next few decades. (Invidiata and Ghisi, 2016)

As can be seen, the electricity consumption in Brazilian office buildings has been increasing for the past years and is likely to increase in the future. The energy system has started to incorporate more fossil fuel energy in its electricity mix in order to meet the growing demand. Accordingly, greenhouse gas emissions from electricity production are increasing at an even faster rate. The negative impact of GHG emissions could be partly limited by reductions of energy use in office buildings. Indeed, it has been shown that cost-effective energy efficiency in commercial buildings is a significant part of greenhouse gas mitigation potential in the Brazilian building sector. (de Melo et al., 2013; McKinsey & Company, 2009) However, surveys among commercial building owners have shown that they are often not aware of the energy reduction potential and they believe the energy consumption cannot be reduced. (Eletrobrás, 2008) Consequently, a number of studies have tried to characterize the current energy consumption level of office buildings and to investigate how the energy demand can be moderated through informed building design and the use of energy-efficient devices. A whole subchapter of this work is devoted to the review of these energy-related studies (see 2.2). These research efforts have contributed to the creation of national initiatives aimed at increasing the awareness of the most beneficial energy-efficiency strategies, with some national programs focused on office buildings in particular. (CBCS, n.d.; PBE, n.d.; PROCEL, n.d.; ProjetEEE, 2020) Despite these activities, a lot remains to be done. A recent report from International Energy Agency identified that reduction of cooling loads in buildings and development of building codes, are two immediate priorities for Brazil to address the building sector growth, its energy consumption, and carbon footprint. (IEA, 2019a)

However, energy efficiency is not the only concern of the Brazilian building industry, as the increasing rate of construction has a range of other impacts as well. Another consequence is the need for more construction materials, particularly concrete and steel. Concrete-based construction is typical for Latin America as a whole, which has one of the highest shares of concrete in building material composition among all world regions. (IEA, 2018) Obviously, the construction practices are not uniform across Brazil: being a country of a considerable size, there are many regional differences, also in the construction sector. The share of residential buildings with wooden walls may serve as an example: there are almost no such buildings in the south-east of the country (states of São Paulo, Minas Gerais, and Rio de Janeiro), while almost half of all residential buildings are made this way in the state of Acre in the west of the country, amidst the Amazon rainforest. (IBGE, 2019b) Nonetheless, buildings made of reinforced concrete and brick masonry with mortar bonding are predominant in most of the country, including the most populated regions.

The need for buildings and infrastructure drives the consumption of steel and cement. As a result, the energy use for production of these two materials shows a growing trend, even though the energy consumption per unit material has been systematically declining since 1970, due to efforts of the Brazilian industry. (MME, 2019) Additionally, the production of construction materials becomes a burden for the environment and the livelihoods of local people. Production of steel requires iron ore and charcoal, both of which induce deforestation of the native Amazon forest. (Sonter et al., 2017) Reis et al. (2019)

performed a material flow analysis study of Brazilian concrete and mortar, and found that national statistical data covers only 10% of all sand needed for concrete and mortar production, with the remaining 90% coming from illegal sand mining activities and small establishments. (Reis et al., 2019) Regulations are unlikely to be effectively imposed on such small-scale and illegal mining activities and thus the potential impact on ecosystems is high.

The production of construction materials leads to numerous negative impacts and the situation is aggravated by the way these materials are managed. In the past years, a number of studies investigated material waste in Brazilian construction sites. (Agopyan et al., 1998; de Souza et al., 2013; Formoso et al., 2002) Clearly, high material waste is a loss for the construction company itself, so there are companies in which the losses are extremely low, but there remain some in which the losses are so high they may even threaten the future existence of the company. (de Souza et al., 2013) Even the most recent study by Reis et al. (2019) shows low material use efficiency: 53% for concrete and 34% for mortar. The authors point out that industrialization of concrete and mortar production could limit the waste rates, reduce CO_2 emissions and even limit informal mining of coarse aggregates used for the production of these materials. (Reis et al., 2019) The waste could also be limited by better management practices. (de Souza et al., 2013; Formoso et al., 2002)

The Brazilian waste management system also awaits improvements, as landfills are currently the main waste disposal method and recycling remains marginal. (OECD, 2015) Brasileiro et al. (2015) performed a literature review of construction and demolition waste (CDW) treatment opportunities in Brazil and found out that majority of CDW waste is discarded in landfills even though the construction sector has a large potential for absorbing recycled CDW. The authors note that collection issues and high initial investment halt the progress of the recycling sector. The market for recycled materials is limited since potential clients are discouraged by the lack of norms that would control the quality of the secondary material, characterized by high variability. (Brasileiro et al., 2015) Low-income clients are the main customer group of demolition products, as such second-hand building materials are often the only ones they can afford. (da Rocha and Sattler, 2009)

The construction sector in Brazil causes progressing deterioration of the environment. Unfortunately, even the country's capital shows weak environmental performance as the existing regulation is not properly reinforced. (Costa et al., 2018) As a result, there is a visibly higher willingness to pay for green buildings compared to developed countries, which is further reinforced by the relative scarcity of such properties. (Costa et al., 2018) Unfortunately, this trend leads to marketing strategies of advertising office buildings as sustainable, even when sustainability is not addressed in an objective way. (Fossati et al., 2008) Sustainability aspects of these buildings should be fully understood so that a legal basis for voluntary and obligatory programs could be created and enforced.

The improvement of office building design, construction and operation could decrease the environmental pressure by reducing the demand of energy and materials, while providing other co-benefits for the society.

The next subsections will cover the recent developments in understanding the energy and material consumption patterns of Brazilian office buildings, and the resulting GHG emissions.

2.2 Energy characteristics of Brazilian office buildings

Operational energy use has been proven to be the biggest contributor to environmental impacts during the life cycle of typical buildings. (Ramesh et al., 2010) At the same time, energy performance of a building results from an interaction of multiple elements, some easier to control than others. Yoshino et al. (2017) identified six main factors influencing energy use: 1) climate; 2) building envelope; 3) building systems; 4) building operation and maintenance; 5) occupant behavior; 6) indoor environmental quality. These factors often interact.

The building envelope, made of external walls, windows, roof and ground-facing floor, separates the building from the surrounding world. Thermal parameters of the building envelope determine the extent to which the building is influenced by *climatic conditions* such as the outdoor temperature, humidity, and solar gains. In warm climates, window-to-wall ratio (WWR) strongly influences the solar gains and thus the cooling loads.

Building systems are often referred to as HVAC systems, as they control heating, ventilation, and air conditioning. Proper *indoor environmental quality* is strongly dependent on the efficient operation of these systems. Their energy performance is influenced by the efficiency. Cooling system efficiency is often given as the coefficient of performance (COP), which is the ratio of useful cooling output to work input. The higher the COP value, the more efficient the system. Building systems may also include plumbing, life safety and others. Mechanical air-conditioning (AC) system may be substituted by passive cooling, known as natural ventilation (NV). Some buildings employ a hybrid strategy, known as a mixed-mode (MM) system.

The energy use is also influenced by parameters related to *building operation*, the most important being the desired indoor temperature levels (temperature setpoints), the fresh air inflow needed for ventilation, and the operational schedule. Building operational characteristics also cover the intensity of internal heat gains from building's occupants, lighting, and electric equipment. These heat gains can lower energy use during the heating season, but they increase it during the cooling season.

Last but not least, *occupant behavior* has been found to strongly affect energy performance, for example causing increased heat exchange with the surroundings by opening windows during heating or cooling regimes of the HVAC systems. The effect of behavioral impacts can be surprisingly big. Up to 10 times difference in energy use has been observed worldwide in office buildings with the same climatic conditions, building functions, occupancy levels and indoor environmental quality. (IPCC, 2014)

All these factors influence the energy use in buildings, although some have been more investigated than others. The following paragraphs describe the findings of researchers investigating energy use of Brazilian office buildings, with research focused on one or more of these factors.

The first studies on Brazilian office buildings typically focused on data collection and statistical analysis of building features. (Carlo, 2008; Fialho, 2007; Lamberts et al., 2006; Minku, 2005) Clearly, before tools such as Google Earth were available, even the investigation of external building features required on-site observations and was time consuming.

Minku (2005) was among the first ones to note the raising popularity of office buildings with highly glazed façades and no appropriate external shading, resulting in poor energy performance. Her study on office buildings in Florianópolis was used as a benchmark for another study by Tamanini Junior and Ghisi (2015) who performed a similar analysis ten years later, and concluded that building designers continue to have little concern for energy efficiency because such an energy-intensive building type became even more popular during this 10-year period. Many other researchers also point to the low energy efficiency of this inefficient office building design with high WWR, strongly dependent on artificial ventilation and lighting. (Carvalho et al., 2010; Lima, 2010; Neves and Marques, 2017; Veloso et al., 2017) Low solar heat gain coefficient (SHGC) can improve the energy performance of this archetype (Carvalho et al., 2010; Lima, 2010; Neves and Marques, 2017), and the visible correlation between fully air-conditioned buildings and low SHGC value observed by some researchers (Veloso, 2017, p. 100; Veloso et al., 2017, Fig. 6) suggests that building designers already exploit this energy efficiency strategy. Interestingly, one author notes that this highly glazed building type is mostly valued for aesthetics, but the occupants are often not satisfied with the performance: fully glazed façade type often makes it necessary to use internal shading to reduce glare issues, imposing the use of artificial lighting and depriving the occupants of visual contact with the outside world. (Lima, 2010)

Low thermal performance of office buildings was also indicated by Lamberts et al. (2006), who used the work of Minku (2005) and other students to analyze features of office buildings spread around the country. The authors pointed out that some characteristics were found to be representative in all regions such as rectangular shape, walls made of ceramic brick masonry, roof made of a slab with either a waterproof cover or ceramic tiles. The study claimed that such a homogeneity is an indication of inefficient design as the office buildings are located in different climates. However, the investigated sample was very small so only limited conclusions can be drawn from the study.

Santana (2006) performed one of the first studies investigating the influence of design parameters on energy performance of Brazilian office buildings. The author found that WWR had the biggest influence on the energy use, followed by wall reflectance, shading and HVAC efficiency. Veloso (2017) performed a multivariate regression analysis and confirmed the importance of WWR and wall reflectance on energy use intensity (EUI). Additionally, Veloso (2017) observed that EUI is highly influenced by SHGC and building ventilation mode, i.e. fully air-conditioned, mixed-mode and fully naturally ventilated. However, due to data availability issues, the regression performed by Veloso (2017) did not include the energy use for lighting and equipment or HVAC system efficiency.

Some studies focus on a particular building type. The Brazilian bank building stock was investigated by Borgstein and Lamberts (2014) and Wong et al. (2019). Borgstein and Lamberts (2014) focused on the influence of climate on EUI and found out that climate zones, as defined by the Brazilian standard NBR 15220 (ABNT, 2003), cannot be used as an adequate correction factor for EUI. The authors show by means of energy simulations that EUI can be better predicted using climatic conditions characterized using cooling degree hours (CDH), especially when calculated using wet-bulb temperature.

Wong et al. (2019) performed an analysis of the bank building stock in Curitiba. By means of statistical methods, they discovered that WWR and occupant density were the two parameters that stand out when differentiating between low and medium-to-high energy consumers.

Another important study was done by Lamberts et al. (2015), who created an energy consumption benchmark for a building archetype called a corporate office: high-rise, with floor area more than 700 m^2 on each floor, with both private and common areas, and close to 100% of fully air-conditioned floor space. The final benchmark of energy use intensity (EUI) includes considerations of factors strongly influencing the energy use but varying from one building to another, such as such as climatic conditions, number of elevators, occupancy density, parking area, and the existence of other energy uses (data processing center, kitchen, emergency power source). In this truly innovative study, the authors gather enough empirical and experimental data to conclude that the cooling system type is not a strong predictor for energy use, as long as we compare only fully air-conditioned buildings. This project gave rise to a benchmarking platform available online. (CBCS, 2016)

An important contribution to characterizing Brazilian office building archetypes was made by Alves et al. (2017), who proposed a methodology for estimating office building EUI, using a case study of high-rise office building stock in Belo Horizonte. This innovative method involved unique methods such as review of land use legislation, use of a building database based on land tax information, and analysis of external building features using Google Earth. Interestingly, external building features were even used to determine the AC system type. Based on all this data, Alves et al. (2017) created three office building archetypes, characterized by different construction period, ventilation mode and other design and operational parameters. This work formed the basis for another journal article which estimated the possible energy savings related to retrofitting of the older office building archetypes. (Alves et al., 2018)

A large group of studies focused on the EUI reduction through passive cooling strategies: natural ventilation (Figueiredo, 2007; Marcondes, 2010), shading (Capistrano, 2008; Lima, 2012), thermal inertia (Brito, 2015; Ramos, 2010), and a combination of different passive strategies (Maciel, 2002). A comprehensive list of passive strategies can be found on a ProjetEEE webpage – a project run by the Brazilian Ministry of Environment that intends to increase energy efficiency in commercial and public buildings. (ProjetEEE, 2020) Research on natural ventilation is accompanied by a wide range of studies primarily aimed at occupant comfort in naturally ventilated and mixed-mode Brazilian buildings. (André, 2019; Andreasi, 2009; Cândido, 2010; De Vecchi, 2015; Lamberts et al., 2013; Marcondes et al., 2012; Mariana, 2013; Neves et al., 2020; Rupp and Ghisi, 2017) These studies show that occupant comfort may go hand in hand with low energy use if careful design of naturally ventilated spaces is employed.

Even with such robust evidence advocating for the use of natural ventilation, fully air-conditioned buildings are usually preferred, partly due to high land prices in the main urban centers, which makes the investors maximize the useful floor space in order to keep high return on investments. (Damasia Gonzalez dos Santos Oliveira, personal communication, 24 March 2020 and 1 April 2020) Indeed, naturally ventilated buildings should be designed with narrow plan depths for sufficient flow of air across interior spaces (Wood and Salib, 2013, p. 165), which can potentially result in smaller floor areas.

Even though mixed-mode buildings do not deliver the true potential of natural ventilation since a mechanical system needs to be provided anyway, they are usually the best-case scenario in real buildings. (Wood and Salib, 2013, pp. 11–12) Mixed-mode buildings are the main subject of a study by Santesso and Chvatal (2018), which explored the influence of different parameters on the performance of such systems in São Paulo-based offices. The study focused on parameters such as room shape, WWR, effective opening area in windows (the percentage of window area that can be opened for ventilation) and cooling setpoint. The authors show that MM buildings offer substantial energy savings over AC buildings in the climate of São Paulo. An important finding of the study shows that just one degree of difference in the cooling setpoint can cause as much as 30% difference in EUI. Possible energy savings are smaller in case of climates warmer than São Paulo. (Brugnera, 2014)

Pereira (2019) investigated 50 real MM buildings in São Paulo to collect information on design strategies of such buildings. Based on this data, energy simulations were performed, which confirmed the previous findings of Santesso and Chvatal (2018) on the significance window opening effective area on energy use. Pereira (2019) also noted the importance of window type and window positioning in the ventilated area.

The most remarkable study on mixed-mode buildings in Brazilian reality was performed by Neves et al. (2019) who performed a full sensitivity analysis of various factors influencing energy loads in MM buildings, such as window opening effective area, solar absorptance, shading, thermal capacity, SHGC, U-value of walls, floor height, WWR, and solar orientation. The authors show through a Monte Carlo analysis that window opening effective area and SHGC are more important for buildings with limited external shading. These three parameters are also the most significant predictors for cooling loads, according to a multivariate regression analysis.

Some important conclusions can be drawn from the work presented above. Firstly, there is a highly active research community in the area of energy performance of Brazilian office buildings. This is despite of data availability issues raised by multiple researchers, especially data for real energy use values. (Alves et al., 2018; Borgstein and Lamberts, 2014; Lamberts et al., 2015; Veloso, 2017) There is also no office building database with details such as physical parameters and operational regimes, required for energy simulations. (Alves et al., 2018)

Secondly, many of the studies focus on a particular group of office buildings, such as corporate offices (Lamberts et al., 2015), bank branches (Borgstein and Lamberts, 2014; Wong et al., 2019) or mixed-mode buildings (Neves et al., 2019; Pereira, 2019; Santesso and Chvatal, 2018). The results of these studies cannot be directly applied to the whole office building stock, but their results could be combined to get a fuller picture of the stock.

Furthermore, relatively little energy research is performed on a national scale, limited to the work by Borgstein and Lamberts (2014), and Lamberts et al. (2015), both focused on such a subgroup of office buildings. This scarcity can be partly explained by low availability of energy use values in real buildings.

Lastly, the presented research suggests that shading, SHGC and WWR are among the most influential parameters for energy performance of office buildings. As shown by Neves et al. (2019), the importance of these parameters changes depending on the baseline conditions but such general trends can be observed in any case. Window opening effective area is another important factor for energy performance, applicable only in case of mixed-mode buildings. (Neves et al., 2019; Pereira, 2019; Santesso and Chvatal, 2018)

2.3 Material characteristics of Brazilian office buildings

As described in the previous section, multiple researchers analyzed features of Brazilian office buildings that are important to their energy performance. The typical materials included in such analyses are materials included in the building envelope and floors, such as concrete, bricks, plaster cement, window glass, roof covering. However, there are multiple materials that have no direct impact on energy use of the building while having a significant influence on material use, and consequently, on emission performance.

Unfortunately, there are no studies investigating the material composition of Brazilian office buildings. Such studies are not available even for residential buildings, which have typically much better coverage in building research. However, there was one study which also required detailed data on material composition: a material flow analysis of residential building stock in Rio de Janeiro, performed by Condeixa et al. (2017). The authors based their material composition modeling on data from the Syndicate of Construction Industry (Sinduscon-MG, 2007), which describes typical design standards for construction projects, as described in NBR 12721, which is a Brazilian standard on construction cost assessment. (ABNT, 2005) These building designs are typical and representative of buildings in Brazil.

Condeixa et al. (2017) mention also another source of material data, so-called TCPO guide which presents Brazilian averages of material and equipment needs for typical activities during construction and demolition of buildings. (PINI, 2010)

The documents from ABNT (2005), Sinduscon-MG (2007) and PINI (2010) can serve as a basis for material composition data for Brazilian construction projects. Additionally, ABNT (2005) and Sinduscon-MG (2007) include some commercial building archetypes: 8-floor office with open-plan layout, 8-floor office with cellular layout, and 16-floor office with cellular layout. These three commercial buildings are shown in two construction standards: normal and high standard.

Furthermore, material data on Brazilian buildings could also be sourced from life cycle inventories of life cycle assessment studies. However, as will be presented in the next section, there are no such studies on whole office buildings in the Brazilian context.

2.4 Emission characteristics of Brazilian office buildings

Greenhouse gas emissions associated with buildings can be calculated using EN 15978. (CEN, 2012) Although this is a European standard, it is used in countries outside of Europe, including Brazil. (Gomes et al., 2018; Morales et al., 2019; Rohden and Garcez, 2018) The standard offers a framework for life cycle assessment (LCA) of buildings and building products, taking into account four life cycle stages of a building: construction, use, demolition, and possible benefits outside of the building itself, related to material reuse, recycling, and recovery.

Emissions associated with Brazilian office buildings are not well understood, as there are few national studies focused on office buildings (Brugnera, 2018; Najjar et al., 2019; Taborianski and Prado, 2012). Furthermore, none of them concerns a whole building LCA with a full analysis of all life cycle stages of the building. However, there are multiple LCA studies investigating GHG emissions of Brazilian buildings, components, and materials. This work is analyzed in the following paragraphs in order to understand the impacts of the Brazilian construction industry. Many of these studies are not specific to offices or even to commercial buildings – however, the differences within the Brazilian construction sector are still likely to be smaller than the differences between office buildings located in different countries.

As it turns out, whole building LCA studies are extremely limited in Brazil. (Gomes et al., 2018) The available studies investigate social housing (Morales et al., 2019; Paulsen and Sposto, 2013), residential buildings (Evangelista et al., 2018) and university buildings (Gomes et al., 2018). Even though these building types are distinct from office buildings, these whole building LCA studies are nonetheless analyzed in order to understand the most important takeaways.

Paulsen and Sposto (2013) were among the first ones to perform a whole building LCA study in Brazil. The operational energy use was estimated based on statistical data, assuming that cooling loads were zero due to lack of cooling devices. The only estimated environmental impact was energy – embodied energy for material-related stages, and operational energy.

Morales et al. (2019) performed another study of social housing. Again, the use of AC was disregarded. The authors analyzed multiple environmental impacts, including climate change impact measured using global warming potential (GWP) for a time horizon of 100 years, denoted as GWP100. The results show the relative importance of operational energy use for GWP impacts while the material GWP impacts were dominated by concrete, steel and cement mortar. An important contribution of this study was a comparison of material impacts depending on life cycle inventory (LCI) data adopted: global data resulted in up to two times higher GWP impact than regionalized data. Regionalization was performed by adapting the available data to the Brazilian electricity grid and local production processes.

Evangelista et al. (2018) investigated 4 types of Brazilian residential buildings in a whole building LCA study. The GWP impacts differed with the building type and the highest GWP impact was associated with a low standard single-family housing. Again, material-related emissions were dominated by concrete and steel.

Gomes et al. (2018) performed an LCA study of a university building. This is the only whole building Brazilian study that incorporated energy simulation to determine operational energy use. A photovoltaic array was included for on-site energy generation in two modeled scenarios: net zero energy (NZE) and energy positive (E+) building. One of the conclusions is that replacement has a strong influence on the LCA results while there is high uncertainty related to the service life of building components. The authors point to modeling issues associated with the lack of national material LCI databases, forcing LCA practitioners to mix LCI databases. Stage A (pre-use phase) turned out to be the most emission-intensive, which is a typical result for NZE and E+ buildings. Emissions associated with stage C (end-of-life phase) were practically negligible.

A number of studies investigated material emissions related to Brazilian buildings. The studies show high contribution of the main structure and wall masonry to GWP impacts (Medeiros et al., 2018), and a significant influence from production of just a few materials: concrete, steel, and cement (Saade et al., 2014; Silva, 2013). Tavares (2006, pp. 144, 151) found out that paint has a relatively high GWP impact considering total material emissions (including replacements), preceded only by cement in one of the investigated cases. Saade et al. (2014) observed the impact of different concrete and cement types on the LCA results.

Material emissions were also calculated by Najjar et al. (2019), who used a multi-story office building as a case study to show the advantages of LCA and building information modeling (BIM) integration. Najjar et al. (2019) modeled two alternatives: a concrete construction using typical building materials (concrete, brick, ceramics, wooden windows) and a steel construction using drywall and curtain wall systems with aluminum window frames. The climate change impacts of the concrete building were dominated by cement and ceramics while impacts of the steel construction – by aluminum and steel. Najjar et al. published another similar study in 2017. (Najjar et al., 2017)

Moreover, Ecoinvent 3.6 database includes three datasets of Brazilian hotels. (Santa Rosa Rocha, 2019a, 2019b, 2019c) The datasets are modeled to include the whole construction phase and material replacement, which is equivalent to modules A1-A4 and B4 according to EN 15978. (CEN, 2012) Taking into account the building area (including ancillary floor area) and building lifetime, the GWP impacts associated with these hotels range from 3.9 to 10.5 kg CO_2-eq/m^2/year.

There are also authors who created life cycle inventories of particular Brazilian construction materials: cement and concrete (Silva et al., 2018), concrete blocks (John et al., n.d.), ceramic bricks (Soares and Pereira, 2004) and particleboard (Silva, 2012).

The Brazilian-based LCA studies investigated also particular building elements: the main structure (Bento et al., 2013; Bento, 2017; Rohden and Garcez, 2018), façades (Brugnera, 2018; Taborianski and Prado, 2012), masonry walls (Condeixa et al., 2014; Morales et al., 2020), and roof (Souza et al., 2015). This work is briefly described in the following paragraphs.

The studies on the main building structure were primarily focused on concrete type, as it is the predominant material used in Brazilian building structures. Specifically, the authors investigate structures with concrete of different compressive strength values. The least emission-intensive systems included concrete C40 (Bento, 2017), concrete C35 (Bento et al., 2013) or a mixture of all concrete types from C25 to C50, contrasted with the use of concrete C25 only (Rohden and Garcez, 2018).

The least emission-intensive façade system for office buildings is a brick wall with mortar, which is the conventional building style in Brazil, while structural glazing (also known as a curtain wall system) with colorless glass is the most emission-intensive. (Brugnera, 2018, p. 161; Taborianski and Prado, 2012) Changing the glass to reflective significantly reduces the emissions. (Taborianski and Prado, 2012) The work shows that aluminum causes the highest emission levels among all façade materials (Brugnera, 2018, p. 161; Taborianski and Prado, 2012), preceded only by aluminum composite panels (ACM) (Taborianski and Prado, 2012).

Condeixa et al. (2014) performed an LCA study of masonry walls. The authors estimated the amount of material waste and distances of transportation from material suppliers to the site, and from the site to landfill. Condeixa et al. (2014) find high impacts caused by wasted material and suggest that solutions could include the improvement of workforce qualifications, construction planning and waste management.

Morales et al. (2020) investigated masonry walls with a focus on replacement of paint and mortar. The authors discovered large impact differences depending on the choice of service lifetime for paint and mortar. It was also shown that regionalized LCI data shows lower impacts than global data.

Finally, an LCA study on roof systems done by Souza et al. (2015) concludes that ceramic tile system is associated with lower GHG emissions than concrete tile system, mainly due to high temperatures used during cement calcination.

The presented LCA research shows a growing interest in environmental assessment studies of the Brazilian construction industry. Many researchers point to representativeness issues related to the lack of national LCI datasets. (Gomes et al., 2018; Morales et al., 2019; Souza et al., 2015) Some authors use data regionalization to adapt foreign system processes to Brazilian context. (Morales et al., 2019, 2020) However, the persistent effort of Brazilian LCA researchers allowed to create national system processes for materials such as cement and concrete, available in Ecoinvent v3.6. (Silva et al., 2018)

2.5 Sensitivity analysis in building research

Energy consumption and environmental impacts of buildings are subject to changes depending on the parameter choice. This fact has made multiple researchers explore this topic. The following paragraphs describe the current state of knowledge on the importance of different factors on the energy and emission performance of buildings. If available, studies on office buildings were preferred.

Lam and Hui (1996) performed a sensitivity analysis of energy use in office buildings in Hong Kong. The authors found out that cooling setpoint, cooling efficiency parameters (chiller COP) and occupancy density are the most impactful factors. Shading and WWR were among the least impactful factors.

Korolija et al. (2013) investigated the office building stock in UK. Although the authors did not perform a thorough sensitivity analysis, they created building archetypes using model parametrization, which allowed them to create a whole array of buildings that represent the majority of the existing building stock. Therefore, this study shows that using Monte Carlo or other sampling methods to represent variability in building stock is a valid method for energy performance or carbon emission analysis.

As already described in the previous sections (see 2.2), Santana (2006) and Veloso (2017) analyzed parameters influencing energy use in Brazilian office buildings. Using multivariate regression analysis, Santana (2006) concluded that EUI is highly dependent on WWR, wall reflectance, shading, and HVAC efficiency while Veloso (2017) underlined the importance of SHGC and the building cooling strategy.

Another study introduced in the energy research section is a remarkable study by Neves et al. (2019), which includes a full sensitivity analysis of energy loads in Brazilian mixed-mode buildings. The study used sensitivity analysis methods such as OAT (one-at-a-time), Morris method and Monte Carlo with a multivariate regression to show that the most important parameters are window opening effective area, SHGC and shading.

As for the emission performance of buildings, Chay et al. (2012) analyzed CO_2 emissions associated with the superstructure of a high-rise office building in Hong Kong, with the study scope covering material production, transport, assembly and replacement. The modeled building had a reinforced concrete frame and floors, aluminum windows, and plasterboard wall finishes. Material emission factors (kg CO_2/kg of material) were the source of variability in the input data, derived from embodied energy intensities for materials and emission factors for electricity. The average CO_2 emissions was found to be 215 kg CO_2/m^2, with the 95% confidence interval from 86 to 460 kg CO_2/m^2, assuming a lognormal curve. External walls and internal floors were the biggest contributor to this impact, followed by suspended ceilings and finishes. The authors also explore strategies for reducing the emissions, concluding that lifetime extension for the building components is the most effective option, followed by diverting construction waste to recycling.

Hoxha et al. (2014) performed another sensitivity analysis study focusing on material impacts. The authors use a single-family detached house in France as a case study to demonstrate sensitivity of the overall environmental impact on parameters such as material lifetime, material amount and elementary impact of the material production processes. It was found that on the whole building level, thermal insulation, bitumen, and

PVC are the three materials contributing the most to the uncertainty. On the material level, service life was usually the biggest source of uncertainty. For a few materials, uncertainty related to elementary impact was the most important (concrete, structural clay materials, structural wood, plaster). Material amount was the smallest source of material-level uncertainty, but it was likely influenced by the modeling choices – the material amount was only varied between -5% and +10%. Reinforced concrete variant of the building was characterized by a variation in GWP impact between 469.7 and 674.5 kg CO_2-eq/m^2.

Heeren et al. (2015) explored the possible environmental impacts associated with wooden and massive (concrete-based) residential and small office buildings in the context of Switzerland. In a Monte Carlo analysis, 22 variable parameters were randomly sampled. The parameters were divided into a few categories: material (e.g. construction material), design (e.g. WWR), operation (e.g. occupancy) and exogenic parameters (climate, electricity mix). The results show that the massive variant (more relevant to this study as Brazilian buildings are mostly concrete-based) shows the biggest correlation between GWP impacts and the following parameters (in descending order): electricity mix, ventilation rate, thermal generator type, construction material, material service life.

Häfliger et al. (2017) investigated sensitivity of impacts related to material modeling choices. Again, Switzerland was used as a case study. In particular, the authors focused on the sensitivity related to database choices, system boundary definitions and scenarios for replacement of building materials. Wood and insulation turned out to be among the factors with the highest impact variation depending on the database choice. As for the replacement scenarios, insulation and windows and doors have a high impact variation, while at the same time they make up a large share of total impacts. The total GWP impact uncertainty caused by different replacement scenarios depends on the building type and its building lifetime, but it ranges between 10 and 20% of the overall impact.

Finally, a previously mentioned Brazilian study on masonry walls performed by Morales et al. (2020) confirmed the findings by Häfliger et al. (2017) suggesting a big influence of material service life on the final GWP values.

The work on sensitivity analysis in building research presented above allows to draw some important conclusions. First of all, one should be careful when comparing the results of energy-related sensitivity analyses performed in locations with different climatic conditions. Lam and Hui (1996), based in Hong Kong, found that shading is the least important while Santana (2006) and Neves et al. (2019), based in Brazil, concluded that shading is among the most important parameters.

Multiple researchers have focused on the environmental impacts related with materials, which are not as location dependent as studies involving operational energy use. It was found that material service life can have a high contribution to variance for GWP values. (Häfliger et al., 2017; Hoxha et al., 2014; Morales et al., 2020)

Lastly, the study by Heeren et al. (2015) was the only one which analyzed the impact associated with all the life cycle stages, including the operational energy use. In this work, the authors show that electricity mix shows the strongest correlation with GWP impact.

This chapter summarized the available literature, showing the current state of knowledge on Brazilian office buildings: their energy and material requirements and the resulting emissions. As it was shown, there are no studies on emission performance of these buildings, showing an important research gap that remains to be addressed.

The next chapter will describe the methodology adopted to analyze the carbon footprint of Brazilian office buildings and perform a sensitivity analysis of the results.

3 Methodology

This chapter describes the steps taken to address the research questions of this study. Literature review presented in the previous chapter serves as a starting point for a model, whose main purpose is to assess the possible range of carbon footprint values of Brazilian office buildings.

The framework used in this work consists of several steps, which is illustrated in the form of a schematic representation in Figure 2. Firstly, office building archetype is defined. Physical characteristics of the modeled buildings are specified, based on the data collected by means of the literature review. The parameters considered critical for building performance are characterized in terms of their typical range. Some of them are chosen to resemble those typically found in real buildings and others are chosen to investigate possible improvement options. Later, these parameters are being altered as a means of exploring a wider range of carbon footprint values.

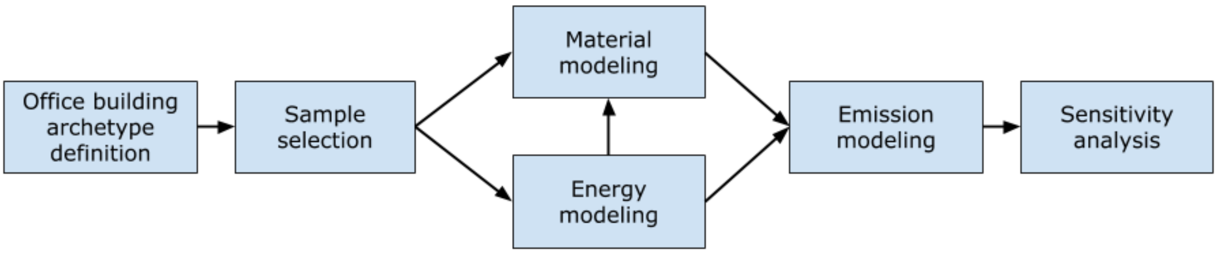

Figure 2 Schematic representation of the methodology.

The second step involves a description of the sample selection method. The variable parameters chosen in the previous step open a wide range of possible combinations, and it is unfeasible to investigate them all due to computational constraints. Therefore, sample selection methods are required to sufficiently cover the parameter space in a way that is not too computationally intensive. As a result, a sample with the selected parameter combinations is chosen, representing multiple buildings.

As the next step, the chosen sample of buildings is modeled in building energy simulation software. At this point, some additional modeling assumptions need to be made, partly as a means of model simplification in aspects that are unlikely to have a large result on the carbon footprint calculations.

Further, material modeling is performed in order to quantify material flows associated with the modeled buildings. A part of the data is extracted from the energy simulation software while the rest is applied based on the collected building archetype data. This procedure makes it possible to investigate the interaction between energy and materials, so evident for example in case of a building envelope.

Next, GHG emission modeling is done using the quantified flows of energy and materials from the previous stages. The magnitude of these flows is used to calculate the carbon footprint associated with the modeled buildings. The impact is divided into building life cycle stages, with accordance to EN 15978 standard (CEN, 2012).

Lastly, a sensitivity analysis of the results is performed. The life cycle assessment done in the previous stage results in a whole range of climate change impact values for the buildings. These values are analyzed by means of a multiple linear regression in order to understand the sensitivity of the calculated carbon footprint to changes in the variable parameters.

The following sections describe each of these steps in more detail.

3.1 Office building archetype definition

The first step of model development requires definition of building archetypes, which includes specification of all the parameters needed as inputs in building energy software, such as climate, building geometry and construction materials, windows and shading, HVAC system, internal heat gains, and others. The archetype definition includes also full material composition description, needed for material and emission modeling.

The following subsections describe the assumptions made with regards to these parameters. While most of the parameters are fixed, some of them are considered variable as they have a particular significance for energy or emission performance. A range of typical values is assigned to each such parameter.

3.1.1 Climate

As has been shown in numerous studies, climate is one of the most important predictors of energy use in buildings, which also applies to Brazilian office buildings. (Borgstein and Lamberts, 2014; Lamberts et al., 2015) Thus, climate is subject to alterations during the simulation stage. The simulated building is located in one of the 12 biggest Brazilian cities: São Paulo, Rio de Janeiro, Brasília, Salvador, Fortaleza, Belo Horizonte, Manaus, Curitiba, Recife, Goiânia, Belém, and Porto Alegre. These cities were depicted in Figure 1, which also shows that such a selection of cities ensures there are at least two cities in a given region. As explained in section 2.1, office floor area can be approximated using employment statistics such as IBGE (2019a). The 12 chosen cities are the biggest cities in their 12 respective states (IBGE, 2011), and these states employ almost 85% of the total number of workers employed in office-related professions such as IT, communication, finance, real estate, professional and administrative activities. (IBGE, 2019a) Therefore, these cities are likely to represent the great majority of office floor area in the country.

3.1.2 Geometry and construction materials

The archetypes are based on commercial building types specified in the Brazilian national standard NBR 12721 (ABNT, 2005), further described by the Syndicate of Construction Industry (SINDUSCON) (Sinduscon-MG, 2007). NBR 12721 lists multiple building types, including residential and commercial ones, specifying their main characteristics and material composition, while Sinduscon-MG (2007) gives additional information on each of these buildings, such as floor plans. These building types were created for construction cost assessment purposes and the data used for their creation represents typical construction practices. Thus, building archetypes built upon this data should be a good representation of typical Brazilian buildings.

Three archetypes were considered in this work, all of them based on NBR 12721 and their commercial building types built in normal standard. NBR 12721 distinguishes also high-standard constructions, but relatively small differences between the two standards exist. Three office building archetypes were considered, and they will be referred to as OPL-8, CL-8, and CL-16. The main information about them can be found in Table 1. The material data of the archetypes is listed in Appendix 1.

It must be noted that NBR 12721 lists the material data in the form of components, which needed to be converted to the amount of a given material type, for the purpose of this work. Some assumptions needed to be made in the process. Additionally, some components listed in NBR 12721 have been excluded from this work, such as door handles, circuit breakers, pressure valves, steel pipes. The amounts of these components were insignificant so this simplification should not influence the results of the study.

Table 1 Three office building archetypes and their main characteristics.

	Archetype 1 (OPL-8)	Archetype 2 (CL-8)	Archetype 3 (CL-16)
Reference in NBR 12721	CAL-8	CSL-8	CSL-16
Standard	Normal	Normal	Normal
Floor layout	Open plan	Cellular	Cellular
Floors	8	8	16
Number of elevators	2	2	3

All the considered buildings have a rectangular form, with a footprint of 20 meters by 30 meters, and the long axis aligned with the east-west axis. Given such footprint, each floor has 600 m^2 of floor area, which is similar to the floor size of the building types described in NBR 12721. The buildings have either 8 floors (OPL-8 and CL-8) or 16 floors (CL-16). Depending on the city, the most common office building height falls within the range of 10-15 floors. (Alves, 2017; Fialho, 2007; Minku, 2005; Neves et al., 2019) This way, buildings of 8 and 16 floors can be considered typical, as they represent the two sides of this spectrum. The height of each floor is 2.8 meters.

Based on the collected material intensity data (Appendix 1), the archetype buildings are considered to have their main structure made of reinforced concrete. Both internal and external walls are made of brick masonry with mortar bonding. The bricks are 9 cm wide, with 2.5 cm of plaster on both sides of the wall, which is a structure typically found in Brazilian construction. (Morishita et al., 2011) Such wall construction is used for internal walls in all of the archetypes, and external walls for 8-floor archetypes (OPL-8 and CL-8). The 16-floor archetype (CL-16) has the same type of external wall construction but with a brick of 13.5 cm thickness, another brick size common in Brazil. (Morishita et al., 2011) Internal walls were modeled so that the total amount of brick intensity agrees with the data from NBR 12721: 21.6 m^2 and 146.4 m^2 of internal walls per floor for the open plan layout (OPL-8) and cellular layout (CL-8 and CL-16), respectively. These additional walls influence the energy simulation because their mass increases thermal inertia of the building.

The roof is covered by fiber cement roof tile of 6 mm thickness, as reported in NBR 12721. All the internal floors and the roof include a 10 cm-thick concrete slab, while the external floor includes a 20 cm-thick concrete slab to account for the thermal mass associated with foundations. Additionally, there is 6 cm of air space between the fiber cement roof tile and the concrete slab. (Morishita et al., 2011) On each floor, there is a 5 mm carpet tile and a 125 mm-thick acoustic ceiling with an additional ceiling air space. These two materials were not present in the original dataset from NBR 12721 but were added because such layers decrease the extent to which the thermal mass of a concrete floor slab can be utilized, thus influencing energy performance of the building.

The materials mentioned above are used as inputs to the energy simulation. However, most of the materials listed in NBR 12721 do not have any influence on operational energy use of the building, so they are considered only at the material modeling stage of model development (see 3.4).

3.1.3 Windows and shading

Various studies have suggested the importance of window-to-wall ratio (WWR) for energy performance of buildings. (Lima, 2010; Santana, 2006; Wong et al., 2019) Therefore, WWR is also an important factor for emission performance, considering that operational energy often constitutes a majority of the carbon footprint of a building. (Ramesh et al., 2010) This parameter may take values of 30%, 50%, 70%, or 90%, which represents a whole range of office buildings found in Brazil: from low WWR values typically found in mixed-mode buildings (Neves et al., 2019) up to high WWR values typical for newer construction (Lima, 2010; Minku, 2005; Tamanini Junior and Ghisi, 2015; Veloso et al., 2017). The same window-to-wall ratio applies to all the building façades.

The glazing found in the windows has 6 mm of thickness. Various researchers point to solar heat gain coefficient (SHGC) as a parameter that can strongly influence the amount of solar heat gains inside the building, and thus the energy need for cooling. (Carvalho et al., 2010; Lima, 2010; Neves et al., 2019; Neves and Marques, 2017) Therefore, SHGC is varied during the building simulations and it takes on a value of 0.2, 0.4, 0.6 or 0.8.

Window opening effective area can be defined as the share of window that can be opened for ventilation purposes. This parameter is an important factor for cooling load of mixed-mode buildings, in which windows can be opened to benefit from natural ventilation when appropriate conditions are met. (Neves et al., 2019) On the other hand, it does not influence the energy use of fully air-conditioned buildings, in which windows are often fixed because opening of windows can be detrimental to the performance of the HVAC system. As such, window opening effective area was chosen as another variable parameter, whose value also reflects the choice of cooling strategy.

A fully AC-dependent office building is often referred to in Brazilian scientific literature as the typical modern archetype. (Carvalho et al., 2010; Lamberts et al., 2015; Lima, 2010; Veloso et al., 2017) Therefore, a window opening of 0.0 represents this cooling strategy, which can be reasonably assumed to be the most common in real Brazilian office buildings.

Mixed-mode cooling strategy is likely less common in real buildings, which is reflected in visibly smaller research coverage, even though this strategy allows for significant energy savings. (Neves et al., 2019) Therefore, it was decided to include mixed-mode cooling regime in this study in order to explore possible energy savings, which are likely to also affect emission performance. Window opening effective area is typically around 0.27 (Neves et al., 2019), but a wider range of values was adopted to explore possible improvements related with mixed-mode ventilation implementation. The parameter takes on values of 0.1, 0.3, 0.5, 0.7 or 0.9, which correspond to the range considered by Neves et al. (2019).

External shading is another parameter related to windows that was proven by many to have a large importance on energy use of the building. (Carvalho et al., 2010; Neves et al., 2019; Santana, 2006; Veloso et al., 2017) Again, a whole range of parameters was adopted to explore possible emission savings, even though most real buildings have almost no external shading. (Lima, 2010; Minku, 2005; Neves et al., 2019; Pereira, 2019; Tamanini Junior and Ghisi, 2015)

Shading can take various forms, among which overhang is the easiest one to model so it was the shading type assumed in this study. During the simulations, shading takes on values from 0.0 (no shading) up to 1.0 (overhang of the same depth as the height of the window below), with steps of 0.2.

3.1.4 HVAC system

It was decided that an ideal HVAC system will be modeled in this study: a system that meets all the load requirements but consumes no energy. The cooling systems common in Brazil can be generally divided into a few types: central AC system with fan coil units, self-contained units, split units, window units, variable refrigerant flow (VRF) systems. (Lamberts et al., 2015; Pereira, 2019) However, it was found that the system type doesn't determine energy use of the building – even though some systems are usually less energy-efficient than central AC systems, they do not require chilled water pumping through the building. (Lamberts et al., 2015) Although some research suggests that buildings with window or split units are less energy-intensive (Veloso et al., 2017), it is often a result of differences in cooling regimes. These devices are often seen in mixed-mode buildings (Pereira, 2019) and, as a consequence, they are not more energy-efficient per se, they are just less utilized. Therefore, modeling the HVAC system as an ideal system should not influence the representativeness of the results to a significant degree, while allowing for considerable time savings in data collection and modeling.

The cooling and heating loads are then translated to energy use by means of energy efficiency coefficients. In case of heating, electric heating with 100% efficiency is assumed. Efficiency of cooling is decreased in relation to theoretical values to account for energy use of the HVAC system. Doing otherwise may lead to underestimated energy consumption values which is undesirable considering its typically high contribution to emission performance of the building. Additionally, the prevalence of cooling needs in Brazil suggest that cooling efficiency is a significant factor for emission performance. As a result, a range of efficiency values was adopted, based on literature.

Brazilian study performed by Inmetro (2017) have shown that split and window units available on the market are generally characterized by COP values of 2.8 to 3.3 W/W. On the other hand, Lamberts et al. (2015) found that a typical value of COP in corporate offices (dominated by central AC systems) is 4.8 W/W. Consequently, cooling efficiency values adopted in this study are in range of 2 to 4, which is lower than the COP values found in the literature to account for energy use of the HVAC system.

It was assumed that no energy source other than electricity was used. This is supported by figures on energy consumption by Brazilian commercial buildings: electricity was around 92% of the total energy use in 2018. (MME, 2019) Therefore, the exclusion of non-electric energy sources is unlikely to have a significant impact on the results.

Temperature setpoints are another category of parameters that are significant to the final energy consumption of the building. In Brazil, cooling setpoint has a particular meaning as it determines the total cooling load: the lower the cooling setpoint, the higher the load. Cooling setpoint is another variable parameter, changed between 22 and 25°C, according to values reported by Lamberts et al. (2015). Heating setpoint is fixed at 20°C. It is assumed that the HVAC system can be activated only during working hours, i.e. between 6 AM and 6 PM on weekdays.

Regarding fresh air intake, airflow rate of 7.5 liter/s/person was assumed, which is the ventilation rate recommended by the Brazilian Health Surveillance Agency. (ANVISA, 2003)

3.1.5 Internal heat gains

Internal heat gains include lighting, equipment, and occupants, all characterized by intensity (occupancy rate in case of people) and schedule. The same operating schedule was used for all internal heat gains: they are assumed to have their maximum value during the working hours (from 6 AM to 6 PM on weekdays), and they are assumed to be zero otherwise. This results in a binary (0-1) type of schedule.

The power intensity of lighting and equipment was adopted as 10.5 W/m^2 and 14 W/m^2, respectively. These values were adopted by Alves et al. (2017) for their open plan office building archetype located in Belo Horizonte, based on suggestions from the Chartered Institute of Building Services Engineers (CIBSE) (CIBSE, 2004). These values are also in line with the energy benchmark for Brazilian corporate office buildings, developed by Lamberts et al. (2015).

According to the NBR 16401-3 standard, office buildings with medium occupant density have 14 people per 100 m^2 of floor space. (ABNT, 2008) However, around 20% of floor area in office buildings is used for purposes other than workplaces. (stairs, elevators, corridors, technical support etc.) (Alves et al., 2017) Accounting for this, the adopted occupant density is 11 people/100 m^2.

3.1.6 Lifetime

Building lifetime can potentially have a significant influence on the carbon footprint (Häfliger et al., 2017), especially in concrete buildings (Heeren et al., 2015). At the same time, there are no studies on lifetime of Brazilian buildings. Brazilian standard NBR 15575-1 defines the main structure lifetime as minimum 50 years. (ABNT, 2013) However, Brazilian office buildings are normally concrete-based structures, which are known for their durability, so lifetime of 100 years could also be possible. Therefore, building lifetime value was chosen to be 50, 75 or 100 years.

However, some building components cannot be used throughout the whole building lifetime and thus they need replacement. Brazilian standard NBR 15575-1 defines building element lifetimes, distinguishing between minimum values and recommended ones, taking into account what is technically possible with today's technology. (ABNT, 2013) On the other hand, Building Owners and Managers Association (BOMA) issued a guidebook with typical lifetime values for different building components. (BOMA, 2010) Based on these two sources, lifetimes for different materials were adopted. The exact values can be found in Appendix 2. In many cases, the values have a wide range of possible lifetimes, so it was decided to include material lifetime as another variable parameter. The materials that last for the whole building lifetime are left unchanged, while the other materials have their lifetime values adopted as 75%, 100% or 125% of the values seen in Appendix 2. These three values are referred to as material lifetime multipliers.

3.1.7 Archetype definition summary

The previous sections present a full description of Brazilian office building archetypes. Ten of these parameters are considered critical for energy and emission performance, so their values are altered throughout the model simulation in order to represent a number of buildings with distinct features. The list of these variables and the values they may assume can be found in Table 2.

The next section describes how a sample of buildings is created to explore the possible carbon footprint values for different variable parameter combinations.

Table 2 Overview of the variable parameters for office building archetypes.

Variable parameter	Values	Unit	Comment
City	São Paulo, Rio de Janeiro, Brasília, Salvador, Fortaleza, Belo Horizonte, Manaus, Curitiba, Recife, Goiânia, Belém, Porto Alegre	-	-
Building type	OPL-8, CL-8, CL-16	-	Determines building height and material composition (incl. external wall type and internal wall area)
WWR	30%, 50%, 70%, 90%	-	-
SHGC	0.2, 0.4, 0.6, 0.8	-	-
Window opening effective area	0.0, 0.1, 0.3, 0.5, 0.7, 0.9	-	Value of 0.0 represents a building with no natural ventilation (fully air-conditioned)
Shading	0.0, 0.2, 0.4, 0.6, 0.8, 1.0	-	-
Cooling setpoint	22, 23, 24, 25	°C	-
Cooling efficiency	2.0, 2.5, 3.0, 3.5, 4.0	W/W	-
Building lifetime	50, 75, 100	years	-
Material lifetime multiplier	75%, 100%, 125%	-	-

3.2 Sample choice

The Brazilian office building archetypes presented in the previous section have 10 variable parameters, which assume one of 3 to 12 possible values. In total, there is almost 4 million variable combinations possible, which makes the investigation of all possible combinations extremely unfeasible due to computational constraints. As a consequence, there is a trade-off between computation speed and accuracy. The choice of a suitable sampling method allows for satisfactory speed-accuracy results.

The sampling method chosen for this study is the Latin Hypercube Sampling (LHS). This sampling method proposed by McKay et al. (1979) divides the whole range of values of each variable into a number of sections, called strata. The total number of strata is equal to the sample size. Then, for each of the variables, just one sample is taken from each stratum. The components of the different variables are matched at random, making this a quasi-random method. Such sampling ensures that the parameter space is uniformly covered. Depending on the problem type, performance of LHS varies compared with other methods where random variables are independent and identically distributed (Owen, 2019), such as the classical Monte Carlo sampling. However, it has been shown both theoretically and empirically that LHS cannot be much worse than conventional random sampling, while it often performs significantly better. (Chrisman, 2014; Owen, 2019)

Latin hypercube sampling was performed in Python programming language using the pyDOE library (Lee, 2013). The LHS method in pyDOE library returns values from 0 to 1 for each variable for each sample item. These values are multiplied by the total number of possibilities for a given variable, and then rounded down. This way, the resulting array clearly points to the parameter values, as listed in Table 2, that should be adopted for each sample item. Each such sample item corresponds to one building with a given combination of variable parameters' values. Such a sample selection method is equivalent to uniform discrete distribution for all the considered parameters – this fact, among others, means that the results will not be representative of the whole Brazilian office building stock.

A sample size of 1000 buildings was chosen for the study. This number is a trade-off between computational time (around 7 hours) and accuracy – a sample of 1000 corresponds to 100 model evaluations per parameter, which is the minimum value to reach model convergence, as described by Mutel et al. (2013).

3.3 Energy modeling

The software used for building energy simulations was EnergyPlus 9.2.0, developed by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). (DOE, n.d.) EnergyPlus requires a weather file (epw format) to run the simulation with climatic conditions of a given location. The climate of the 12 chosen Brazilian cities was simulated using weather files with a typical meteorological year (TMY) for each of these locations, based on data collected from weather stations of the national meteorological institute of Brazil (INMET) during the years 2000-2010. (Roriz, 2012) The weather files are available on the EnergyPlus webpage. (DOE, n.d.)

EnergyPlus input files were created based on the data described in the previous sections, with the use of open source code ParIDF developed by Santesso (2018). The code enables to modify values of variable parameters in EnergyPlus input files in a systematic, automated manner.

Building geometry was set up using zone multipliers – a feature allowing for convenient modeling of buildings with multiple stories, with the same floor size and internal gains. Zone multipliers allow for significant time savings while yielding accurate results. (Big Ladder Software, n.d.; Chen and Hong, 2018; Ellis and Torcellini, 2005)

Thermal properties of materials were modeled based on national-specific data from Morishita et al. (2011) and built-in EnergyPlus material datasets (ASHRAE, 2005). Internal walls were modeled using internal mass objects which allow to enter the surface area of internal walls, and do not require specific coordinates for these objects. The height of windows is adjusted according to the chosen WWR value.

HVAC system was modeled as an ideal loads system which meets the heating and cooling loads but consumes no energy. The heating and cooling loads calculated by EnergyPlus were translated to electricity use at a later stage of model development.

Mixed-mode ventilation was modeled based on Neves et al. (2019), with the help of the open source code by Santesso (2018). Multizone airflow network (AFN) objects were used to simulate window openings. The airflow through windows was modeled using AFN surface objects with the window opening factor equal to the chosen window opening effective area (see Table 2). Energy management system (EMS) objects were used to model mixed-mode ventilation on each building floor. By means of code written through EMS program object, four ventilation regimes are created:

1. Outside of the working hours, when the office is not occupied, both the natural and mechanical ventilation are off, i.e. the windows are closed, and the HVAC system is not active.
2. During the working hours, when the thermal comfort of the occupants is not satisfactory, the HVAC system is turned on and the windows are closed. Thermal comfort is assessed using adaptive comfort model proposed in the ASHRAE-55 standard. (ASHRAE, 2017) The thermal comfort is considered unsatisfactory when less than 90% of the occupants is satisfied with the thermal environment (90% acceptability status).
3. During the working hours, when the occupants are satisfied with their thermal comfort (again, assessed using the 90% acceptability status) and the outdoor temperature is lower than the indoor one, natural ventilation is turned on, i.e. windows are opened. At the same time, HVAC system is turned off.
4. During the working hours, when the occupants are satisfied with their thermal comfort and the outdoor temperature is higher than the indoor one, both systems are turned off, i.e. the windows are closed, and the HVAC system is not active.

These four regimes were also based on the work by Neves et al. (2019). However, the authors use ASHRAE-55 adaptive model with 80% acceptability status. This way, by the time when HVAC system is activated, less than 80% of the people is satisfied with the thermal conditions. Therefore, this work uses 90% acceptability status as it gives higher satisfaction of occupants with the indoor environment, even at the expense of higher cooling loads. For the purpose of the thermal comfort assessment, it was assumed that the clothing of occupants is equal to 0.5 clo during the whole year.

At the end of the energy simulation, EnergyPlus reports the chosen variables, which include variables needed for later stages of model development: electricity used for lighting and equipment, and energy loads for cooling and heating.

3.4 Material modeling

The material data considered in this work is primarily based on commercial building types specified in the Brazilian national standard NBR 12721. (ABNT, 2005) This data source is convenient because it reflects typical national practices in the construction sector. It also groups the materials into categories that include similar items. (Sinduscon-MG, 2007) For simplification, NBR 12721 assumes that the building has a simple foundation type, and it excludes some equipment types (e.g. elevators, air-conditioning units, ventilation ducts).

The material data is listed in Appendix 1 in the form of material intensity values (weight of a given material per each m^2 of floor space). The data is given for three building archetypes considered in this study, referred to as OPL-8, CL-8, and CL-16, which were created based on the NBR 12721 data (see 3.1.2).

The data was complimented by some industry data to add two more materials, common in office buildings: floor covering (carpet tiles) (Forbo, 2016) and acoustic ceiling (Knauf A/S, 2016). These two materials were additionally included because such layers decrease the extent to which the thermal mass of the concrete slab can be utilized, thus influencing energy performance of the building.

On top of the conventional materials, the data in Appendix 1 includes devices such as elevators and AC units, whose amount as measured in kg/m^2 of floor space was added based on data from Sinduscon-MG (2007) and Ecoinvent database (Primas, 2010).

It is assumed that the material intensity data includes on-site material losses. In case of NBR 12721, this assumption can be supported by the fact that the dataset was created for project pricing calculations, and material losses make up a part of project costs.

The materials considered in this study can be divided into categories, according to the data processing procedure, as can be seen in Figure 3. The procedure is intended to create final material data from the initial material data (as listed in Appendix 1) and/or from material data exported from EnergyPlus. Material data extraction from EnergyPlus is done using BuildME framework developed by Heeren (2019) in order to calculate building material from EnergyPlus input files.

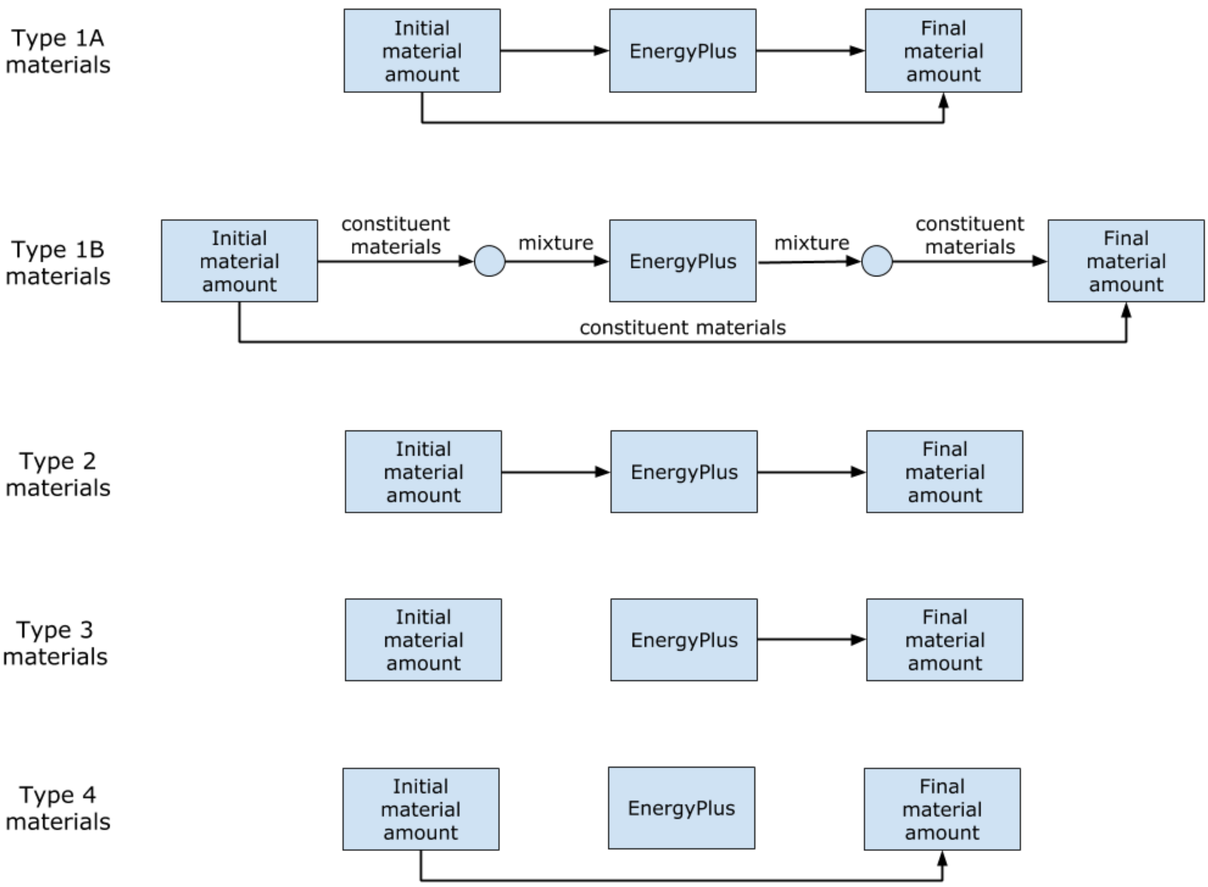

Figure 3 Material types according to the data processing procedure.

Type 1A materials, such as concrete and fiber cement, are partly included in EnergyPlus i.e. the material amount used in EnergyPlus is lower than the total amount of material as reported in the initial data. The difference is compensated for, so that the final material amount is equal the initial amount. In case of fiber cement roof tiles, this difference can be attributed to the fact that a flat roof with non-overlapping tiles was modeled, which may not reflect the real design of the buildings used to develop the initial material amounts. In case of concrete, the difference between the initial data and the material amount reported by EnergyPlus comes from the fact that only concrete floor slabs are modeled in EnergyPlus, while other parts of the concrete structure, such as load-bearing columns and foundations, were not modeled. The external floor slab was modeled two times thicker than internal floor slabs to account for higher thermal mass associated with foundations. Such a simplification is typical for energy simulations and should not significantly influence the energy performance of the building. Both for concrete and fiber cement tiles, the difference was assumed to also include on-site material losses.

Type 1B materials are similar to type 1A materials, with the difference that EnergyPlus uses material data which is a mixture of a few materials in the initial data. This is the case for cement, hydrated lime and sand, whose mixture makes up plaster mortar, used on walls modeled in EnergyPlus. To divide plaster into these constituent materials, a ratio of 1:2:10 was used (cement to lime to sand), according to Brazilian guidelines for masonry workers. (Thomaz et al., 2009, p. 41) Again, as with the type 1A materials, the difference between EnegyPlus data and the initial material amount is compensated for, so that the final material amount is equal to the initial material amount.

Type 2 materials, such as brick, floor covering (carpet), and acoustic ceiling, are modeled in EnergyPlus in such a way that the material amount exported from EnergyPlus is exactly the same as the initial material amount. As a consequence, the data does not need to be additionally adjusted. This type of materials involves some simplification, which comes from the fact that initial material data is assumed to include also on-site material losses, while here, 100% of these materials is included in the building simulation. However, in practice, carpet and acoustic ceiling are typically not used everywhere in the building, which is not accounted for in the simulation. On top of that, mortar between bricks is also not modeled in EnergyPlus which treats the whole wall as being a homogenous brick wall. Such simplifications do not significantly influence the energy loads in the building, but they result in slightly overestimated amount of these materials. This difference could roughly account for the on-site material losses.

Type 3 materials are those for which no initial material data was used, which is the case of glass and aluminum, making up windows. The material intensity is calculated based on EnergyPlus data, and the result is dependent on a given window-to-wall ratio (WWR), as listed in Table 2. Assuming glass density of 2500 kg/m^3 and glazing thickness of 6 mm, there is 15 kg of glass for every 1 m^2 of glazing. Based on data for the commercial building archetypes of normal standard in NBR 12721, it is assumed that there is 4 kg of aluminum for each 1 kg of glass. (ABNT, 2005) These values are recalculated to kg/m^2 of floor space, so that the final data includes material intensity of glass and aluminum.

Finally, type 4 materials include ones that are not directly modeled in EnergyPlus as they do not have any meaningful influence on the energy loads of the system. These materials are generally used in smaller amounts so, even if they are applied to the building envelope, their contribution to the total thermal performance of the building envelope is negligible. All type 4 materials are directly added to the final material data. Examples of these materials include steel (acting as concrete reinforcement), doors, paint, and plastic pipes. Devices such as elevators and AC units are also treated as Type 4 materials.

The procedure of data processing described above and shown in Figure 2 allows to reflect the material data found in sources such as NBR 12721 (ABNT, 2005), while at the same time it ensures that the material-energy interaction in buildings is also taken into account. Such interaction is particularly evident in case of materials making up the building envelope and/or the thermal mass of the building. For example, the material intensity of glass and aluminum is directly related to the window-to-wall ratio of the building, and thus, influences its operational energy use. Another example could be bricks, whose amount used in external walls was smaller than the total brick material intensity, so internal walls were explicitly modeled (see 3.3) to meet the material intensity value, and thus account for additional thermal mass. Such an approach ensures that emission modeling is based on reliable data, in which the energy-material interaction is included.

3.5 Emission modeling

During the previous phases of model development, energy and material flows were quantified, allowing for GHG emission modeling. The emission model is built according to the European Standard EN 15978, which sets guidelines for assessment of environmental performance of buildings, based on life cycle assessment (LCA) methodology. (CEN, 2012) The standard specifies the approach that should be taken to quantify the flows of mass and energy associated with the building, all of which determine its environmental impact. It also describes the way in which the boundaries of the system should be set. The approach presented in EN 15978 is widely accepted in the scientific community, also within Brazil. (Gomes et al., 2018; Morales et al., 2019; Rohden and Garcez, 2018) Therefore, application of the same approach ensures comparability with the work of other researchers.

Life-cycle stages and particular modules of construction products, according to EN 15978 (CEN, 2012), can be found in Table 2. This work investigates the chosen stages: stage A (pre-use stage), stage B4 (replacement), stage B6 (operational energy use) and stage C (end-of-life stage). Modules B1, B2, B3, B5 and B7 were not included in the study. These modules are typically associated with low impacts, so they are rarely included in whole building LCA studies. (Frischknecht et al., 2019; The Carbon Leadership Forum, 2018) Stage D is related to reuse, recycling, and energy recovery outside the system boundary. As the potential for material and energy recovery from construction and demolition waste is very limited in the Brazilian reality (Gomes et al., 2018), stage D was also excluded from the study.

Table 3 Life-cycle stages of construction products according to EN 15978. (CEN, 2012) Highlighted modules are the ones investigated in this study.

Product stage	**A1**	**Raw material extraction and processing**
	A2	**Transport to the manufacturer**
	A3	**Manufacturing**
Construction process stage	**A4**	**Transport to the building site**
	A5	**Installation into the building**
Use stage	B1	Use or application of the installed product
	B2	Maintenance
	B3	Repair
	B4	**Replacement**
	B5	Refurbishment
	B6	**Operational energy use**
	B7	Operational water use
End-of-life stage	**C1**	**Deconstruction, demolition**
	C2	**Transport to waste processing**
	C3	**Waste processing for reuse, recovery and/or recycling**
	C4	**Disposal**
Benefits/loads beyond the system boundary	D	Reuse, recovery and/or recycling potentials

The system boundary for the lifecycle modeling is in line with the boundaries for each considered module, as defined by EN 15978 (CEN, 2012). The functional unit is defined as

1 m^2 gross floor area of a building during 1 year of operation. The considered environmental impacts are limited to climate change impacts measured using GWP100 metrics, as given by the ReCiPe midpoint method (H) V1.13. The life cycle inventory datasets used in the study were sourced from ecoinvent v3.6 database (allocation cutoff), complemented by some industry data in case a given process could not be found in ecoinvent. The life cycle inventory datasets can be found in Appendix 3, 4 and 5.

The total impact d_i for a given item i is generally calculated using the impact multiplier m_i and the external demand y_i:

$$d_i = GWP_i \cdot y_i \tag{1}$$

The elementary impact GWP_i is derived from life cycle inventory datasets and it stands for the GWP impact per unit of item i, measured in "kg CO_2-eq/unit". The external demand y_i stands for the amount of item i associated with one functional unit, i.e. 1 m^2 gross floor area of a building during 1 year of operation. Thus, the external demand y_i is measured in unit/(m^2.year). In some cases, the calculation of y_i requires an additional adjustment of the units. This is the case for materials or construction and demolition processes, which need to be divided by the total building lifetime.

The following chapters describe the assumptions made for the considered life cycle stages of the building.

3.5.1 Modules A1-A4: Production and transport to the building site

Modules A1-A4 are associated with the production and transport of materials used in the construction of buildings. The impact associated with the production of material i can be calculated using equation (1). The elementary impact GWP_i is derived from the production process dataset for material i found in Appendix 3. The external demand y_i is the final material amount calculated in section 3.4 divided by the building lifetime, in order to adjust the units in equation (1). As explained during material modeling description in section 3.4, for most materials (except for glass and aluminum), the final material amount is equal to the initial material amount as listed in Appendix 1.

The life cycle inventory datasets for material production processes were chosen to best reflect the original data from NBR 12721 (ABNT, 2005). For example, as described in NBR 12721 and the complementary report from Sinduscon-MG (2007), aluminum was in the form of window frames, so the production process chosen for this material was *market for window frame, aluminium, U=1.6 W/m2K, GLO*. When no material details were available in NBR 12721 or the data was non-conclusive, country-specific reports were used for reference. For example, concrete of compressive strength of 20 MPa was reported in NBR 12721 (ABNT, 2005), while concrete of 25 MPa was reported by Sinduscon-MG (2007). Based on national data on concrete consumption, concrete of 25 MPa of compressive strength was chosen, as it is the most common in Brazil. (Silva et al., 2018, Tab. 14)

During dataset selection, country-specific datasets were preferred. If no Brazilian process was available, other datasets from ecoinvent database were chosen. In case of acoustic ceiling, no appropriate ecoinvent process was found, and no Brazilian industry data was available. In this situation, industry data from Denmark was used, in form of an environmental product declaration (EPD). (Knauf A/S, 2016)

Ecoinvent database v3.6 offers a process type known as *market for product*, which includes a typical consumption mix of a given product, together with average transport values and losses in trade and transport. Depending on data availability, these market processes may relate to the global market or a given country's market. (Ecoinvent, n.d.) All the system processes selected for this study are of the *market* type, and so they include unit processes related with the transportation to the construction site. Some of the system processes are Brazilian, reflecting average transportation distances for a given type of product. Others are global processes, so the transportation distances may be not in line with Brazilian reality.

The ready-made datasets used for life cycle inventory included 'cradle to gate' unit processes for material production, as defined by EN 15978 (CEN, 2012). Additionally, the choice of *market* process type assures that the transport to the building site is also included in the dataset. As such, the datasets cover life cycle modules A1-A4.

3.5.2 Module A5: Installation into the building

According to EN 15978, module A5 includes multiple processes related to the construction process, e.g. ground works, on site product transformation, installation of products into the building, waste management of construction waste. (CEN, 2012) It was assumed that most of the climate change impact originates from construction machinery operating on site and the energy use associated with it. Therefore, waste management of construction waste (related to on-site material losses) was not included.

The original data from the Brazilian national standard NBR 12721, used for office building archetype definition, lists the operation time of construction machinery, taking a concrete mixer of 320 liters as an approximation for all the machinery. (ABNT, 2005) According to market data, such mixers are usually powered by electricity and have around 2 hp (horsepower) of power. Using this information, energy used in construction of 1 m^2 of floor space was calculated for each building archetype, as seen in Table 4.

Table 4 Energy use for construction of office building archetypes.

Concrete mixer, 320 l	OPL-8	CL-8	CL-16
Operation time (days/m^2) (ABNT, 2005)	0.64	0.27	0.64
Operation time (hours/m^2)	15.32	6.52	15.32
Energy used (kWh/m^2)	22.86	9.73	22.86

The calculated energy use for construction processes associated with a chosen building archetype is the external demand y_i in equation (1), which can be used to calculate climate change impacts. The elementary impact GWP_i is derived from the electricity process datasets found in Appendix 5. The processes are region-dependent, so the elementary impact of electricity depends on the choice of a city, as listed Table 2. The external demand y_i needs to be divided by the building lifetime, in order to adjust the units in equation (1).

Electricity used by the machinery is complemented by impacts associated with the production of machinery itself. The impacts were calculated from equation (1), using an ecoinvent dataset for building machinery (Appendix 4). It was assumed that 1.34E-07 unit of a building machine is used for each 1 MJ of energy used. (Kellenberger, 2010) Again, the external demand y_i needs to be corrected for the building lifetime.

3.5.3 Module B4: Replacement

Replacement module includes the production of the replaced product and its transportation to the site, as well as waste management of the removed product. (CEN, 2012)

The impact d_i of replaced material i is calculated using a modified version of equation (1):

$$d_i = GWP_i \cdot y_i \cdot \left(\frac{BL}{ML_i} - 1\right) \tag{2}$$

The elementary impact GWP_i is derived from *both* the production and end-of-life process dataset for material i found in Appendix 3. The total elementary impact GWP_i should be equal to the sum of production and end-of-life elementary impacts (as measured in kg CO_2-eq/kg of item i). Analogically to calculation for modules A1-A4 described in section 3.5.1, the external demand y_i is the final material amount calculated in section 3.4 divided by the building lifetime. The last factor in equation (2) stands for the number of replacements during the building lifetime BL, determined by the material lifetime ML. Each material i has its own service life ML_i, listed in Appendix 2. As can be evident from the equation, materials whose lifetime is equal to the building lifetime are not being replaced.

The material lifetime multiplier is applied at this point. It is a variable explained in section 3.1.6, whose values are listed in Table 2. The material lifetime ML_i is multiplied by the material lifetime multiplier (75%, 100% or 125%) which results in faster, typical, or slower replacement cycles, respectively. As already mentioned in section 3.1.6, materials whose lifetime is equal to the building lifetime are not subject to change.

It was assumed that replacement can take on fractional values. Although this may seem counterintuitive, this approach is logical considering the full picture. Assuming that the expected building lifetime will have been over in 10 years, how many facility managers would decide to replace an elevator, whose lifetime is 25 years? In such a case, a fractional replacement value calculated for the remaining lifetime ($10/25 = 0.4$) would be equivalent to 40% of facility managers deciding to replace the elevator.

A particular situation could also take place: if a building lifetime of 50 years is adopted while the material lifetime multiplier is 125%, some materials could have higher lifetime than the building itself (e.g. aluminum). Nonetheless, it was decided that the full burden of this material should be placed upon the building, as it is unlikely that such a product would be used in another building for the remaining lifetime.

3.5.4 Module B6: Operational energy use

The environmental impacts related to operational energy use were calculated using data obtained during energy modeling described in section 3.3. EnergyPlus simulation results include the electricity used for lighting and equipment, and energy loads for cooling and heating. The heating and cooling loads are translated to electricity use using efficiency values described in section 3.1.4: heating efficiency of 100% and a chosen cooling efficiency value in range of 2 to 4 W/W (cooling efficiency is a variable parameter, as seen in Table 2).

The four components of electricity consumption (lighting, equipment, cooling, heating) are measured in kWh/m^2/year. Using these electricity end-uses as external demand values y_i, the calculation of impact from equation (1) is straightforward. The elementary impact GWP_i is derived from the electricity process datasets found in Appendix 5. The processes are region-dependent, so the elementary impact depends on the choice of the city, which is a variable parameter as shown in Table 2.

3.5.5 Module C1: Deconstruction, demolition

Module C1 includes all on-site operations which are necessary for the deconstruction and/or demolition processes. (CEN, 2012) The initial dataset from NBR 12721, used for office building archetype definition, does not include any information on demolition processes. However, a guide called TCPO (Price Composition Tables for Budgets) presents Brazilian averages of material and equipment needs for construction and demolition of buildings. (PINI, 2010)

Concrete makes up the great majority of total material weight in the office building archetypes (Appendix 1), so it is used as an approximation of demolition processes. Other building elements of Brazilian building (e.g. brick walls) are often dismantled manually (PINI, 2010, pp. 58–62), often due to lower costs of manual deconstruction. (da Rocha and Sattler, 2009) According to the TCPO guide, the machinery used for reinforced concrete demolition is a hydraulic breaker with an air compressor of 47 kW, powered by diesel. The air compressor is used for 5 hours to demolish 1 m^3 of reinforced concrete. (PINI, 2010, p. 59) Assuming concrete density of 2380 kg/m^3, the energy used for demolition can be calculated as seen in Table 5.

Table 5 Energy use for demolition of office building archetypes.

Air compressor, 47 kW	OPL-8	CL-8	CL-16
Operation time (hours/m^3 concrete) (PINI, 2010)	5.00	5.00	5.00
Concrete material intensity (kg/m^2) (ABNT, 2005)	895.40	885.05	1247.02
Operation time (hours/m^2)	1.88	1.86	2.62
Energy used (MJ/m^2)	318.28	314.60	443.27

The calculated energy use for demolition processes associated with a chosen building archetype is the external demand y_i in equation (1), which can be used to calculate climate change impacts. The elementary impact GWP_i for diesel is derived from the process dataset found in Appendix 4. The external demand y_i needs to be divided by the building lifetime, in order to adjust the units in equation (1).

The diesel dataset already includes machinery wear due to operation, which could be an approximation for wear of the referenced hydraulic breaker with an air compressor.

3.5.6 Modules C2-C4: Waste processing and disposal

The last building life cycle stage to be considered is related to waste transportation from the building site, waste treatment, processing, and disposal. (CEN, 2012) The procedure is analogical to the one for modules A1-A4 described in section 3.5.1, with two main differences: (1) instead of production processes, disposal processes were considered; (2) transportation impacts were calculated manually.

The impact associated with the disposal of material i can be calculated from equation (1). The elementary impact GWP_i is derived from the disposal process dataset for material i found in Appendix 3. The external demand y_i is the final material amount calculated in section 3.4 divided by the building lifetime, in order to adjust the units in equation (1).

Brazilian datasets were chosen for the disposal processes whenever possible. According to process data of one of these Brazilian datasets, the typical disposal mix is composed of: 88% unsanitary landfill, 8% open dump, 3% open burning, and 1% municipal incineration.

(Symeonidis, 2019) Therefore, the waste products for which no Brazilian dataset could be found were modeled in a way to resemble this Brazilian reality to a greatest extent possible. Unfortunately, unsanitary landfill processes were available only for materials with ready-made Brazilian disposal datasets. In this case, inert material landfill was chosen where applicable. (Doka, 2009, p. 27) If a given product was made of multiple materials, the material making up the majority of the product was chosen for the disposal process. For example, a waste gypsum process was chosen for gypsum plasterboard and a waste wood process was chosen for wooden doors.

In modules A1-A4 described in section 3.5.1, market processes were chosen to include transportation distances in the ready-made datasets. However, a majority of materials does not have country-specific datasets, and adoption of global disposal datasets would mean that the disposal methods are far from Brazilian reality. Additionally, the Brazilian disposal datasets include an industry average of 77 km of transportation distance. (Symeonidis, 2019) However, most of the considered office buildings would likely be located in big cities, where disposal sites are nearby. For example, Condeixa et al. (2014) assume 11 km of distance to disposal site for a building located in Rio de Janeiro.

Due to the above reasons, transportation was considered separately. For non-market processes, transportation of 11 km was added for each kg of material. For market processes, the distance was corrected to 11 km. The mode of transport was adopted after (Symeonidis, 2019), who used market for transport, freight, lorry, unspecified, RoW to model the transportation of demolition waste. The same process was adopted in this study, as road freight is particularly common in Brazil. (Condeixa et al., 2014; Gomes et al., 2018)

3.5.7 Emission modeling summary

The previous subsections presented the process of GHG emission modeling. The modeling was performed using data on flows of energy and materials, quantified at the previous stages of model development, as was shown on the diagram in Figure 2. The operational energy, whose modeling was described in section 3.3, was used to calculate the impacts associated with module B6. On the other hand, the materials whose modeling was described in section 3.4 were used to calculate the impacts related to modules A1-A4, B4 and C2-C4. The impacts of modules A5 and C1 were calculated independently.

The individual impacts of modules described above can be summed up to obtain the total climate change impacts, also known as the carbon footprint. The total impacts can be calculated for all the buildings selected in the sampling process. The next step is then to analyze the results using methods of sensitivity analysis.

3.6 Sensitivity analysis

The life cycle assessment done in the previous stage results in a whole range of climate change impact values for the buildings. Understanding the significance of the variable parameters on the GWP impacts requires a statistical analysis of the results.

A multivariate regression analysis was used to quantify the sensitivity of the results to the input variable parameters. The regression was based on a linear regression equation, adopted from Hygh et al. (2012):

$$y(x_1, x_2, \ldots, x_{10}) = \beta_0 + \sum_{i=1}^{10} \beta_i x_i \qquad (3)$$

where y is the dependent variable, such as the total GWP impact; x_i represents the value of a variable parameter i and β_i is the corresponding regression coefficient. The coefficient of determination (denoted R^2) describes goodness-of-fit i.e. how close the datapoints are to the fitted regression line. Adjusted R^2 is often used instead of R^2 to account for the number of independent variables in the model.

The sensitivity analysis results are interpreted using standardized regression coefficients. There are two ways of obtaining these standardized coefficients, with both yielding the same results: 1) standardizing all the variables prior to the regression analysis; 2) performing the regression analysis on unstandardized variables and then adjusting the coefficients using standard deviation values of the variables. (Bring, 1994) In this work, the first method is used, even though Hygh et al. (2012) used the second method. As such, the standardized regression coefficients were calculated from formulas adopted from Bring (1994):

$$x_i^* = \frac{x_i - \bar{x}_i}{x_i} \quad (4)$$

$$y^* = \frac{y - \bar{y}}{s_y} \quad (5)$$

where x_i^* and y^* are standardized variables, $\bar{x}_i$ and $\bar{y}$ are the means of each variable in the sample and x_i and s_y are the standard deviations.

Therefore, the final form of the regression equation is:

$$y^*(x_1, x_2, \ldots, x_{10}) = \sum_{i=1}^{10} B_i x_i^* \quad (6)$$

where B_i are the standardized regression coefficients for a variable parameter i. Note that the intercept coefficient β_0 found in equation (3) vanishes due to standardization.

The standardized coefficients obtained in this way can quantify parameter sensitivity by providing information on the relative impact of each parameter. These coefficients are dimensionless which allows for direct comparison between the variables, even if they have different units. The same would not true for unstandardized coefficients. The standardized coefficients reflect the sensitivity of the dependent variable y (e.g. the total GWP impact) on changes in values x_i of the variable parameters i. The bigger the absolute value of coefficient B_i, the more sensitive y is to the changes in parameter i. The sign of B_i indicates the correlation i.e. if the coefficient B_i is positive, then an increase in parameter i will cause the dependent variable y to increase as well.

To perform a regression analysis, all the categorical variables need to be described using numeric data. In case of this study, there are two categorical parameters: city and building type, as seen in Table 2.

Climate was simulated by choosing one of 12 Brazilian cities. However, as it turned out during emission modeling, electricity mix is dependent on the region (see 3.5.4). As a result, the choice of a particular city has two different effects on the model: 1) it influences the climatic conditions which determine the energy need of the building; 2) it influences the electricity mix which determines the emissions associated with each kWh of electricity used. Therefore, it was decided that these two effects should be separated for a better understanding of the model's results. During the regression analysis, they are treated as independent variables.

Climatic conditions are characterized numerically using annual cooling degree hours (CDH) from Versage et al. (n.d.), who calculated CDH with a wet-bulb temperature of 15°C. Such metric was shown by Borgstein and Lamberts (2014) to be the most appropriate for describing the cooling energy demand of Brazilian climates. Electricity mix is characterized by elementary GWP impact of 1 kWh of electricity. The values of CDH and elementary GWP impacts of electricity for each investigated city is listed in Appendix 5.

Building type was changed to numeric data by creating two new 'dummy' variables with a binary notation: CL-8 and CL-16. Each of these binary variables will have a value of 1 if a given sample item is of the given building type and a value of 0 otherwise. As a consequence, if for a given sample item both CL-8 and CL-16 variables are zero, then this sample item belongs to the third building type (OPL-8). This way, the standardized regression coefficients for variables CL-8 and CL-16 should reflect the change in the dependent variable y associated with switching the building type from OPL-8 to CL-8 or CL-16.

The final list of 12 independent variables used during the regression analysis can be found in Table 6.

Table 6 Independent variables used in the regression analysis. Derived from Table 2.

Independent variable	Values
Electricity mix	According to the city chosen from Table 2, values listed in Appendix 5
Climate (CDH)	
CL-8	Binary (0 or 1), if both are 0 then building type is OPL-8
CL-16	
WWR	30%, 50%, 70%, 90%
SHGC	0.2, 0.4, 0.6, 0.8
Window opening effective area	0.0, 0.1, 0.3, 0.5, 0.7, 0.9
Shading	0.0, 0.2, 0.4, 0.6, 0.8, 1.0
Cooling setpoint	22, 23, 24, 25
Cooling efficiency	2.0, 2.5, 3.0, 3.5, 4.0
Building lifetime	50, 75, 100
Material lifetime multiplier	75%, 100%, 125%

The sensitivity analysis procedure described above gives a quantitative measure of parameter sensitivity. Variable parameters analyzed in this study can be ranked according to their influence on the results, allowing for interpretation of the results obtained in the previous stages of model development.

4 Results

The methodology described in the previous chapter served as a means of exploring Brazilian office buildings and their carbon footprint. The office building archetypes allowed for a selection of 1000 buildings which were analyzed in terms of energy and materials, eventually allowing for climate change impact assessment. This chapter presents results of these 1000 simulations in terms of energy, materials, and emissions. The plots are were generated using matplotlib and seaborn libraries for Python. (Hunter, 2007; Waskom et al., 2020) The results are also analyzed by means of a multivariate regression analysis.

4.1 Energy modeling results

The results of energy simulations of the 1000 sampled buildings were analyzed from the perspective of energy load – the amount of energy needed by the building to provide services to its occupants. Energy loads for cooling and heating do not include the efficiency of the HVAC system.

The total energy load in the simulated buildings is composed of equipment, lighting, cooling, and heating, as seen in Figure 4. It is characterized by high variability, with values ranging between 90 and 407 kWh/m^2/year and a median of 206 kWh/m^2/year. Converting the energy loads to delivered energy yields values between 82 and 238 kWh/m^2/year.

The predominant end use is cooling with values from 10 to 331 kWh/m^2/year, and a median of 126 kWh/m^2/year. The energy need for equipment and lighting is constant, equal to 43.68 and 32.76 kWh/m^2/year, respectively. The heating load is close to zero, although the exact value is also characterized by some variability, reaching up to 7 kWh/m^2/year.

The cooling load as a function of city is shown in Figure 5. The cities are arranged from left to right in order of increasing CDH. Generally, the total energy load shows an increasing trend with increasing CDH. The median energy load values range from 113 kWh/m^2/year in Curitiba to 290 kWh/m^2/year in Belém.

However, city was just one of the variable parameters considered in this study, whose full list can be found in Table 2. Figure 6 shows the total energy load as a function of all the other variable parameters. For comparability, the y-axis is shared among all the parameters. However, the three bottom parameters (cooling efficiency, building lifetime, and material lifetime multiplier) should do not have influence on energy loads, as they were applied at later stages of the model development. The figure shows all the sampled buildings, which includes both mixed-mode and fully AC buildings.

The biggest influence on energy load can be observed for the window opening effective area, which reflects the effectiveness of natural ventilation strategies. The mean of energy load values ranges from 173 to 269 kWh/m^2/year, with the lowest value for the highest window opening effective area, which was equal to 0.9. As the value of 0 means that windows cannot be opened, this reflects a case where only the HVAC system is active at all times and natural ventilation cannot be used. This is also the reason for the abrupt change between 0 and 0.1 for window opening effective area. A clear trend can also be observed for SHGC, shading, and cooling setpoint.

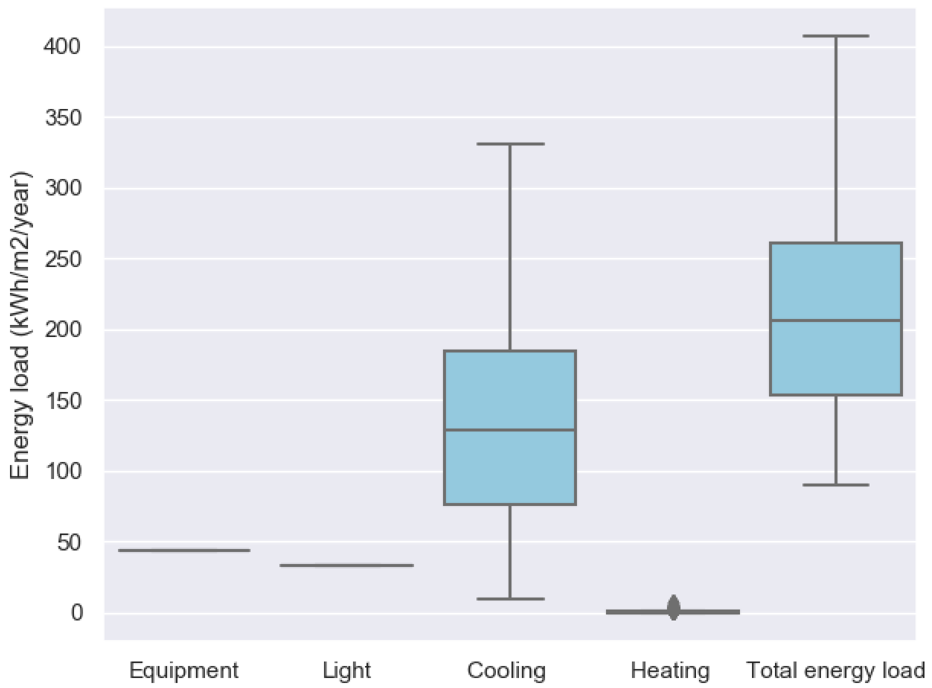

Figure 4 Total energy load and its components: equipment, lighting, cooling, and heating.

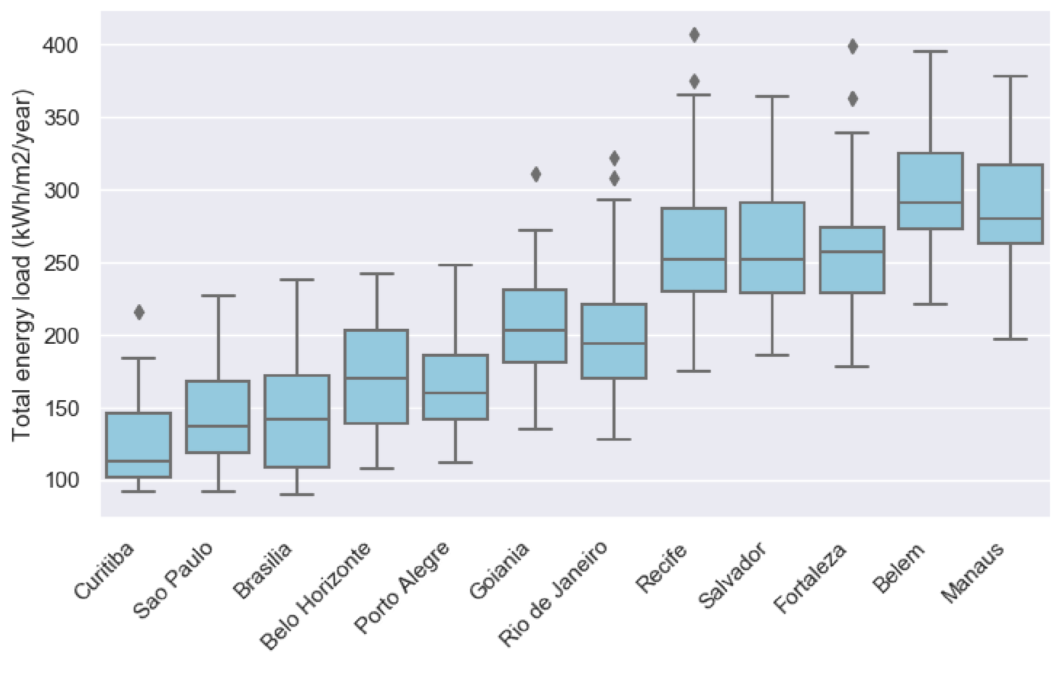

Figure 5 Total energy load as a function of city. The cities are arranged according to increasing cooling degree hours. (Versage et al., n.d.)

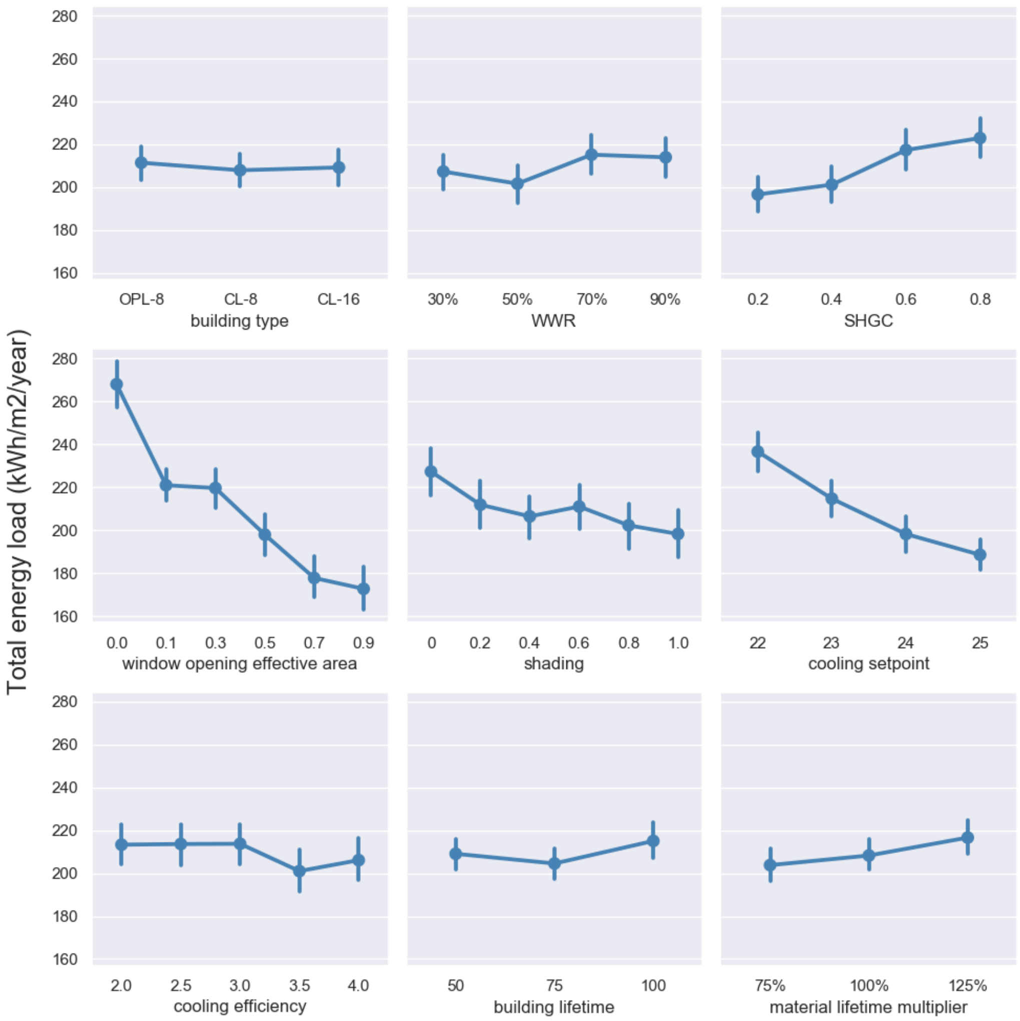

Figure 6 Total energy load as a function of the chosen variable parameters. Parameter 'city' is excluded as it is shown in another plot.

4.2 Material modeling results

Material modeling was mostly based on reconciling values from the initial datasets with the values extracted from EnergyPlus, in order to properly reflect energy-material interactions. As such, the material amounts follow the values from the original material dataset, as presented in Appendix 1. The exception is glass and aluminum, whose amounts are based on data extracted from EnergyPlus using BuildME framework developed by Heeren (2019).

Glass and aluminum are strictly related to the size of windows of the simulated building, and thus their amount is related to WWR, one of the variable parameters. The values for WWR and material intensity of glass and aluminum can be found in Table 7.

The amount of glass and aluminum increases with increasing WWR in a linear manner, with an increase of 1.40 kg/m^2 and 5.60 kg/m^2 for every 20% increase of WWR for glass and aluminum, respectively.

Table 7 Window-to-wall ratio and material intensity of glass and aluminum.

Window-to-wall ratio (WWR)	Glass (kg/m^2)	Aluminum (kg/m^2)
30%	2.10	8.40
50%	3.50	14.00
70%	4.90	19.60
90%	6.30	25.20

4.3 Emission modeling results

Based on the operational energy and the material amount calculated in previous steps, climate change impacts of the buildings were calculated, using GWP100 as metrics. The impacts according to life cycle stages divided by modules can be seen in Figure 7.

The total GWP values vary from 20 to 108 kg CO_2-eq/m^2/year, with 41 kg CO_2-eq/m^2/year median. Module B6 (operational energy use) is visibly the most impactful, characterized by a range of values from 11 to 95 CO_2-eq/m^2/year, with a median of 25 CO_2-eq/m^2/year. Module A1-A4 and B4, related with material production and material replacement, have smaller impacts, with medians of 8 CO_2-eq/m^2/year and 6 CO_2-eq/m^2/year, respectively. Modules A5, C1 and C2-C4 have negligible impacts, with medians of 0.01, 0.40 and 0.23 CO_2-eq/m^2/year, respectively. These modules refer to construction activities, demolition activities and end-of-life impacts associated with materials.

Module B6 concerns operational energy use, and so the emissions are largely dependent on the energy load values, as was shown in Figure 4. The exact relationship between the two variables is demonstrated in Figure 8. As a general rule, higher energy load values seem to be associated with higher GWP impacts, but some datapoints in the upper right of the plot are visibly distinct from this general trend. Consequently, as the energy loads increase, the possible range of GWP values for buildings of similar energy loads increases as well.

Modules A1-A4, associated with material production and transport to the building site, can be decomposed down to material level to investigate which materials have the biggest impact. The GWP impact of these modules is often referred to as embodied emissions. Figure 9 shows embodied emissions as a function of material, divided by building type. For clarity reasons, the selected plot type displays the mean and an indication of uncertainty but not the actual spread of the values.

Aluminum is responsible for the biggest share of embodied emissions, followed by steel, concrete, lime, and brick. The mean aluminum-related impact is 3 kg CO_2-eq/m^2/year. There is also a visible difference between concrete and steel GWP impacts of 8-floor and 16-floor archetypes.

Module B4 is related to material replacement impacts. Its GWP impact is often referred to as recurrent emissions. Similarly to modules A1-A4, GWP impacts as a function of material and building type can be plotted, which was done in Figure 10. For comparison purposes, Figure 9 and Figure 10 have the same y-axis limits.

On average, aluminum and paint have similar recurrent emissions, with the mean value of around 2 kg CO_2-eq/m^2/year. Following are the impacts associated with the AC system, floor covering, doors, and ceramic tile. A significant difference between the building types can only be seen for paint: the 16-floor archetype with a cellular layout (CL-16) has higher paint-related recurrent emissions than the other two archetypes.

The five most impactful materials from Figure 9 and Figure 10 are shown again in Figure 11 and Figure 12, respectively. This time, the plot type depicts more statistical details of the data. The values are divided by building lifetime.

Both Figure 11 and Figure 12 show high variability of aluminum-related impacts. Module A1-A4 has aluminum impacts in range of 1.0 to 6.4 kg CO_2-eq/m^2/year, while module B4 in range of 0.0 to 6.4 kg CO_2-eq/m^2/year. Other materials display much lower variations, usually enclosed within 1 kg CO_2-eq/m^2/year of differences at most. Building lifetime has a clear impact on the GWP values: a higher lifetime decreases the embodied emissions but increases the recurrent ones.

Finally, the relationship between the variable parameters specified in Table 2 and GWP impacts can be explored. Figure 13 shows the total GWP as a function of city, represented by different cities. The cities are arranged according to their annual cooling degree hours, listed in Appendix 5. There is no visible trend between GWP and CDH, which contrasts the trend that was evident for energy loads in Figure 5. Three cities are particularly distinct from the others: Recife, Salvador, and Fortaleza, with median GWP values of around 70 kg CO_2-eq/m^2/year. These cities are characterized by relatively high CDH values. However, there are two cities with even higher CDH values which nonetheless have much lower emissions (around 45 kg CO_2-eq/m^2/year).

Figure 14 shows the total GWP impacts as a function of the variable parameters considered in this study, excluding city parameter which was already analyzed above. For comparability, the y-axis is shared among all the parameters. An increasing or decreasing trend can be seen for all the parameters, the trend is stronger for some and weaker for others.

The highest spread of possible emissions is observed for window opening effective area and cooling efficiency, with the mean values dropping by 16% from around 51 to around 43 kg CO_2-eq/m^2/year as the parameter values increase. General decreasing trends can also be seen for shading, building lifetime, cooling setpoint and material lifetime multiplier. On the other hand, WWR and SHGC are generally associated with increasing emissions with increasing parameter values. CL-16, the only 16-floor archetype, shows higher GWP impacts than the other two archetypes.

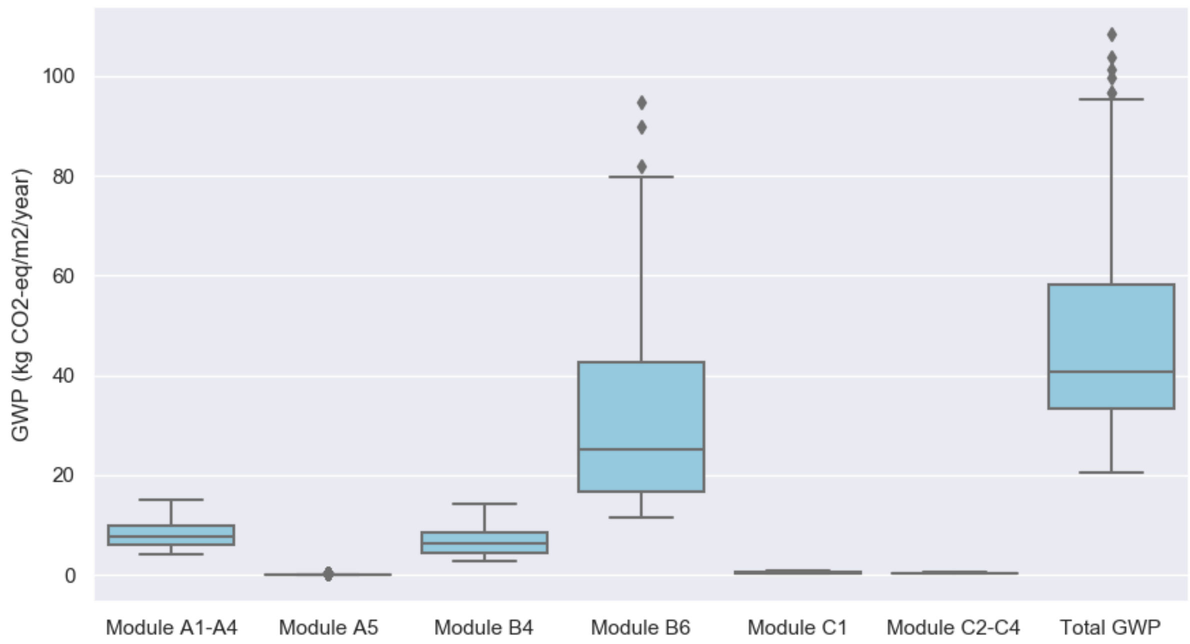

Figure 7 GWP impacts of the building life cycle modules.

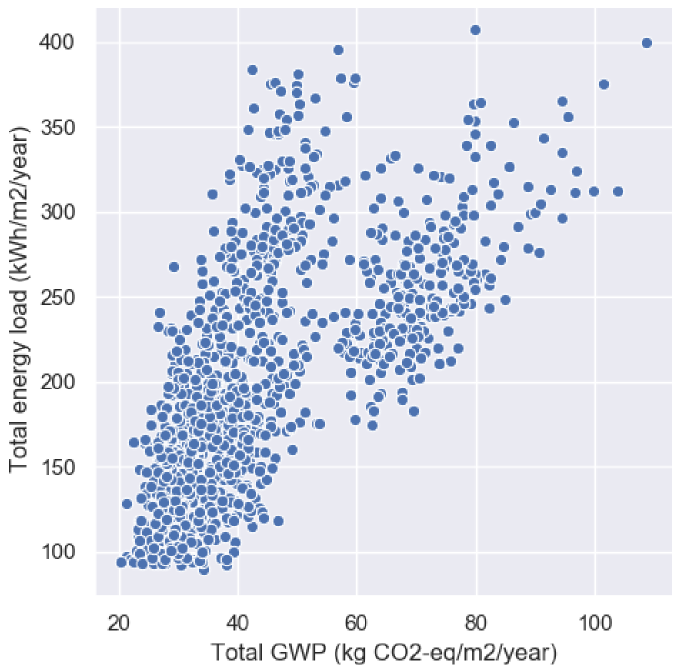

Figure 8 Relationship between the total GWP and the total energy load.

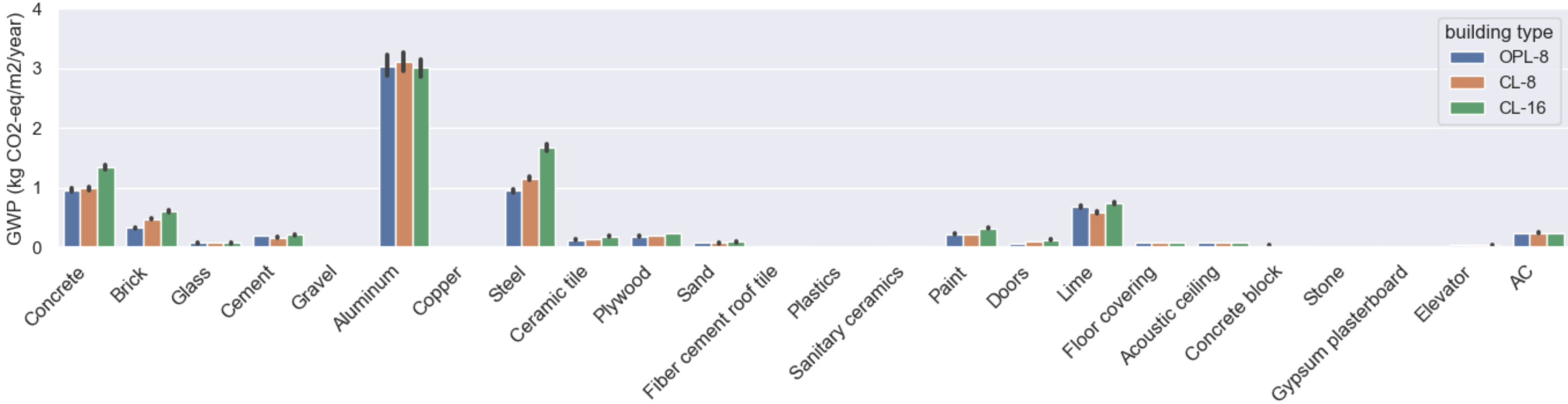

Figure 9 GWP of module A1-A4 as a function of material and building type.

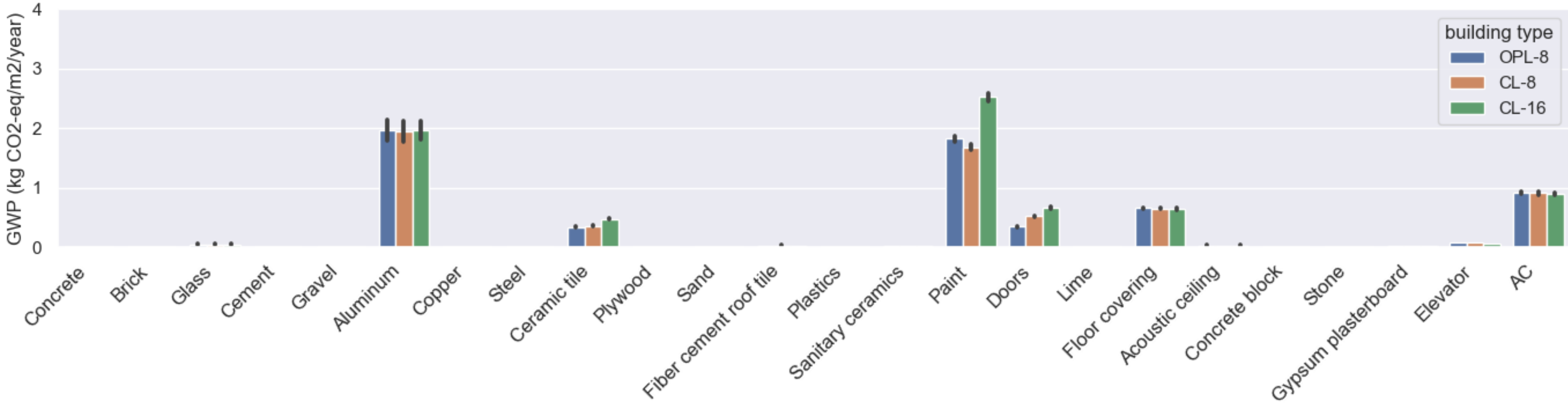

Figure 10 GWP of module B4 as a function of material and building type.

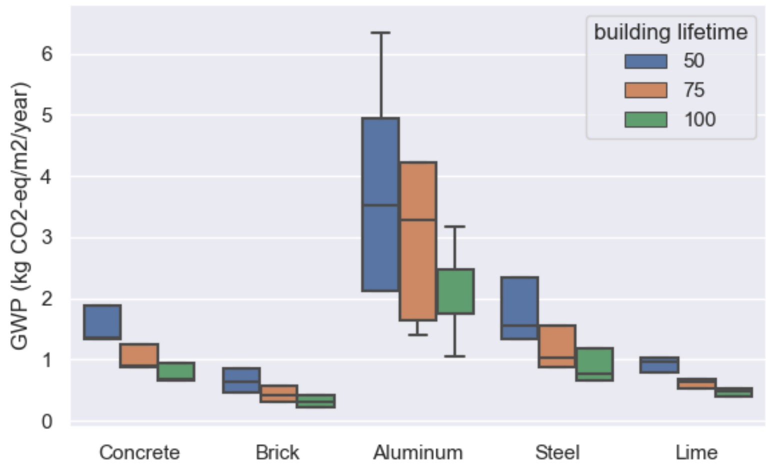

Figure 11 GWP of module A1-A4 as a function of selected materials and building lifetime.

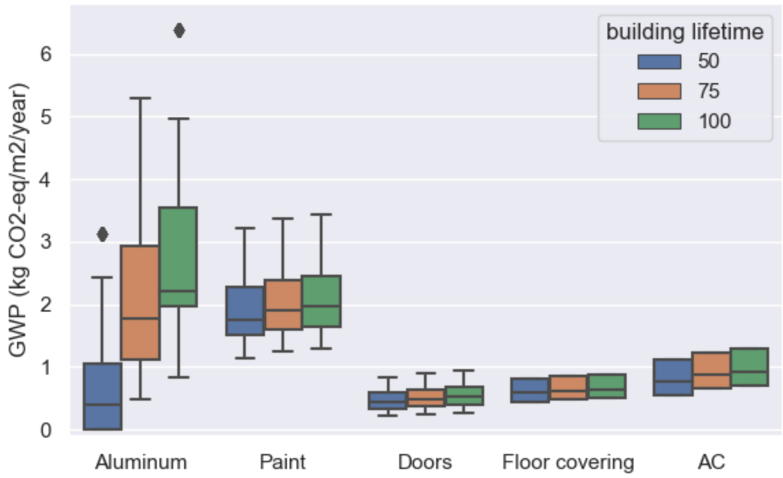

Figure 12 GWP of module B4 as a function of selected materials and building lifetime.

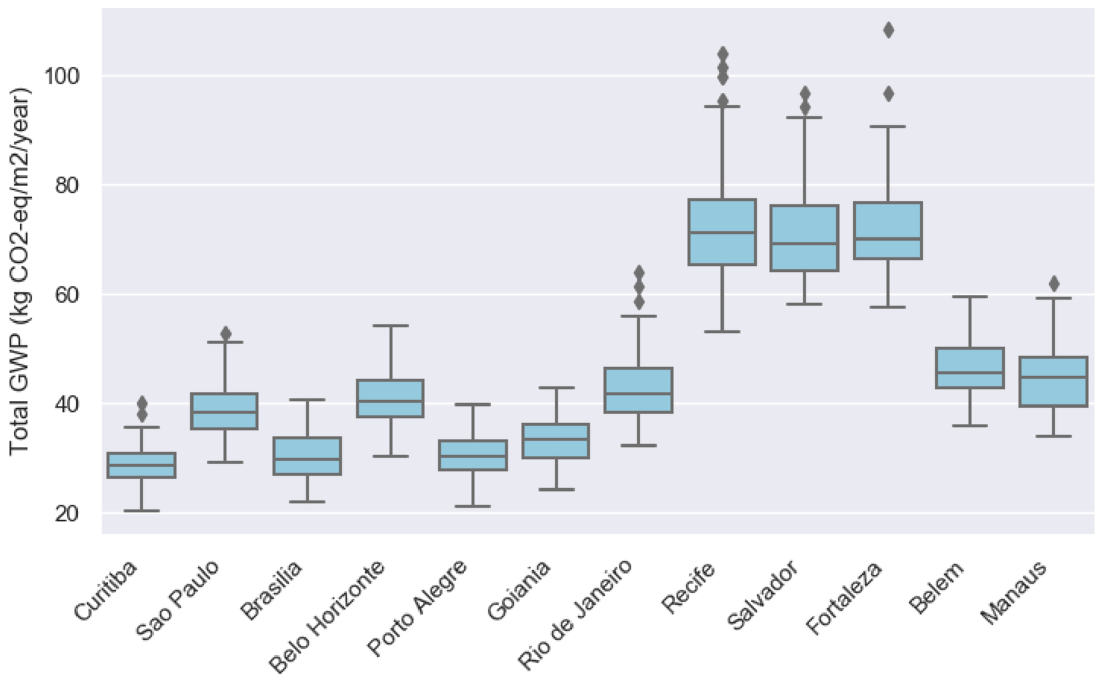

Figure 13 Total GWP impacts as a function of city. The cities are arranged according to increasing annual cooling degree hours. (Versage et al., n.d.)

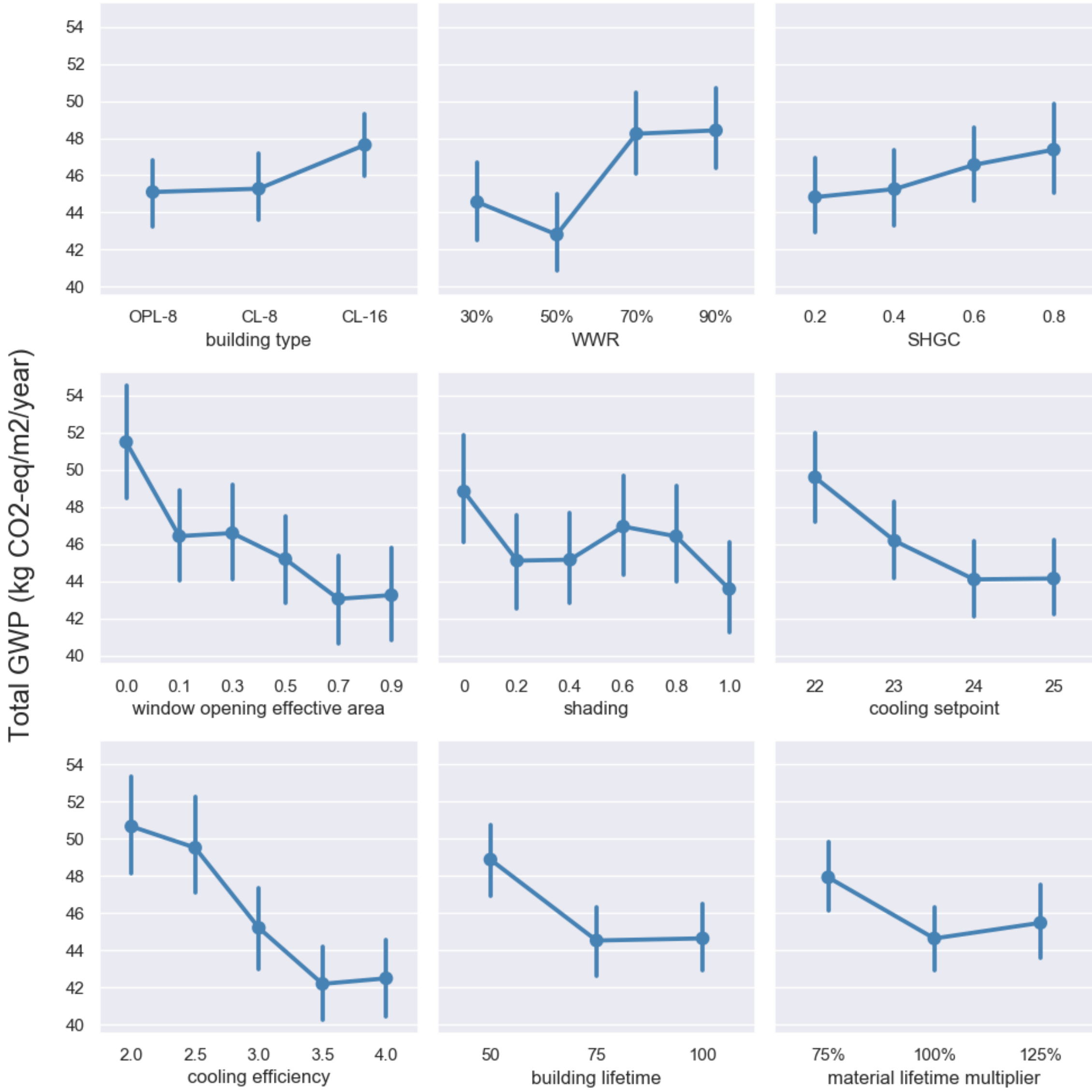

Figure 14 Total GWP impacts as a function of the chosen variable parameters. Parameter 'city' is excluded as it is shown in another plot.

4.4 Regression analysis

The relationship between the variable parameters and the results can also be investigated by means of a multivariate regression analysis.

The results of a regression model for total energy loads can be seen in Table 8. CDH shows the highest influence on the energy loads, followed by window opening effective area, cooling setpoint, SHGC and shading. Similar results can be observed both for mixed-mode and for fully air-conditioned buildings, except for the fact that in fully AC buildings, window opening effective area is a constant, so it was excluded from the analysis. Small differences between the two ventilation modes can be observed for WWR and CDH – mixed-mode buildings are slightly less sensitive to these parameters than fully AC buildings.

The results of a regression model for GWP impacts can be seen in Table 9. The sensitivity analysis was performed for the total GWP impacts and for each of the modules that was shown to have non-negligible impacts according to Figure 7. Modules A1-A4 are the most sensitive to building lifetime, followed by WWR and CL-16. Module B4 is the most impacted by material lifetime multiplier, followed by building lifetime, WWR and CL-16. Module B6 and total GWP show very similar trends: they are strongly influenced by the electricity mix, followed by CDH, cooling efficiency, and window opening effective area. However, the total GWP shows more sensitivity than B6 some of the remaining parameters: WWR, material lifetime multiplier, building lifetime, and CL-16.

Table 8 Results of the multivariate regression analysis of total energy loads.

Independent variable	**Standardized coefficients**		
	All buildings	**MM buildings only**	**AC buildings only**
Electricity mix	-0.03	-0.04	0.02
Climate (CDH)	0.82	0.88	0.91
CL-8	-0.01	-0.02	0.04
CL-16	-0.01	-0.02	0.02
WWR	0.08	0.07	0.12
SHGC	0.14	0.15	0.16
Window opening effective area	-0.42	-0.31	-
Shading	-0.09	-0.11	-0.10
Cooling setpoint	-0.19	-0.20	-0.20
Cooling efficiency	0.00	-0.01	0.00
Building lifetime	0.00	-0.01	0.00
Material lifetime multiplier	-0.01	-0.01	0.00
	Adj. R^2 = 0.934	Adj. R^2 = 0.945	Adj. R^2 = 0.977

Table 9 Results of the multivariate regression analysis of GWP impacts.

Independent variable	Standardized coefficients			
	A1-A4	**B4**	**B6**	**Total GWP**
Electricity mix	0.00	0.01	0.80	0.79
Climate (CDH)	0.01	-0.02	0.21	0.21
CL-8	0.02	0.01	0.00	0.00
CL-16	0.30	0.21	-0.01	0.08
WWR	0.42	0.28	0.02	0.14
SHGC	0.00	0.00	0.06	0.06
Window opening effective area	0.00	0.00	-0.14	-0.14
Shading	-0.01	0.01	-0.03	-0.04
Cooling setpoint	0.00	0.00	-0.07	-0.07
Cooling efficiency	-0.01	0.01	-0.18	-0.17
Building lifetime	-0.84	0.41	0.01	-0.08
Material lifetime multiplier	0.00	-0.82	0.00	-0.12
	Adj. R^2 = 0.952	Adj. R^2 = 0.938	Adj. R^2 = 0.957	Adj. R^2 = 0.957

5 Discussion

This chapter discusses how the results presented in the previous chapter allow to answer the research questions. Further, limitations of the study are listed and suggestions for future work are given.

5.1 Range of carbon footprint values

The first question of the study sought to determine the possible range of carbon footprint values for Brazilian office buildings. The results of the study show that the total GWP values vary from 20 to 108 kg CO_2-eq/m^2/year, with 41 kg CO_2-eq/m^2/year median. These values cannot be compared to any other Brazilian work on office buildings, as there was no study that would show the impacts of the whole life cycle of an office building. Foreign studies were not used because the GWP impact is dependent on climate and other regional factors. The values found in Brazilian literature for other types of buildings show that they are generally in the same order of magnitude. (Evangelista et al., 2018; Gomes et al., 2018)

The distribution of the total GWP impacts across different life cycle stages and modules was shown in Figure 7. The importance of different modules is discussed in the following paragraphs, in the order of decreasing significance for the total GWP values, as observed in Figure 7: operational energy use (B6), material production and transport to the building site (A1-A4), replacement (B4) and the remaining modules (A5, C1, C2-C4).

Operational energy use (B6) was the biggest contributor to the total GWP impact, and at the same time the main source of impact variations. This is an expected outcome, as it widely known in the research community that operational energy is the biggest contributor to environmental impacts of typical buildings. (Ramesh et al., 2010) The whole range of delivered energy values was found to cover values typically found in the Brazilian literature (Alves et al., 2017; Carvalho et al., 2010; Wong et al., 2019), with the exception of some bank branches (Borgstein and Lamberts, 2014) and buildings with special equipment such as data centers (Lamberts et al., 2015). This is a result of the fact that the model included only typical office equipment. Unfortunately, the emissions associated with this stage could not be compared with any literature values for similar reasons as explained above for the total GWP impact. The Brazilian studies that were used there (Evangelista et al., 2018; Gomes et al., 2018) cannot be used for module B6 due to strongly different assumptions on energy use.

The operational energy use was found to be strongly dependent on cooling energy load, which was subject to significant variations (Figure 4). This variability can be mostly attributed to different climatic conditions of the chosen cities (Figure 5), which is additionally supported by the regression analysis (Table 8). Comparison of the findings with those of Borgstein and Lamberts (2014) confirms that annual cooling degree hours measured using a wet-bulb temperature of 15°C can be a good predictor of energy loads in a given climate.

Among variable parameters other than the city, window opening effective area had the strongest effect on annual energy loads (Figure 6), which confirms the findings of Neves et al. (2019). The relation between the total energy load and SHGC, shading, WWR, and cooling setpoints reflects the trends observed by other researchers. (Neves et al., 2019; Santesso and Chvatal, 2018)

The results of the sensitivity analysis (Table 8) enable to conclude that energy loads in mixed-mode and fully AC buildings are sensitive to practically the same similar parameters. The only difference is window opening effective area (constant for fully AC buildings). The regression model also shows that energy loads were almost independent of the building type, suggesting that differences between the archetypes (a greater number of floors in CL-16, less thermal mass in OPL-8) did not significantly affect their energy performance.

Material production and transport to the building site (A1-A4) was the second most important factor in the total GWP impact, according to median values (Figure 7). The median impact was around 8 CO_2-eq/m^2/year. This value is of the same order of magnitude as values found in other studies on Brazilian residential buildings. (Evangelista et al., 2018; Morales et al., 2019) This finding is also in line with embodied GWP impacts of commercial buildings available in deQo database which lists 160 commercial buildings in 10 countries. (De Wolf, n.d.) On the other hand, even considering the full variance, the obtained values were smaller than the impact found by Gomes et al. (2018) in their study on a university building in Brazil. However, this discrepancy is easily explained by the fact that Gomes et al. (2018) studied a net zero energy building, characterized by much higher embodied impacts due to special energy-efficient design and photovoltaic panels.

The impact of modules A1-A4 was found to be dominated by emissions associated with aluminum, followed by steel, concrete, lime and brick (Figure 9). It is somewhat surprising that aluminum is the most impactful material, because various LCA studies have shown that concrete and steel are the two biggest contributors to climate change impacts. (Evangelista et al., 2018; Morales et al., 2019; Saade et al., 2014; Silva, 2013) However, none of these studies was specific to office buildings. On the other hand, the work by Najjar et al. (2019) was focused on Brazilian office building structures and it found that the "modern" building alternative (with a curtain wall system) was associated with extremely high aluminum emissions. Studies on façade solutions have also shown a particularly high levels of emissions for aluminum. (Brugnera, 2018; Taborianski and Prado, 2012)

Archetype CL-16 showed higher embodied emissions than OPL-8 and CL-8 for materials such as concrete, steel, and bricks (Figure 9). This is a direct result of higher material intensity values for CL-16 compared to OPL-8 and CL-8, which is associated with its height (16 floors). The fact that material intensity for structural materials increases with the building height has been mentioned by various researchers. (De Wolf, 2014; Foraboschi et al., 2014; Treloar et al., 2001) The same studies also show that taller buildings are associated with higher embodied energy. Therefore, a logical consequence of this fact is that taller buildings have higher embodied emissions, which was observed in the current study. Results of the regression model also confirm that archetype CL-16 has more impacts for modules A1-A4 (Table 9).

As expected, embodied emissions displayed a clear relationship with building lifetime: the longer the lifetime, the lower the embodied emissions (Figure 11). The widest spread of possible embodied emissions was observed for aluminum, which can be directly attributed to the fact that aluminum was modeled a linear function of WWR (Table 7).

Replacement (B4) was the next module with a relatively high contribution to the total GWP impact. The median impact was around 6 CO_2-eq/m^2/year. This value is of the same order of magnitude as replacement emissions found by Morales et al. (2019) for social housing in Brazil.

These material replacement emissions, also referred to as recurrent embodied emissions, were dominated by aluminum and paint, followed by the AC devices, floor covering, doors, and ceramic tile (Figure 10). Except for aluminum, these are generally materials with minor importance for initial embodied emissions, whose high importance for recurrent emissions results strictly from relatively frequent replacements. The most striking difference between initial and recurrent embodied emissions appears to be the one for paint whose median impact increases by almost 9 times. This is consistent with previous findings, as significance of paint in replacement emissions has been indicated by other researchers. (Morales et al., 2020; Tavares, 2006)

Material lifetime multiplier shows a strong relationship with the GWP impact of module B4 (regression analysis in Table 9), strongly decreasing the impact with increasing material lifetime. Such a strong influence of material service life on the replacement impacts has been noted by Morales et al. (2020), who focused on impacts associated with replacement of paint and mortar.

It is worth noting that building lifetime has the opposite effect for recurrent embodied emissions than for the initial ones, meaning that with longer lifetime, replacement is responsible for more emissions. This is also seen as the opposite sign of regression coefficients for building lifetime in modules A1-A4 and B4 (Table 9). Although the total material emissions decrease with increasing lifetime (some emissions are fixed for the whole lifetime), the significance of replacement-related emissions increases.

The remaining modules (A5, C1, C2-C4) had negligible GWP impacts (Figure 7). These modules refer to construction activities, demolition activities and end-of-life impacts associated with materials. Module A5 is often reported together with module A4 but its impacts are negligible compared to transport-related impacts of module A4. (Gomes et al., 2018) A study on an office building in Thailand has also shown negligible contribution of construction processes to the total impact. (Kofoworola and Gheewala, 2009) Stage C is also commonly found to be insignificant for the overall emission performance. (Evangelista et al., 2018; Gomes et al., 2018; Morales et al., 2019)

5.2 Importance of parameters influencing carbon footprint

The second research question concerned the importance of different parameters on the carbon footprint of Brazilian office buildings. The relationship between carbon footprint and the investigated parameters can be observed from the boxplots shown in Figure 13 and Figure 14 and from the results of a multivariate regression analysis shown in Table 9. The factors are analyzed in the decreasing order of importance according to the regression coefficients for total GWP impacts.

The choice of city had a very strong impact on emission performance of the buildings (Figure 13). However, the first look at Figure 13 shows no apparent trend between these two variables, which can be opposed to a clear trend visible in Figure 5 between energy loads and cities. What is particularly surprising is that Recife, Salvador, Fortaleza have notably higher emissions. An explanation for this finding is that all these three cities are located in the North-eastern region of Brazil, whose electricity is almost twice as emission-intensive than electricity found in the other four regions (Appendix 5). This fact can also be observed in Figure 8, where highly emission-intensive North-eastern buildings are clearly distinct from the other datapoints.

Therefore, warm climate combined with emission-intensive electricity of cities located in the North-east makes their office building stock particularly polluting. This result is consistent with findings of other researchers, showing that electricity mix is the most important parameter for GWP impacts. (Heeren et al., 2015) Results of the regression analysis clearly show that electricity mix has a much stronger influence on the total GWP impacts than climatic conditions represented using CDH.

Following electricity mix and climate, cooling efficiency has the most influence on the total GWP values, as seen in the regression results. The reason is that module B6 is generally responsible for the highest share of total emissions and cooling efficiency directly influences the delivered energy values considered in this module.

Next, the total GWP is sensitive to WWR and window opening effective area to a very similar degree. The source of this impact can be traced back to modules A1-A4 and B4 in case of WWR and to module B6 in case of window opening effective area.

As we see in Figure 14, WWR-GWP relationship shows a very irregular behavior. The likely reason is the amplification of sampling error seen already for the energy load values in Figure 6, exhibiting similar irregularities. The influence of WWR on the total GWP values is mostly related to high aluminum-related impacts observed in modules A1-A4 and B4.

The influence of window opening effective area on GWP has to be interpreted with caution. It results purely from the fact that this parameter has a strong influence on energy loads, as shown in Table 8. However, this factor is only important for MM buildings. The correlation between the final GWP impacts and window opening effective area is relatively stronger because MM buildings are overrepresented in the sample: on average, there is 1 fully AC building for every 5 MM buildings. However, MM buildings are likely a minority within the office building stock in Brazil.

Further, there is material lifetime multiplier and building lifetime impacts on the GWP value. The regression results show that increase in these parameters should have an increasing effect on the total GWP. However, the trends observed in Figure 14 suggest that there is an increase in emissions for the longest building and material lifetime. As it turns out, this is actually an unfortunate result of sampling error. As can be seen in Figure 6, there seems to be an increasing trend for energy load with increasing lifetime of buildings and components, despite the fact that these parameters were only included after energy modeling. This effect likely influences the total emissions. If the building sample was larger than 1000 items, such sampling errors would decrease and there could be a stronger correlation seen between these lifetime parameters and the total GWP.

Building type, represented by binary variables CL-8 and CL-16, shows a relatively small influence on the total GWP impacts. This parameter has a much stronger influence on the material-related modules of the building life cycle (A1-A4 and B4) but its importance decreases for the total emissions due to the dominance of operational energy use impacts. However, this parameter would gain on importance for a building designed in high standard of energy-efficiency.

Lastly, parameters such as cooling setpoint, SHGC and shading turn out to influence the climate change impacts of the building only to a limited degree. This finding is somehow unexpected as many energy-related studies underlined the importance of these parameters to energy performance on office buildings, which was the primary reason of including these parameters in the analysis. This shows that parameters important for energy-efficiency of a building do not necessarily have a strong influence the carbon footprint, as there are multiple other parameters that influence the final results. However, the effect of these variables on the GWP impact is still non-negligible.

5.3 Recommendations for better emission performance

The third question in this work was related to recommendations that could be given to improve the emission performance of the current office building stock in Brazil.

The study found a very strong correlation between electricity mix and total GWP impacts of the investigated building. North-east region with the most polluting electricity mix happens to also have high energy use for cooling due to warm climate. The exact emission intensity of electricity is different on the state level, with some states worse than others. For example, the state of Ceará, where Fortaleza is located, has its electricity mix of 48% coal, 27% wind, 19% gas, and 6% fuel oil i.e. three quarters of electricity is fossil fuel based. (MME, 2016) As mentioned in the literature review, the electricity production in Brazil is based on hydropower (65% in 2018). (MME, 2019) However, the example of Fortaleza and other cities in the North-east shows that in some regions, renewable energy has a much smaller share, leading to high emission-intensity of buildings. What is also concerning is that the electricity mix in Brazil is steadily deteriorating, suggesting that the whole office building stock is increasingly more polluting with each year. This was already described in the literature review and some possible solutions were also suggested.

The two most important recommendations for improving the GWP performance of the Brazilian office buildings are the same as suggestions for issues with deteriorating quality of electricity mix in Brazil: renewable energy development and efforts to limit the growth of electricity consumption. The best result could be obtained by a combination of the two, because increasing national electricity consumption is one of the main reasons for increasing dependence of the country on fossil fuels for power generation.

As already stated in the background chapter, research efforts have contributed to the creation of national initiatives aimed at increasing the awareness of the most beneficial energy-efficiency strategies, with some national programs focused on office buildings in particular. (CBCS, n.d.; PBE, n.d.; PROCEL, n.d.; ProjetEEE, 2020) In the context of the findings presented in this work, these initiatives have a great importance also for emission performance of the stock, influencing it in at least two ways: 1) a direct influence on emission levels caused by smaller consumption of electricity, responsible for the operational energy use impacts of the buildings; 2) an indirect influence caused by smaller pressure on the electricity grid, which on a larger scale could positively influence the electricity mix.

From this perspective, any parameter that was shown to have a strong correlation with operational energy use could potentially be a part of solution to the problem of increasing emission-intensity of the Brazilian electricity mix. Decreasing cooling setpoint temperature, solar heat gain coefficient of glazing and window-to-wall ratio could all be examples of efforts that could be undertaken in all office buildings, regardless of ventilation mode. Additionally, mixed-mode buildings could be promoted as their emission performance is significantly better, particularly if the windows have a large opening area.

5.4 Limitations of the study

The main criticism of this work could be that it does not include national life cycle inventory data for some of the most important processes included in the system, particularly aluminum production. It has been shown by other researchers that data regionalized to Brazilian context can result in significantly smaller environmental impacts than global data. (Morales et al., 2019, 2020) A possible explanation for this trend is a high share of renewable energy in the average Brazilian electricity mix. Therefore, material production impacts can potentially be overestimated.

Adaption of national-specific datasets should also include country-specific transportation data, as many researchers note that Brazilian transportation system is very distinct from the one found in the international database. (Condeixa et al., 2014; Gomes et al., 2018; Taborianski and Prado, 2012) Primarily based on road freight, Brazilian transportation can significantly increase material impacts. (Gomes et al., 2018; Taborianski and Prado, 2012) As a result, higher transportation impacts could partly counterbalance higher material production impacts. Nonetheless, the exact impact of data regionalization in the context of this work can only be found by means of another study.

Another weak point of this work is only a limited consideration of qualities of a mixed-mode ventilation mode. Such systems are strongly dependent on design features such as office partitions (Mariana, 2013) or narrow plan depths, needed for sufficient flow of air across interior spaces (Wood and Salib, 2013, p. 165). Potentially, it could turn out that the considered office geometry does not fit the design requirements for a mixed-mode building. The thermal comfort associated with these two modes was not analyzed either. However, this is partly an intrinsic issue of any study that attempts a comparison between these different ventilation systems, raised for example by Borgstein et al. (2016), who gave Brazilian fully air-conditioned and mixed-mode buildings as an example of these comparability issues.

Likewise, the differences between these two ventilation modes were not fully explored – in real life, each of them can have particular effects on building design and material composition. This would be especially true if a fully naturally ventilated building were considered as well because no AC system would be needed.

Additionally, this work does not consider all the constituents of carbon footprint of a building. Building systems such as drains, ventilation ducts, and fire protection equipment were not included. For material modeling, only elevators and AC units were included, while in real buildings more built-in systems are found. On top of that, some electricity end-uses were not taken into account, e.g. data centers or uninterruptible power sources (UPS), commonly found in Brazil due to regular power fluctuations in the grid. (Borgstein and Lamberts, 2014)

Some more criticism could be directed towards material intensity values which were relatively similar in the considered archetypes, while real buildings are characterized by large variations in material intensity. (De Wolf, n.d.; Heeren and Fishman, 2019)

Finally, the material contribution of shading devices was not considered in this study. Shading devices found in real buildings can be made of aluminum (Brugnera, 2018, p. 149) so their impact on environmental performance on the building could be significant. Incorporating this into the study would also result in interesting trade-off effects related to shading – it would reduce operational energy impacts while at the same time it would increase the embodied material impacts.

5.5 Further research

Despite these promising results, some work remains to be done. First of all, the issues mentioned as limitations of this study could be addressed. This would include an implementation of national life cycle inventories, a full analysis of the differences between the ventilation strategies (fully AC vs. MM), and an addition of material composition data (particularly for shading devices).

To develop a full picture of impacts associated with Brazilian office buildings, additional studies should consider more environmental impact categories besides GWP.

Finally, more data collection efforts could allow to estimate parameter distributions found in real buildings, which would yield results representative for the whole office building stock. In such a study, state-level electricity mix could be used to better estimate the GHG emissions associated with electricity use. Such a characterization of the office building stock could serve as a groundwork for possible future studies, allowing for scenario modeling, and assisting in deployment of low-emission pathways. This could also be complemented by an investigation of factors causing poor environmental performance of these buildings, which would propose potential solutions to the most common issues – as it was found out during the course of this work, such poor performance may often result from forces that are far beyond the control of the building designer or facility manager.

6 Conclusions

The purpose of the current study was to investigate the carbon footprint of Brazilian office buildings. As it was shown by means of a literature review, this topic has not been yet explored so the climate change impacts associated with the office building stock are not understood. The importance of such a study is supported by numerous environmental issues caused by the current state of the Brazilian construction industry, particularly considering the fact that inaction will make the problems aggravate at an even faster rate due to trends of increasing office floor area and energy use of the sector.

To explore the topic of the carbon footprint of Brazilian office buildings, this work intended to find out what is the range of carbon footprint values of these buildings, which parameters have the strongest impact and how this impact could be reduced.

This was done by means of methodology which included 6 steps: archetype definition, sample selection, energy modeling, material modeling, emission modeling and sensitivity analysis of the results. Archetype definition involved the specification of material composition, basic design features, and operational regimes. The archetypes were created based on the available literature, with some features resembling those typically found in real buildings (such as cooling efficiency), while others are chosen to investigate possible improvement options (such as shading). The archetype definition included 10 variable parameters which were explored using the Latin hypercube sampling method. By means of energy and material modeling, an LCA model was built to assess the climate change impacts associated with the sampled buildings.

The results of the model have shown that the total GWP values vary from 20 to 108 kg CO_2-eq/m^2/year, with 41 kg CO_2-eq/m^2/year median. The main contributor, and the main source of variations, was the operational use phase (B6), with a median impact of 25 CO_2-eq/m^2/year. This phase, in turn, was mainly influenced by cooling energy loads, strongly dependent on climatic conditions. The delivered energy was in line with available empirical data. However, the calculated emissions associated with operational energy use could not be benchmarked against any other study.

The life cycle GWP impacts were also influenced by emissions embodied in material. Initial embodied emissions caused by material production and transport to the building site (modules A1-A4) had a median of around 8 CO_2-eq/m^2/year. This value was found to be of the same order of magnitude as values found in other studies, both in Brazil and abroad. The impact of modules A1-A4 was found to be dominated by emissions associated with aluminum, followed by steel, concrete, lime and brick. The predominant role of aluminum can be supported by findings of other researchers which investigated façade systems typical for office buildings.

Further, the climate change impacts were influenced by recurrent embodied emissions from replacement (module B), whose median impact was around 6 CO_2-eq/m^2/year. Such order of magnitude of these impacts was also found in another Brazilian study. These material replacement emissions were dominated by aluminum and paint, followed by AC devices, floor covering, doors, and ceramic tile. High significance of paint in replacement emissions is consistent with previous findings.

The GWP impacts associated with construction activities, demolition activities and end-of-life impacts associated with materials (modules A5, C1, C2-C4) were negligible.

The carbon footprint was mainly influenced by the choice of city, which was associated with both with the change of climate (cooling loads) and with emission intensity of electricity. The highest impact values were observed for cities located in the North-east, a region which combines warm climate with a relatively polluting electricity mix. Other parameters with strong influence on the total GWP impacts include cooling efficiency, window opening effective area, and WWR.

Based on these findings, it was suggested that most efforts towards improving the carbon footprint of the Brazilian office buildings should focus on reducing the emission-intensity of the electricity mix, which can be done by increasing the share of renewable energy and by energy-efficiency efforts. In this sense, every parameter that was found to influence operational energy use of the buildings could potentially be a part of the solution. Promotion of mixed-mode buildings was also suggested as a means of decreasing impacts through decreased operational energy use.

The present study provided the first comprehensive assessment of the possible range of carbon footprint values of Brazilian office buildings. It contributes to our understanding of parameters which influence climate change impacts of these buildings during their life cycle stages: construction, operation, and demolition. This new understanding helps to identify strategies that could be used to decrease the environmental impact while still providing the necessary service level needed by the building occupants.

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Appendices

Appendix 1: Material intensity for materials and equipment in three building archetypes.

Material/equipment	Material intensity (kg/m2)			Source	Assumed density/weight
	OPL-8	CL-8	CL-16		
Concrete	895.40	885.05	1 247.02	(1)	2380 kg/m^3
Brick	72.38	102.34	135.94	(1)	2.2 kg/unit
Concrete block	28.37	16.11	13.87	(1)	16.2 kg/unit
Steel	33.31	38.89	58.70	(1)	-
Cement	19.86	16.28	21.51	(1)(2)	-
Lime	49.66	40.70	53.78	(1)(2)	-
Gravel	62.09	45.72	57.29	(1)	1430 kg/m^3
Sand	324.26	274.44	364.62	(1)	1500 kg/m^3
Fiber cement roof tile	1.68	2.12	1.30	(1)	1900 kg/m^3
Plywood	16.13	16.66	20.71	(1)	625 kg/m^3
Doors	2.10	3.16	4.12	(1)	27.6 kg/m^2
Ceramic tile	11.20	11.85	16.03	(1)	15.56 kg/m^2
Glass	according to the window-to-wall ratio			-	15 kg/m^2
Aluminum	according to the window-to-wall ratio			(3)	50.7 kg/m^2
Stone	0.65	0.38	0.47	(1)	78 kg/m^2
Gypsum plasterboard	1.20	1.24	1.81	(1)	6.6 kg/m^2
Paint	2.31	2.13	3.26	(1)	1.1 kg/liter
Copper	0.49	0.29	0.77	(1)	-
Sanitary ceramics	0.70	0.72	0.72	(1)	25 g/unit
Plastics	0.09	0.10	0.09	(1)	0.24 kg/m
Bitumen emulsion	4.84	2.31	2.88	(1)	-
Floor covering	1.80	1.80	1.80	(4)	-
Acoustic ceiling	11.10	11.10	11.10	(5)	-
Elevator	1.04	1.04	0.78	(6)	2490 kg/unit
AC unit	2.56	2.56	2.56	(7)	143 kg/unit

(1) ABNT (2005)
(2) Cement and lime reported as one value in ABNT (2013); they were separated using a proportion of 1:2.5, assuming that half of the final product is plaster (1:2) and half is mortar (1:3). (Thomaz et al., 2009, p. 41)
(3) Assumed 1:4 proportion of glass to aluminum. (ABNT, 2005)
(4) Forbo (2016)
(5) Knauf A/S (2016)
(6) 8-floor and 16-floor archetypes have 2 and 3 elevators, respectively. (Sinduscon-MG, 2007)
(8) Assumed AC capacity 900 m^3/h which is average capacity from the Ecoinvent process data (Primas, 2010), airflow 7.5 liter/s/person (see 3.1.4) and occupant density 0.11 people/m^2 (see 3.1.5).

Appendix 2: Lifetimes of materials and equipment used in buildings.

Material/equipment	Element type	Lifetime range (years)	Adopted lifetime (years)	Source
Concrete	Main structure	-	building lifetime	(1)(2)
Brick	Façade	40-building lifetime	building lifetime	(1)(2)
Concrete block	Façade	40-building lifetime	building lifetime	(1)(2)
Steel	Main structure	-	building lifetime	(1)(2)
Cement	Façade	40-building lifetime	building lifetime	(3)
Lime	Façade	40-building lifetime	building lifetime	(3)
Gravel	Other	40-building lifetime	building lifetime	(3)
Sand	Façade	40-building lifetime	building lifetime	(3)
Fiber cement roof tile	Roof	10-100	35	(1)(2)
Plywood	Main structure*	-	building lifetime	(1)(2)
Doors	Windows & Doors	5-20	12	(1)(2)
Ceramic tile	Finishes	13-50	20	(1)(2)
Glass	Windows & Doors	20-60	45	(1)(2)
Aluminum	Windows & Doors	20-60	45	(1)(2)
Stone	Finishes	-	30	(4)
Gypsum plasterboard	Finishes	13-30	20	(1)(2)
Paint	Finishes	3-12	8	(1)(2)
Copper	Other	20-40	30	(1)(2)
Sanitary ceramics	Other	30	30	(2)
Plastics	Other	20-40	30	(1)(2)
Bitumen emulsion	Roof	10-100	35	(1)(2)
Floor covering (carpet)	Finishes	5-12	8	(1)(2)
Acoustic ceiling	Finishes	60	60	(5)
Elevator	Systems	10-50	25	(2)
AC unit	Systems	10-20	15	(2)

* Plywood is used as formwork for concrete casting.
(1) ABNT (2013)
(2) BOMA (2010)
(3) Assumed to be a part of the façade.
(4) Marble countertops, assumed 30 years of lifetime
(5) Knauf A/S (2016)

Appendix 3: LCI datasets for materials and equipment.

Material/equipment	Production process	Disposal process
Concrete	market for concrete, 30MPa, BR	treatment of inert waste, inert material landfill, RoW
Brick	market for clay brick, GLO	treatment of inert waste, inert material landfill, RoW
Concrete block	market for concrete block, BR	treatment of inert waste, inert material landfill, RoW
Steel	market for reinforcing steel, GLO	treatment of scrap steel, inert material landfill, RoW
Cement	market for cement, unspecified, BR	treatment of inert waste, inert material landfill, RoW
Lime	market for lime, hydrated, packed, RoW	treatment of inert waste, inert material landfill, RoW
Gravel	market for gravel, crushed, BR	treatment of inert waste, inert material landfill, RoW
Sand	market for sand, BR	treatment of inert waste, inert material landfill, RoW
Fiber cement roof tile	market for fibre cement roof slate, GLO	treatment of inert waste, inert material landfill, RoW
Plywood	market for plywood, for indoor use, RoW	market for waste wood, untreated, BR
Doors	market for door, inner, wood, GLO	market for waste wood, untreated, BR
Ceramic tile	market for ceramic tile, GLO	treatment of inert waste, inert material landfill, RoW
Glass	market for flat glass, coated, RoW	market for waste glass, BR
Aluminum	market for window frame, aluminium, U=1.6 W/m2K, GLO	treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing, RoW
Stone	market for natural stone plate, cut, GLO	treatment of inert waste, inert material landfill, RoW
Gypsum plasterboard	market for gypsum plasterboard, GLO	treatment of waste gypsum, inert material landfill, RoW
Paint	market for alkyd paint, white, without water, in 60% solution state, RoW	treatment of waste paint, inert material landfill, RoW
Copper	market for wire drawing, copper, GLO	market for copper scrap, sorted, pressed, GLO
Sanitary ceramics	market for sanitary ceramics, GLO	treatment of inert waste, inert material landfill, RoW
Plastics	market for extrusion, plastic pipes, GLO	market for waste plastic, mixture, BR
Bitumen emulsion	market for bitumen adhesive compound, cold, GLO	treatment of waste bitumen, sanitary landfill, RoW
Floor covering	market for textile, non woven polypropylene, GLO	market for waste polypropylene, BR
Acoustic ceiling	no Ecoinvent process, an Environmental Product Declaration (EPD) used instead (Knauf A/S, 2016)	
Elevator	market for elevator, hydraulic, GLO	(not applicable – disposal included in the production process)
AC unit	market for blower and heat exchange unit, central, 600-1200 m3/h, GLO	treatment of used blower and heat exchange unit, central, 600-1200 m3/h, RoW

* Ecoinvent 3.6, cut-off allocation. ReCiPe midpoint H method.

Appendix 4: LCI datasets for construction and end-of-life processes.

Reference name	Process*
Diesel	diesel, burned in building machine, GLO
Machinery	building machine production, RoW
Transport	market for transport, freight, lorry, unspecified, RoW

* Ecoinvent 3.6, cut-off allocation. ReCiPe midpoint H method.

Appendix 5: Selected Brazilian cities, their cooling degree hours (CDH), region, LCI datasets, and elementary GWP impact of the regional electricity.

City	CDH*	Region	Electricity process **	GWP (kg CO_2-eq/kWh)***
São Paulo	14172	South-east	market for electricity, low voltage, BR-South-eastern grid	0.227
Rio de Janeiro	45016	South-east	market for electricity, low voltage, BR-South-eastern grid	0.227
Brasília	16624	Mid-west	market for electricity, low voltage, BR-Mid-western grid	0.145
Salvador	67930	North-east	market for electricity, low voltage, BR-North-eastern grid	0.398
Fortaleza	71394	North-east	market for electricity, low voltage, BR-North-eastern grid	0.398
Belo Horizonte	23883	South-east	market for electricity, low voltage, BR-South-eastern grid	0.227
Manaus	82005	North	market for electricity, low voltage, BR-Northern grid	0.197
Curitiba	9397	South	market for electricity, low voltage, BR-Southern grid	0.137
Recife	63550	North-east	market for electricity, low voltage, BR-North-eastern grid	0.398
Goiânia	31081	Mid-west	market for electricity, low voltage, BR-Mid-western grid	0.145
Belém	81393	North	market for electricity, low voltage, BR-Northern grid	0.197
Porto Alegre	23954	South	market for electricity, low voltage, BR-Southern grid	0.137

* Calculated by Versage et al. (n.d.) with a wet-bulb temperature of 15°C
** Ecoinvent 3.6, cut-off allocation.
*** Ecoinvent 3.6, cut-off allocation. ReCiPe midpoint H method.

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