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Embodied, operation, and commuting emissions: A case study comparing the carbon hotspots of an educational building

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a b s t r a c t

Building operational energy, mobility energy, and materials embodied energy contribute to a significant portion of the global greenhouse gas emissions. Buildings stand at the intersection of these three contributors and, as a result, are largely responsible for the scale of society's carbon footprint. The global consensus on limiting climate change to a 2° Centigrade temperature increase is forcing nations to become carbon-centric and to adopt a range of carbon-neutral strategies in their building standards and codes. However, most of these standards define carbon-neutrality only in terms of energy efficiency, with very few organizations introducing a holistic approach for assessing the built environment carbon footprint. Mobility of tenants, for instance, has been indicated as a carbon hotspot by several studies. Thus, several green building standards have been inclined to include mobility emissions in the short- term future. However, emissions from daily transportation of a building's occupants are rarely measured and explored by building $LCCO_2A$ studies, thus the share of mobility emissions compared to embodied and operational emissions is not well-known. In this paper, we consider embodied, opera- tional, and mobility of tenants as Carbon Intensive Stages (CIS). The study attempts to (1) quantify and compare the CIS of a building, and (2) propose a framework to facilitate the quantification of the carbon footprint of the building environment. We provided a case study on an US educational building, where we found that building operational phase accounted for 70% of the total carbon emissions, followed by mobility (24%) and embodied carbon (6%). These results help better understand the weight of mobility emissions in the built environment and, in fact, suggests that mobility, operational, and embodied carbon should be targeted as the triple bottom line of building carbon footprint assessments and highly encouraged by green building certification standards.

1. Introduction

Building operations, embodied energy, and mobility/transportation contribute to most of the total greenhouse gas (GHG) emissions in our society and all three of these categories are directly associated with the built environment. Buildings stand at the intersection of these three contributors and, as a result, are largely responsible for the enormous scale of society's carbon footprint (Fenner et al., 2018). Building operations alone consume over 30% of worldwide energy production and emit over 30% of the process-related global greenhouse gases (Sbci, 2009; Deru and Torcellini, 2007), although these values can vary significantly between developed and developing countries, as well as between urban and rural areas (Huo et al., 2019a, 2020; Cao et al., 2016; Wu et al., 2016; Berardi, 2015). According to many life-cycle studies, the operational phase represents the largest share of total carbon emissions, mostly due to the continuous energy-related emissions over the lifespan of buildings (Fenner et al., 2018; Junnila et al., 2006). Embodied emissions, which are associated with the extraction of natural resources and their transportation and conversion into building products, are the second largest contributor (Fenner et al., 2018; Chau et al., 2015). Embodied emissions have received substantial attention because high performance buildings continue to reduce their energy consumption, thereby increasing the significance of embodied energy (Röck et al., 2020). There is also a significant discussion about how to lower the embodied emissions of building construction products since their manufacturing process is relatively difficult to alter. Thus, more attention has been given to the design stage as a starting point for defining the total carbon emissions of the future buildings (Zhang and Zheng, 2020a). Lastly, the construction and the dismantling/disposal phases contribute to a small fraction of the total emissions and are typically not considered in most Life-Cycle Carbon Emission Assessment studies ($LCCO_2A$) (Cuéllar-Franca and Azapagic, 2012).

Recent studies have also speculated on the need to consider mobility emissions in the total GHG emissions of buildings. While transportation emissions associated with building materials are usually small (Fenner et al., 2018; Biswas, 2014), some studies suggest that daily commuting of tenants could represent a significant share of the total GHG emissions of a building (Ozawa-Meida et al., 2013; Klein-Banai and Theis, 2013; Augustsson, 2014; Thomas et al., 2015; Piano, 2019; Pérez-Neira et al., 2020). With respect to this, the building location plays an important role in reducing the carbon footprint of our society since it directly affects the preferred transportation mode used by tenants (Heinonen et al., 2013; Onat et al., 2014; Wilson and Navaro, 2007; Pérez-Neira et al., 2020; Yu et al., 2019). However, emissions from daily transportation of a building's occupants are rarely measured and explored by building $LCCO_2A$ studies, thus the share of mobility emissions compared to embodied and operational emissions is not well-known.

As society is shifting toward a "carbon-centric" point of view and green building certification systems are beginning to account for carbon emissions, this study attempts to (1) quantify and compare the above-mentioned Carbon Intensive Stages (CIS) of a building, i.e. embodied, operational, and commuting emissions, and (2) propose a framework to facilitate the quantification of the carbon footprint of the building environment. This is accomplished by introducing an analysis model that provides practical results when making decisions about low-carbon design. The proposed methodology is a holistic but straightforward approach that can help building owners, designers, researchers, and other stakeholders easily evaluate the $LCCO_2A$ of single buildings and establish measures to reduce carbon emissions. The proposed methodology is best used for strategic development planning of large institutions or buildings with transient occupancy such as university campuses, large urban developments, and office buildings.

2. Low carbon-built environment

2.1. *Concept and terminology*

There is an emerging global trend towards the development of building energy performance standards and the expansion of their scope to include GHG emissions. As building policy shifts to a "carbon-centric" model, the building construction section has seen an increase in the number of definitions and standards addressing carbon neutrality. While there are various and contradicting definitions and ways to achieve it (Bales et al., 2018), carbon neutrality in this paper is defined as achieving net zero carbon emissions by balancing the total amount of carbon through strategies such as sequestering, offsetting, or buying carbon credits. On the other hand, zero carbon or carbon-free is defined as a situation where no carbon is emitted in the process, thus there is no need to offset carbon.

Currently, most green building standards lack a holistic approach for quantifying carbon emissions. In fact, most have adopted the carbon neutrality focusing on the operational energy- related emissions of the building and on carbon offsetting strate- gies. A few standards and/or organizations have introduced or suggested the inclusion of other life-cycle stages, alternatives, or a broader carbon neutrality definition. For example, the World Green Building Council (Laski and Burrows, 2017) has called for the dual goals of, (1) all new buildings operating at net zero carbon from 2030, and (2) all buildings operating as close as possible to zero carbon by 2050 by prioritizing lower carbon intensity strategies rather than by carbon offset strategies. The GBC has also indicated that this approach may incorporate embodied emissions in the future. The Australian Government (Department of the Environment and Energy, 2017) released a voluntary standard for carbon neutrality of building accounting for emissions as a result of the operation of a building. Tenant mobility emissions were deemed relevant, but inclusion was considered impractical due to the current lack of data and calculation methodologies. The Canada Green Building Council (B.C. Canada Green, 2017) is now requiring reporting of embodied emissions from structural and envelope materials, indicating future plans to establish emission targets. The City of Vancouver (City, 2018) has indicated future targets for embodied emissions and occupant travel while considering oper- ational emissions. Architecture 2030 (A. 2030, 2018) has revised its targets to include a reduction of 50% of the GHG emissions for tenant mobility and water consumption by 2030 and zero embodied emissions by 2050. The Carbon Neutral Design Project (Boake et al., 2012), which was developed in response to the Ar- chitecture 2030 Challenge, recommends calculating GHG emissions from the operational phase, embodied energy, and for occupant mobility. Switzerland has adopted the most advanced low-carbon building standards with the establishment of specific targets. Switzerland has implemented the 2000-Watt Society concept, suggesting everyone should reduce their power consumption to 2000 Watts (Stulz et al., 2011; Heeren et al., 2012). The 2000-Watt-Society takes a holistic approach to carbon neutrality, considering the operational phase, the embodied emissions, and mobility emissions of tenants. Embodied energy and associated GHG emissions are calculated continuously during the building's lifetime. The City of Zürich, for example, has committed to the 2000-Watt Society vision and has set a target for residential building GHG emissions by 2050 to be 16.5 kg CO_2e/m^2/year, which is distributed as 2.5 kg CO_2e/m^2/year for operation; 8.5 kg CO_2e/m^2/year for embodied energy; and 5.5 kg CO_2e/m^2/year for mobility. The 2000-Watt Society template offers a policy trajectory that regulates design and construction processes, while also including behavioral changes.

2.2. *Life-cycle carbon emission assessment*

$LCCO_2A$, a subset tool of Life-Cycle Assessment (LCA) analysis, has become essential for decision-making processes as the evi- dence of climate change and its consequences in the environment have become noticeable (Chau et al., 2015). The greatest benefit of LCA is its ability to compare several features of a product in order to identify possible impactful characteristics and, from the results, develop strategies that could potentially minimize and/or eliminate the harm. $LCCO_2A$ has been widely used in the building construc- tion sector as a means of learning how to evaluate the environ- mental effects of a specific product over its life cycle (Wang et al., 2018) and how to reduce the carbon impacts of buildings (Sbci, 2009; EPA, 2011). The literature abounds with carbon footprint studies focusing on particular materials (Cole, 1998; Cang et al., 2020), systems/stages/processes (Taborianski and Prado, 2012;

Resch et al., 2020; Cang et al., 2020; Zhang and Zheng, 2020b), whole buildings (Chau et al., 2015; Geraldi and Ghisi, 2020), and country and/or community building stock (Huo et al., 2019b;Geraldi and Ghisi, 2020; Huo et al., 2020; Wu et al., 2016). However, carbon emission calculations often diverge in terms of boundaries, scopes, greenhouse gas units, and methodologies, making it difficult to compare studies (Fenner et al., 2018). Diffi- culties in applying LCA in the building industry have also been noted because of general and unspecific requirements, large quantities of data with its respective uncertainties, and the time and effort required for assessment, the long-life span of some buildings, and the unique design of some buildings (Basbagill et al., 2013). Furthermore, emissions from different life-cycle phases vary greatly (Roh and Tae, 2017) but are handled in a way such that less impactful phases receive the same attention as phases with greater emissions, while other emissions associated with buildings, such as those causing eutrophication and acidification, are not even considered in most studies.

2.3. *Carbon Intensive Stage boundary*

Several studies reviewed the carbon footprint of building over their life-cycle (Fenner et al., 2018; Amanjeet et al., 2011; Cabeza et al., 2014; Anand and Amor, 2017). A typical building $LCCO_2A$ usually reports emissions in four life-cycle stages: material pro- duction, construction, operations, and dismantlement/disposal (Fig. 1). As mentioned above, the product stage (A1-3) and opera- tional energy use (B6) comprise for most carbon emissions. Some studies also suggest that daily commuting of tenants (B30) could represent a significant share of the total GHG emissions of a building, but these emissions are rarely measured and explored by building $LCCO_2A$ studies. The following will highlight the main literature findings about these three carbon hotspots, ie. A1-3, B6, and B30 (Fig. 1).

2.3.1. *Embodied carbon emissions*

As reported by several studies, embodied carbon emissions constitute a significant fraction of the total carbon footprint of buildings. Studies have shown that the total embodied emissions of a building can range from 10 to 50% in a typical LCA assessment depending on the building type, lifespan, location, and relative energy consumption performance (Fenner et al., 2018; Röck et al., 2020). Considering the first law of thermodynamics, in which en- ergy is conserved, the embodied emissions can be associated with the unitary mass of materials used in a project. Consequently, materials comprising the major fraction of the building mass will likely have higher embodied emissions than those with less mass. Cement- and steel-related materials represent the greatest share of emissions because their manufacturing processes are more energy intensive (Guggemos and Horvath, 2005; Cang et al., 2020). The frame, substructure and external walls are considered carbon hot- spots in typical projects (Victoria and Perera, 2017). The envelope of a building can account for around 20% of the total embodied emissions (Asdrubali et al., 2013), while the combined emissions from bricks, windows, drywall, and structural concrete can reach to 60e70% of the total embodied emissions of a building (Norman et al., 2006). Critical carbon-intensive building elements may vary between buildings according to the design and the use of a typical building materials (Ashworth and Perera, 2015; Cang et al., 2020). However, if typical materials are used, the carbon footprint of a building could be measured by assessing emissions from major emitters and adding a percentage for the additional materials.

A significant number of research papers present a detailed calculation of the embodied emissions (De Wolf et al., 2017). In most cases, the detailed analysis includes several barriers and as- sumptions that can make the calculation complex and difficult to perform by most building professionals. The Pareto Principle or the 80/20 Rule can be used to help provide a rapid estimate of embodied carbon emissions. This approach implies an unequal relationship between the inputs and the outputs and states that roughly 80% of the effects come from 20% of the causes (Koch, 2011). Although the 80/20 Rule has not been widely investigated in the building construction sector, several studies have highlighted that a small portion of construction materials accounts for the majority of emissions. Victoria and Perera (2017) found that 36% of construction materials were responsible for around 80% of the total embodied emissions. In another study, emissions from concrete- related and steel-related materials correspond to around 60% of the total embodied emissions, while brick, cement, and mixed mortar contributed an additional 25% (Li et al., 2016). Due to these reasons, building certifications are now requiring reporting of embodied emissions from main construction components, such as building superstructure and building envelope.

2.3.2. *Operational carbon emissions*

The operational stage has been found to be the dominant fraction of emissions in $LCCO_2A$ studies, mainly due to the continuous emissions over the building lifecycle. As noted in other studies, the

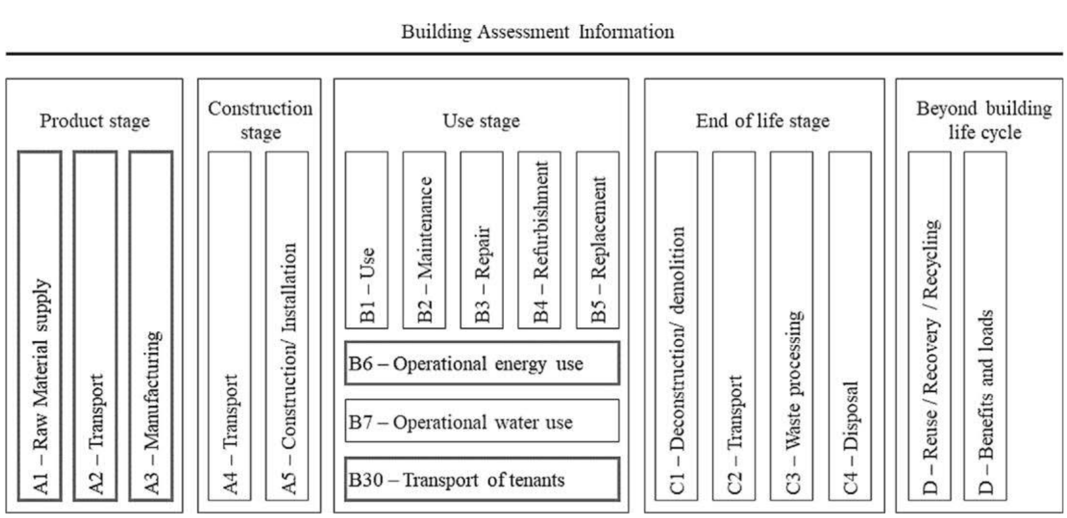

Fig. 1. Life-cycle stages for assessing the environmental performance of buildings and boundary for the study. Source (E.N. CEN, 2012; E.N. CSN, 2011; ISO 14040 , 2006; ISO 14044, 2006).

building location, occupation type, energy source, and building systems directly affect the energy consumption of a building and its relative emissions (Airaksinen and Matilainen, 2011; Huo et al., 2019a; Cao et al., 2016; Berardi, 2015). Air conditioning, lighting, equipment, and appliances are considered the categories that most contribute to energy consumption (Kofoworola and Gheewala, 2008;Biswas, 2014; Cao et al., 2016). Advances from modern life, such as improving living conditions especially in rural communities, have also contributed to an increase of the building operational carbon emissions. In China, for example, residential rural building energy intensity increased around 5% between 2000 and 2015 (Huo et al., 2019a). Due to climate change, it is also estimated that global heating and cooling demands will increase by 34% and 72%, respectively, directly impacting building energy use intensity and carbon emissions (Cao et al., 2016). This could also worsen economic inequalities, especially for marginal and low-income population, where investing in energy efficiency strategies is highly difficult due to initial costs. Thus, programs such as rebates or tax credit return should be considered to incentivize hyper-efficient and carbon-neutral strategies across society (Fenner, 2019).

Fortunately, the operational stage energy carbon emissions are continually decreasing in new buildings due to the development of energy-efficient equipment, implementation of zero-energy strategies and standards, and use of renewable or cleaner energy sources (Röck et al., 2020). For instance, advanced building envelope design could reduce heating and cooling demands by 40%, causing direct energy and carbon emission savings (Cao et al., 2016). However, reducing operational carbon emissions has shifted the burden to other life-cycle stages, such as material manufacturing and commuting emissions from tenants (Fenner et al., 2018; Röck et al., 2020).

2.3.3. *Mobility carbon emissions*

Although transportation embodied emissions are considered minimal, the emissions from daily commute of tenants are expected to represent a significant share of the total carbon footprint of a building. The building connectivity within the urban gridline plays a major role in reducing the carbon footprint. Several studies have highlighted the correlation between urban space and transportation modes with mobility emissions (Heinonen et al., 2013; Onat et al., 2014; Wilson and Navaro, 2007; Lai, 2015; Hodges, 2010; Cervero and Murakami, 2010; Ewing and Cervero, 2010; Pérez-Neira et al., 2020). It has also been suggested that emissions from daily mobility for an average office building in the US could exceed the operational energy use by 30% (Wilson and Navaro, 2007). In another study comparing a BREEAM certified and a fictive office building, commuting emissions were around 2 to 31 times higher than the energy-related emissions from the use stage, respectively (Augustsson, 2014). Piano (2019) examined the GHG emissions of 10 office buildings in the US and found that Scope 3 emissions, travel miles and commuting, were higher than energy-related emissions. Klein-Banai and Theis (2013) examined the carbon emissions of 135 colleges and universities and found that commuting (Scope 3) were between 10% and 51% of total emissions per square meter. However, the data for Scope 3 was inconsistent as fewer schools reported commuting emissions.

While other sectors of society have successfully increased efficiency over time, the GHG emissions from the transportation sector have been continuously increasing in most countries. In the US, transportation GHG emissions increased by over 20% since 1990 (EPA, 2018; Bahramian and Yetilmezsoy, 2020). The growing population, urban sprawl, and low fuel prices are considered the main factors. In 2016, the GHG emissions of the transportation sector exceeded the emissions from the electricity sector and, for the first time in history, became the main emitter of GHG emissions in the country accounting for 28.5% of the total emissions. In the transportation category, passenger cars represent the largest source of GHG emissions, accounting for 42.2% of the sector emissions (EPA, 2018).

Daily mobility emissions are often described as not directly owned or controlled by the building owner. However, several low-carbon strategies can be implemented over the life-cycle of a building (Pérez-Neira et al., 2020). During the design process, the site location has an enormous impact on the final transportation emissions that could be minimized if the owner were forced to take precautions. During the operational phase, stakeholders can also incentivize alternative transportation methods that could reduce mobility emissions. Thus, green building certifications are starting to realize the importance of this sector when performing building life-cycle assessments (Augustsson, 2014). It should also be noted that city, regional, and provincial governments can greatly assist the reduction in the mobility carbon footprint by virtue of appropriate urban planning practices to include the location of communities versus commercial and industrial zones, and the types of transportation infrastructure that are planned and financed.

3. Methodology and framework

The proposed framework uses a simplified $LCCO_2A$ analysis model to calculate a reasonably accurate and practical carbon footprint of a building. The proposed framework classifies carbon emissions into three Carbon Intensive Stages (CIS) which are considered by the literature as potential hotspots and major contributors to the carbon footprint of the built environment, as shown in Fig. 1. The carbon footprint of a building is then the sum of the three CIS's normalized to the building gross area in square meters and year, as shown in Equation (1):

$$\text{Carbon Footprint (Kg } CO_2\text{-eq/m}^2\text{/year)} = (\text{CIS 1/building service life} + \text{yearly CIS 2} + \text{yearly CIS 3})\ \text{building area} \qquad \text{Eq. (1)}$$

Where:

CIS 1 = embodied carbon emissions per building service life
CIS 2 = yearly operational carbon emissions
CIS 3 = yearly tenant mobility carbon emissions

The key advantage of measuring the CIS enables the effectiveness and progress of policies and strategies to monitor GHG emissions. Stakeholders can use this proposed framework for benchmarking and designing buildings in different ways. During the design process, where information is scarce, energy and transportation emissions can be estimated to represent a design parameter to be compared when the building is operating. The embodied emissions will generally not vary from the design to the operational stage unless additional materials are used for maintaining the building. Therefore, a benchmark for embodied emissions can be used as a target for carbon-efficient design strategies. During the operational phase, stakeholders can either quantify the energy and transportation emissions continuously or simulate carbon efficient strategies for both stages. Lastly, the proposed method can be used to recognize low-carbon strategies, to benchmark carbon emissions, and to easily compare the carbon-intensity of different buildings.

In addition to combining the carbon intensive phases into a total for the building project, the individual stages, CIS 1 through CIS 3, can be compared to determine trends and fine-tune building design and construction strategies. The following sections briefly describe different methods that can be used for measuring emissions for each CIS according to the data available in each project.

3.1. *CIS 1: Embodied carbon emissions*

Embodied emissions include GHG emissions associated with the mining, transportation, processing and production of construction materials. The total emissions from this life-cycle stage can be calculated by Equation (2).

CO_2-eq embodied ¼ CO_2-eq extraction þ CO_2-eq manufacturing þ CO_2-eq transportation Eq. (2)

The embodied carbon emissions can be estimated through two different methods. In the first method, the carbon emissions are calculated by multiplying the energy use for manufacturing each material with the appropriate Energy Emission Factor (EEF) and the mass of the building material (Equation (3)). The energy intensity is defined as the energy required to produce a material per unit of mass from its raw form, while the EEF is the emission value for each unit of energy generated from the respective energy source. It is expressed in units of kilograms of carbon equivalent per kilowatt-hour of energy input (kgCO_2-eq/kWh. In this method, the emission factors are largely affected by the source and quality of energy. Thus, emission factors vary based on location, the energy mix, manufacturing technologies, and other specific characteristics. Table 1 shows a range of EEF for different energy sources.

CO_2-eq embodied (kgCO_2-eq) ¼ Energy Intensity (kWh/kg) × Energy Emission Factor (kgCO_2-eq/ kWh) × Mass of Material (kg) Eq. (3)

For the second method, the carbon emissions are calculated using Equation (4) by directly multiplying the quantity of each material with its respective Material Emissions Factor (MEF). Table 2 shows a range of MEF for typical building materials. As noted in the literature, regional and local databases should be considered for more precise carbon footprint calculation (Kwok et al., 2016). In the U.S., these databases have been generated by the National Institute of Standards and Technology, the Building for Environmental and Economic Sustainability, the U.S. Environmental Protection Agency, and U.S. Energy Information Administration websites.

CO_2-eq embodied (kgCO_2-eq) ¼ Quantity of materials (kg) × Material Emission Factor (kgCO_2-eq/kg) Eq. (4)

3.2. *CIS 2: Operational energy carbon emissions*

CIS 2 corresponds to the emissions from the consumption of purchased electricity, steam, or other sources of energy. The US EPA (EPA, 2016) has established a simple and accessible method to measure emissions from purchased electricity. The calculation consists of multiplying the purchased electricity by the appropriate local-based Energy Emission Factors (EEF), see Equation (5). If regional emission factors are not available, emissions values from Table 1 can be used for an overall estimation. It must be noted that for electricity consumption, the specific grid to which the building is connected must be taken into account because the types of power plants or energy sources drive the carbon emissions per Kwh. For example, a utility in the northwest US that largely utilizes hydropower or nuclear energy in its power plants would have a very low carbon emissions factor compared to a utility in the southeast US supplied by coal and natural gas plants. In general, this factor has not been taken into account in most research into carbon footprinting even though each US utility has a published EEF for its electrical energy generation.

Table 1
Range of Energy Emissions Factors (EEF) for most typical energy sources. Values extracted from (Chau et al., 2015; Circular Ecology, 2015; GBI, 2010; Deru and Torcellini, 2007).

Types of primary energy	Energy Emission Factor (kg CO_2-eq/kWh)
Biomass	0.026e0.156
Coal (bituminous)	0.341e0.486
Fuel oil (residual)	0.311
Gas/diesel oil	0.248e0.340
Kerosene	0.248e0.259
Gasoline	0.249e0.252
Grid-delivered electricity	0.758
Natural gas	0.18e0.232
Off-site renewable electricity	—0.758

Table 2
Range of Material Emission Factors (MEF) of typical building construction materials. Values extracted from (Chau et al., 2015; Circular Ecology, 2015).

Typical building material	Material Emission Factor (kg CO_2-eq/kg)
Aluminum	1.45e13.10
Brick	0.24
Cement	0.32
Glass	1.06e1.50
Plywood	0.75e1.35
Precast concrete element[a]	Add 0.029 to concrete mix MEF
Reinforcing bar and structural steel	1.72e2.82
Reinforced concrete	0.05e5.15
Stainless steel	3.38

[a] Concrete mix MEF must be calculated for each specific mix design.

CO_2-eq operational (kgCO_2-eq) ¼ quantity of electricity purchased (kWh) × Energy Emissions Factor (kgCO_2-eq/ kWh) Eq. (5)

3.3. *CIS 3: Mobility carbon emissions*

CIS 3 refers to indirect emissions associated with the daily commuting of tenants. Calculating the total GHG emissions from transportation can be more complicated because of the different gases, such as CH4, N_2O, and HFC that are dependent on the design of the engine and the emissions control systems of the mode of transportation. However, CO_2 emissions represent 95e99% of the total GHG emissions after accounting for their global warming potential. The remaining 1e5% represent emissions from the other sources (EPA, 2016). There are two main methods for calculating carbon emissions from transportation: the fuel-based method and the distance-based method (EPA, 2016; GHG Protocol, 2005). The fuel-based method has two different sub-approaches based on the amount of data available. The first approach, indicated in Equation (6), is recommended when data about the fuel heat or carbon content is lacking, but quantities of fuel consumption are known.

This method has the highest level of uncertainty since emissions factors are based on default fuel data rather than actual fuel heat or carbon content.

CO_2-eq emissions ¼ Quantity of Fuel × Emissions Factor 1 Eq. (6)

Where:

CO_2-eq Emissions ¼ Mass of CO_2-eq emitted
Quantity of Fuel ¼ Mass or volume of fuel combusted

Emission Factor 1¼CO$_2$-eq emissions factor per mass or volume unit from Table 3

In the second, fuel-based approach, the fuel use data is calculated by multiplying the fuel use in energy units by the energy content of the fuel and the respective emissions factor of the fuel (Equation (7)). This approach is preferable over the other fuel- based method because emissions factors based on energy units are less variable than emission factors per mass or volume units. This is because the carbon emissions are more closely related to the heat content of the fuel rather than the physical quantity of fuel.

CO$_2$-eq mobility ¼ Fuel Use × Energy Content × Emission Factor 2 Eq. (7)

Where:

Emissions ¼ Mass of CO$_2$-eq emitted
Fuel Use ¼ Mass or volume of fuel combusted
Energy content ¼ Fuel heat content in units of energy per mass or volume of fuel
Emission Factor 2¼CO$_2$-eq emission factor per energy unit from Table 3

The third approach, indicated in Equation (8), is the distance-based method. This approach is recommended when travel dis- tance data is available, but fuel economy data is lacking. The dis- tance is then multiplied by an average emissions factor for each transportation mode, as shown in Table 4. In this case, it is also important to notice that emissions factors are expressed in different units for each transportation method. Emissions factors for privately owned vehicles are often expressed in distance units, in which emissions are allocated to the entire vehicle regardless of the number of persons traveling together. On the other hand, public transport emission factors are usually expressed in passenger per distance traveled, in which travel emissions are allocated to each seat.

CO$_2$ transportation ¼ Distance Traveled × Emissions Factor 3 Eq. (8)

Where:

Emissions ¼ Mass of CO$_2$ emitted
Distance traveled ¼ kilometers, passenger-km
Emission factor 3 ¼ CO$_2$ emission factor per transportation mode from Table 4

Table 4
Emission factors by transportation mode (EIA, 2016; EEA, 2016; EPA, 2015).

Transportation mode	Emissions factor 3
U.S. average air flight	0.26e0.40 (kg CO$_2$/passenger-km)
U.S. average rail	0.27(kg CO$_2$/passenger-km)
U.S. average light duty truck	0.780 (kg CO$_2$/vehicle-km)
U.S. average motorcycle	0.307 (kg CO$_2$/vehicle-km)
U.S. average bus	0.088 (kg CO$_2$/passenger-km)
U.S. average ferry	0.115 (kg CO$_2$/passenger-km)
U.S. average passenger car	0.571 (kg CO$_2$/vehicle-km)
Europe average motorcycle	0.072 (kg CO$_2$/passenger-km)
Europe average passenger car	0.042e0.158 (kg CO$_2$/passenger-km) [a]
Europe 2015 policy passenger car	0.13 (kg CO$_2$/passenger-km)
Europe 2021 policy passenger car	0.095 (kg CO$_2$/passenger-km)
Europe average bus	0.068 (kg CO$_2$/passenger-km)
Europe average metro	0.014 (kg CO$_2$/passenger-km)
Europe average air flight	0.2885 (kg CO$_2$/passenger-km)

[a] Number ranging from 4 passengers to 1 passenger, respectively.

4. Case study

Although there is an immense opportunity for single buildings, especially high-rise projects, the proposed methodology would best be used for strategic development planning of large in- stitutions, such as university campuses or large urban de- velopments. Thus, an analysis of a university academic building will be used to demonstrate the described approach. The proposed framework will be applied to Rinker Hall, an academic building located at the University of Florida in the US. The building is an educational facility and home of the M.E. Rinker, Sr. School of Construction Management. Rinker Hall includes a mix of class- rooms, teaching labs, student facilities, and administrative offices. The building received a LEED Gold certification in 2004, the first building in the State of Florida to achieve this rating. Table 5 shows basic information about Rinker Hall.

41. *Carbon emissions associated with CIS 1: Embodied carbon*

The boundary for embodied carbon emissions considers the raw material supply, transportation, and manufacturing of the building materials (stage A1-3 from Fig. 1). Materials that compose the

Table 5
Basic project information about the Rinker Hall building.

Name of the Project:	Rinker Hall
Location:	Gainesville, Florida, USA
Type:	Educational, University
Date of construction completion:	March 2003
Area:	4392 m^2
Number of stories:	3

Table 3
Types of fuel and respective emissions factors per unit of mass or volume and energy unit. Adapted from (EPA, 2018; EPA, 2016; EIA, 2016).

Type of Fuel	Emission Factor 1 (kgCO$_2$/Liter)	Energy content (kWh/Liter)	Emission Factor 2 (kgCO$_2$/kWh)
Aviation gasoline	2.20	9.30	0.24
Biodiesel (100%)	2.50	9.96	0.25
Compressed Natural Gas[a]	1.95	10.81	0.18
Diesel fuel	2.70	10.81	0.25
Kerosene-type Jet Fuel	2.58	10.61	0.24
Ethanol (100%)	1.52	6.62	0.23
Gasoline	2.32	9.89	0.24
Liquefied Natural Gas (LNG)	1.18	6.67	0.18
Liquefied Petroleum Gases (LPG)	1.50	7.33	0.20
Motor Gasoline	2.32	11.99	0.23
Residual Fuel oil	2.98	12.03	0.25

[a] Values in cubic meter.

building superstructure, building envelope, interior walls, and roof were selected. These materials typically account for the majority of the embodied emissions of a building, last through the entire life of the building, and are used by the Canada Green Building Council framework, as mentioned in Section 2.1 (Victoria and Perera, 2017; Li et al., 2016; Monahan and Powell, 2011). Table 6 shows the total calculated embodied emissions in kgCO_2-eq for the Rinker Hall building. The quantity takeoff estimates the pieces, mass, length, or volume of materials used in the building. This case study uses the method described in Equation (4). Emission factors for materials were found from existing databases and local Environmental Product Declarations (Gypsum Association, 2014; CCMPA, 2016;CMC, 2015; MCA, 2014; SDI, 2015; Hammond and Jones, 2008). The emissions factors are usually expressed in units of weight (kg) or area (m^2) of building materials. The unit weight or density of materials were found from literature and multiplied by the calculated quantity (Walker, 2016).

Construction activities have inherent waste which may increase due to poor construction practices. The total waste and extra materials for the building is expected to be in the range of 5e15% of the takeoff quantities (Dagostino and Feigenbaum, 1999). In this study, 10% of waste was added to the quantity of materials for estimation.

42. *Emissions associated with CIS 2: Operational energy emissions*

The operational data required for the carbon analysis of Rinker Hall was accessible through the University of Florida Physical Plant Division (PPD). PPD is responsible for providing the campus with central utility services and overseeing energy management. The utility data was recorded monthly from 2005 to 2016 for electricity and chilled water. Fig. 2 illustrates the utility energy consumption pattern through the service life of the building. The source of energy for heating and cooling systems are steam and chilled water that is generated in sizable central plants that feed a specific part of campus. The steam and chilled water sent to the building are metered separately. The efficiencies and coefficient of performance of the systems are known. Therefore, it is possible to obtain the total energy consumption of the building. The same data is used to calculate the carbon equivalent emissions of energy consumption considering the sources of energy. The data indicate a relatively constant pattern for electricity consumption. We can see an increase in energy consumption for steam and chilled water over the same time frame. For the purpose of energy and carbon analysis, we use the median numbers to mitigate the effect of unusual patterns. Table 7 illustrates the amount of energy consumption in kWh and the emissions in kgCO_2-eq. The emission factors were obtained using the Power Profiler data source platform provided by the US EPA website (EPA, 2017). The emission factors are calculated based on the sources of energy to produce one kWh of energy and varies in relation to the location. For steam, the source of energy is natural gas. According to the US EPA (EPA, 2018), the carbon dioxide emissions are determined by multiplying heat content times the "carbon coefficient times the fraction oxidized times the ratio of the molecular weight ratio of carbon dioxide to carbon (44/12)". The average heat content of natural gas is 0.1 MMBtu per therm (EPA, 2018). The average carbon coefficient of natural gas is 14.46 kg carbon per MMBtu (EPA, 2018). The fraction oxidized to CO_2 is 100%. The efficiency of the heating system is considered to be 83%. Regarding the cooling system, each ton-hour of chilled water represents 3.516 kWh of heat removal and the source of energy to produce chilled water is electricity. The coefficient of performance (COP) for the central plant was calculated to be 4.5 using data from the operations of the central plant. The equivalent energy for the process water consumed was negligible compared to the other energy measures and therefore, it was not taken into account. The method for measuring emissions from the operational stage fol- lows the method established by the US EPA (EPA, 2016) and iden- tified in Equation (5).

43. *Emissions associated with CIS 3: Mobility emissions*

An online survey was distributed to faculty, staff, and students of the Rinker Hall during a recent academic year. A copy of the survey is available in the supplemental files along with the original data. The response rate for faculty and staff was 52% and 100%, respectively. For the program Ph.D., Masters, and Bachelor students the response rates were 34.6%, 15.7%, 11.6%, respectively. In addition to program students, the building classrooms are also used by other majors. A total of 41 non-program students from 13 different majors were interviewed. Based on the information obtained from the school's administrative office, the school has 21 faculties and 11 staffs. Furthermore, the total amount of students enrolled in the program for Bachelors, Masters, and Ph.D. is 300, 70, and 52, respectively. The total population of non-program students was obtained from the Registrar's Office by adding up all students enrolled for classes at Rinker Hall. Working days for students were obtained from the academic calendar. Summer classes are not usually held at the Rinker Hall, therefore, only Ph.D. students were accounted during the summer semester.

The survey contained behavioral travel questions such as the share of hours per week the user spent in the building relative to the total hours spent at the university, the daily round-trip dis- tance, and the transportation mode ratio. The travel behavior was assumed to be constant over the year. Mobility emissions were then calculated for each user using the distance-based method showed in Equation (9) and the emissions factors shown in Table 4 (EPA, 2015).

Table 6
Results of the embodied emissions analysis for Rinker Hall building.

Material Name	Quantity (unit)	Unit Weight	Total Weight (kg)	Emissions Factor	GHG emissions (kgCO_2-eq)
Cast-in-place concrete	1020 (m^3)	2400 (kg/m^3)	2,448,000	0.36 (kgCO_2-eq/kg)	881,280
Rebar	63 (metric tons)	e	63,000	1.95 (kgCO_2-eq/kg)	122,850
Structural steel	280 (metric tons)	e	280,000	1.53(kgCO_2-eq/kg)	428,400
Glass	999 (m^2)	20 (kg/m^2)	19,980	1.35 (kgCO_2-eq/kg)	26,973
Gypsum board	10,445 (m^2)	e	e	1.04 (kgCO_2-eq/m^2)	10,863
Brick	99,328 (pcs)	7.90 (kg/pcs)	784,691	0.24(kgCO_2-eq/kg)	188,326
CMU	5067 (pcs)	34 (kg/pcs)	172,278	0.107 (kgCO_2-eq/kg)	18,434
Aluminum	1653 (m^2)	e	e	30.05 (kgCO_2-eq/m^2)	49,677
CIS 1 Total (kgCO_2-eq)					1,726,802
CIS 1 Total per unit of area (kgCO_2-eq/m^2)					393.17
CIS 1 (kgCO_2-eq/m^2/year (over 50 years)					7.86

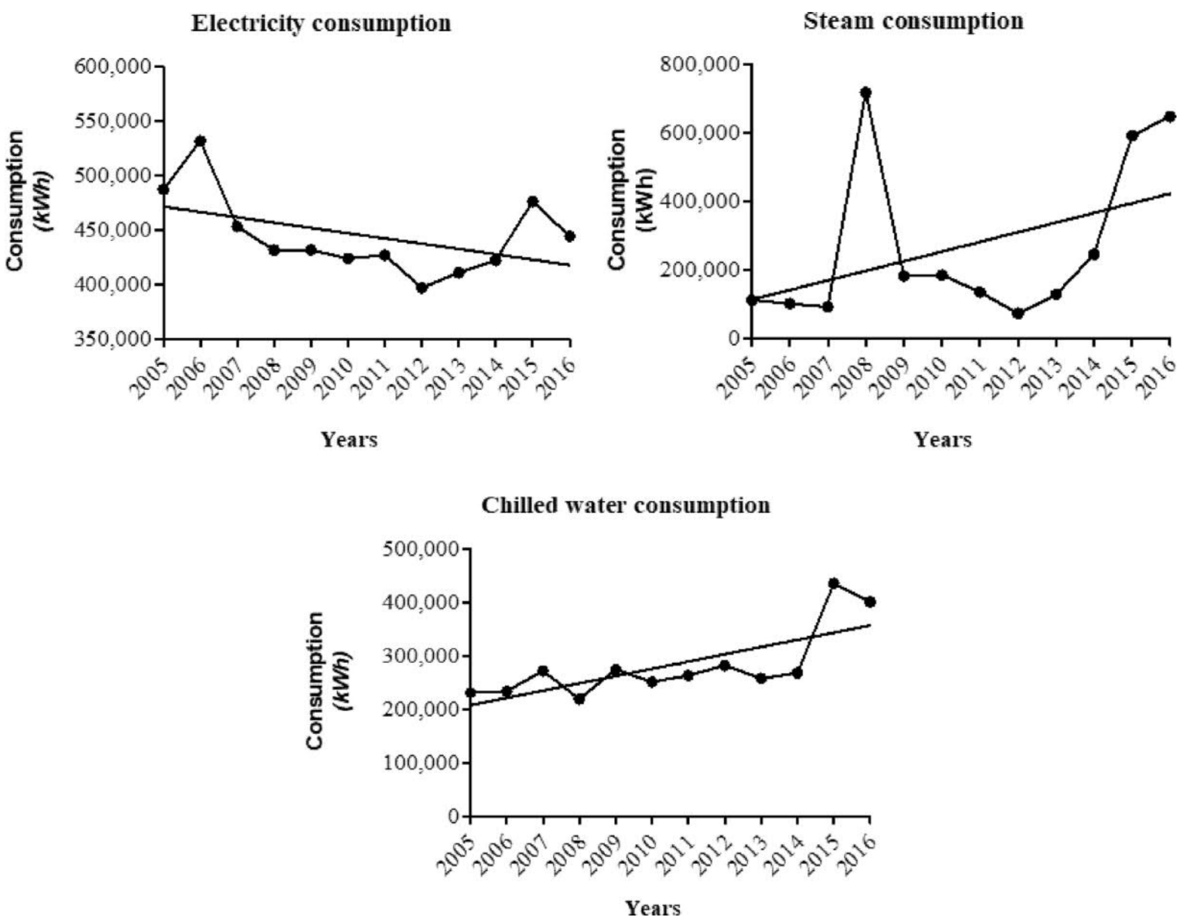

Fig. 2. Utility consumption pattern of Rinker Hall building from 2005 to 2016.

Table 7
Operational emissions of the CIS 2 for Rinker Hall Building.

Type	Average Consumption	Emission Factor (Kg CO_2-eq/kWh)	kWh equivalent	GHG Emission (kgCO_2-eq/year)
Electricity	431,637 kWh	0.52	431,600	224,000
Steam	540 Klb	0.18	190,700*	34,500
Chiller	340 Ktons-hr	0.52	265,600**	137,900
CIS 2 Total per year			887,900 kWh/year	396,400 kgCO_2-eq/year
CIS 2 (Total/m²/year)			202.1 kWh/m²/year	90.3 kgCO_2-eq/m²/year

Kwh eq ¼ Klb/hr*1000 lb/Klb *1000 Btu/lb*2.2 lb/Kg * 1 Kwh/3.
** kWh equivalent is the electricity needed to produce the cooling energy: Kton-hr * 3516 kWh/Kton-hr * 1/COP, where COP is the central plant COP.

CO_2 transportation ¼ Round-trip distance × Emission Factor per transportation mode × transportation mode ratio × building occupancy ratio Eq. (9)

Fig. 3 shows the variability and median of the emissions per capita per year. The yearly emissions per capita were significantly spread for each of the user categories, therefore a 95% confidence interval was calculated with the Wilcoxon Test and the *t*-test distribution for each category. The blue lines correspond to the upper and lower bounds from *t*-test where the confidence interval is calculated based on the mean, while the grey area correspond to the confidence interval of Wilcoxon test calculated based on the median. The range of emissions per capita differs significantly among all categories mostly due to variances in the preferred transportation mode and the round-trip distances. Since the data is asymmetric, the median of each category is the preferable measure for central tendency as it is less affected by outliers. Table 8 shows the total yearly emissions associated with the CIS 3 of Rinker Hall extrapolated from the survey to cover the entire building population. Number of users represent the total population in each category.

5. Discussion

Fig. 4 illustrates the detailed breakdown of the emissions for each CIS. The carbon emissions of the building totaled 129.22 kg CO_2-eq/m²/year.

The CIS 1 emissions from building materials totaled 6.08% of the total emissions per year, considering a life-cycle of 50 years. The analysis shows that steel-related and concrete-related materials correspond to most of the total embodied emissions, similar to (Guggemos and Horvath, 2005; Cang et al., 2020). Fig. 5 shows a comparison of the embodied emissions of several buildings that used a process-based detailed assessment and the case study here

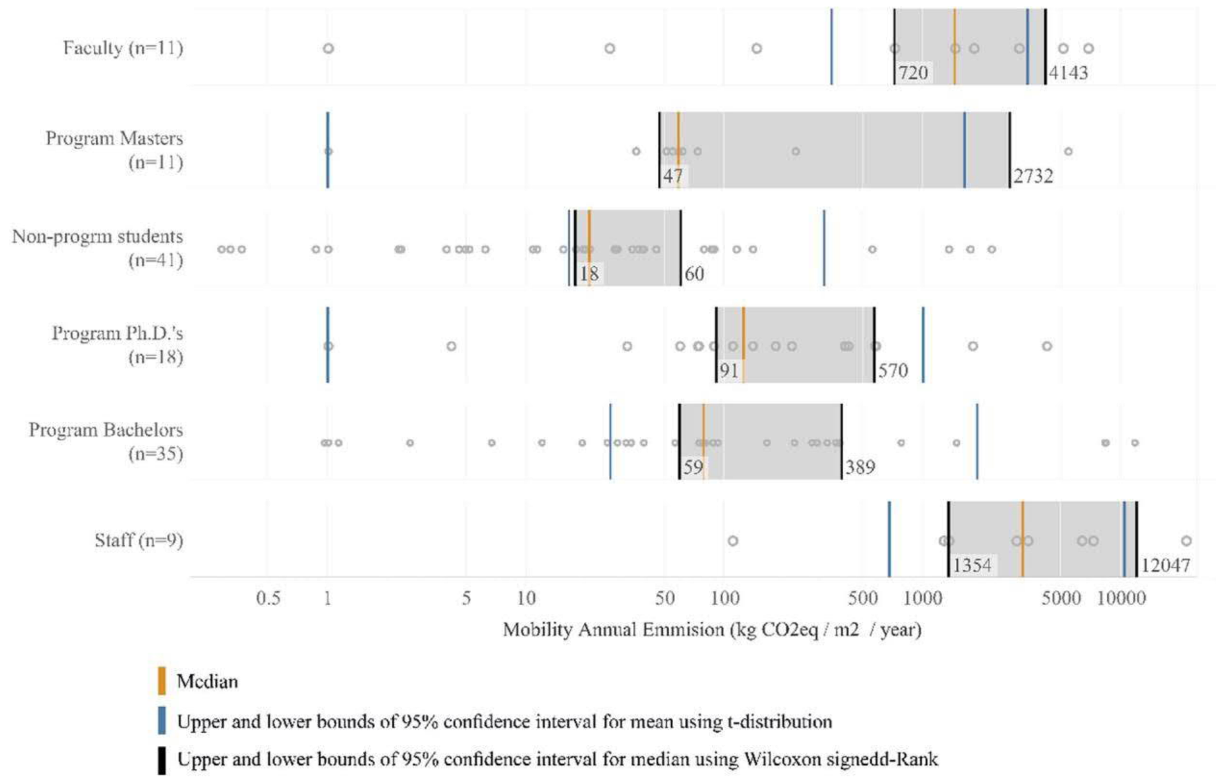

Fig. 3. Variability and median of mobility carbon emissions per capita per year.

Table 8
Mobility emissions of the CIS 3 framework for Rinker Hall Building.

User type	Total number of users	Median emission per capita per year (kgCO_2eq/per capita/year))	Total Emissions (kgCO_2eq/year)
Faculty	21	1441	30,261
Staff	11	3382	37,202
Program Ph.D.'s	52	124	6448
Program Masters	70	54	3780
Program Bachelors	300	73.7	22,110
Non-program students	1887	19.4	36,607
CIS 3 Total (kg CO_2-eq/year)			136,408
CIS 3 (kg CO_2-eq/m^2/year)			31.06

presented normalized by gross building area (Fenner et al., 2018). The average embodied emissions for all studies was 461.5 CO_2-eq/m^2 with most studies showing results close or under the mean, similar to the presented case study. The 3 highest studies are from Italy and Japan, countries with relatively high embodied carbon in their processes.

The emissions from the operational phase (CIS 2) accounted for 69.88% of the total emissions in the Rinker Hall. Electricity consumption and the cooling system represent the biggest emitters in this stage. From the comparisons with other studies in Fig. 5, Rinker Hall has shown to emit more than the average from other studies. However, most studies have not accounted for chiller and steam emissions as in this study. If only electricity were considered (51 kgCO_2-eq/m^2/year), the operational emissions from Rinker Hall would correspond to the average of all studies. It is important to note as well that the energy intensity varies significantly among different regions and building characteristics (Huo et al., 2019a, 2020; Cao et al., 2016; Wu et al., 2016; Berardi, 2015; Airaksinen and Matilainen, 2011). The energy performance of a building is usually established in the design phase, but the continuous moni- toring of energy consumption is also important. By doing so, stakeholders can monitor carbon emissions fluctuations from behavioral changes or the introduction of low-carbon strategies.

Fig. 6 shows the median and total emissions per year for each group using a 95% confidence interval with the Wilcoxon Test. For this analysis, the total mobility emissions vary from 20.23 to 152.51 kg CO_2-eq/m^2/year. Considering the median values, the emissions from the CIS 3 totaled 31.06 kg CO_2-eq/m^2/year or 24.04% of the total emissions. This value was similar to another study (Klein- Banai and Theis, 2013), where the average commuting emissions for doctoral granting universities were 35.39 kg CO_2-eq/m^2/year. However, our values differ from (Wilson and Navaro, 2007; Wang et al., 2017). The main reason could be associated with the build- ing type, large number of assumptions used in previous studies, and differences in methodology. Augustsson (2014), for example, found that commuting could be 19.17e19.68 kg CO_2-eq/m^2/year for an office building, but occupancy assumptions were used instead of surveys. Wang et al. (2017) suggested a commuting baseline of 4.8 metric tons/person by using non-project specific on-road vehicle data from the US transportation sector.

Considering the median values, staff were the biggest emitters in this stage followed by non-program students and faculties.

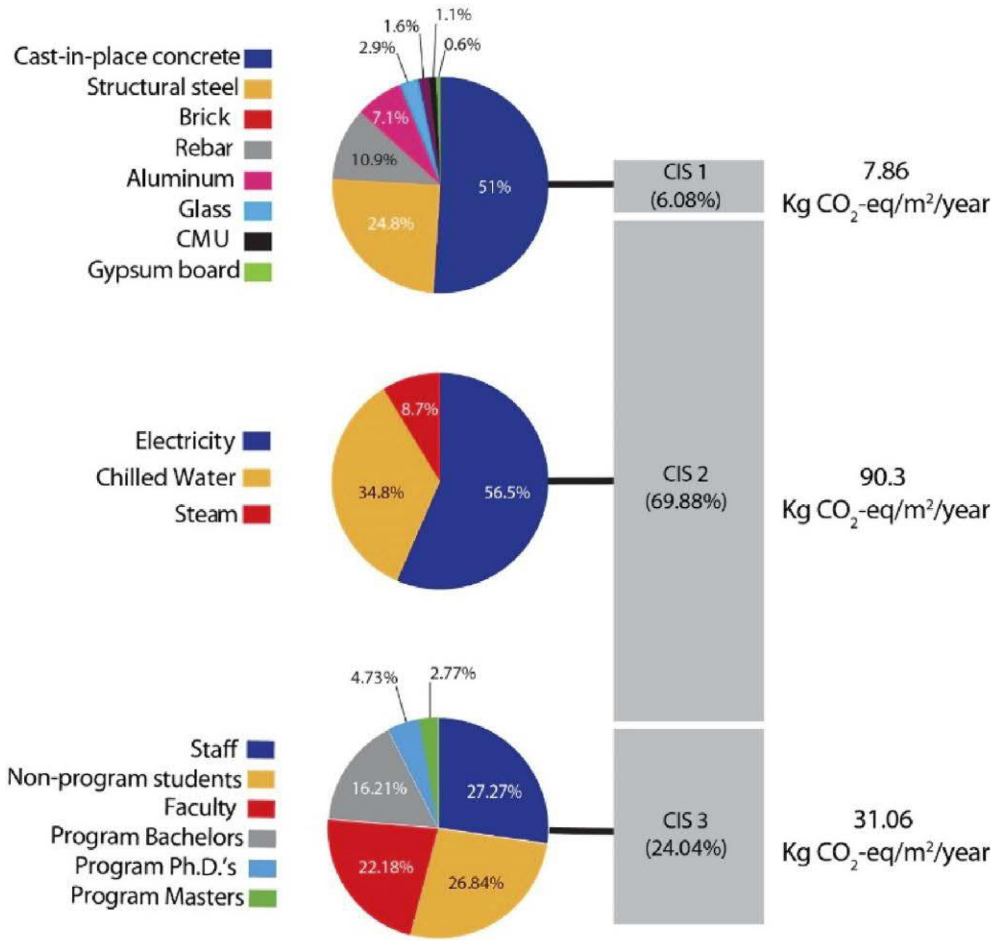

Fig. 4. Detailed emissions for each Carbon Intensive Stage of Rinker Hall.

However, as observed in the literature, emissions for the transportation stage is highly dependent on the tenant's behaviors (Augustsson, 2014; Pérez-Neira et al., 2020). Although non-program students corresponded to a representative share of the total emissions of Rinker Hall per year, the emissions per capita for students remained the lowest in the analysis. The emissions from staff daily commuting deserve special attention in this case since it corresponds to 2.3 times the emissions per faculty, 27e63 times program students, and almost 175 times the emissions per non-program students, as shown in Table 8. Although working days and building occupancy ratio may differ among categories, the average daily travel distance and the transportation mode played a key role in the total emission of this category, similar to Pérez-Neira et al. (2020).

Fig. 7 shows the transportation mode ratio and the average round-trip distance for each category. As seen in the figure, staff and faculties are heavily depended on private cars and reside 2e6 times further than students. It should be noted that Rinker Hall is a LEED Gold certified building with several points accounted for high urban connectivity and accessible alternative transportation methods. The building also has a significant number of bicycle racks used mostly by students and faculty. As part of the sustainable strategies, the University of Florida has also limited the use of cars by students. All these aspects justify the high usage of buses and non-polluting transportation modes among students, who also generally prefer to live close to the campus. On the other hand, staff and faculty usually live in the suburb and drive to the university as parking restrictions are not as strict as for students. Therefore, applying further restrictions on private cars and encouraging living closer the campus or places with direct public transportation connection are the strategies that would significantly impact the total mobility emissions of the building, as also noted by Pérez-Neira et al. (2020) and Klein-Banai and Theis (2013).

6. Conclusions

The energy, transportation and building environment sectors represent the dominant share of the total carbon emissions in our society. Consequently, these same sectors have received remarkable attention in recent years. Buildings represent the intersection of the energy and transportation sectors and, perhaps, are the primary reason for the continuous carbon footprint increase in our society. This study aimed to quantify the Carbon Intensive Stages (CIS) of a building (embodied, operation, and mobility) and propose a framework that facilitates the quantification of the carbon foot- print of the building environment in a comparable way. The pro- posed methodology can also be used to identify and measure the efficacy of low-carbon strategies both during the design and operational stages of a building. For continuous improvement, annual assessment should be encouraged for the operational and commuting emissions to monitor the progress of implemented strategies and assess behavioral changes.

Based on the CIS case study, the operational phase (CIS 2) is the highest carbon emitter, accounting for 70% of the total carbon

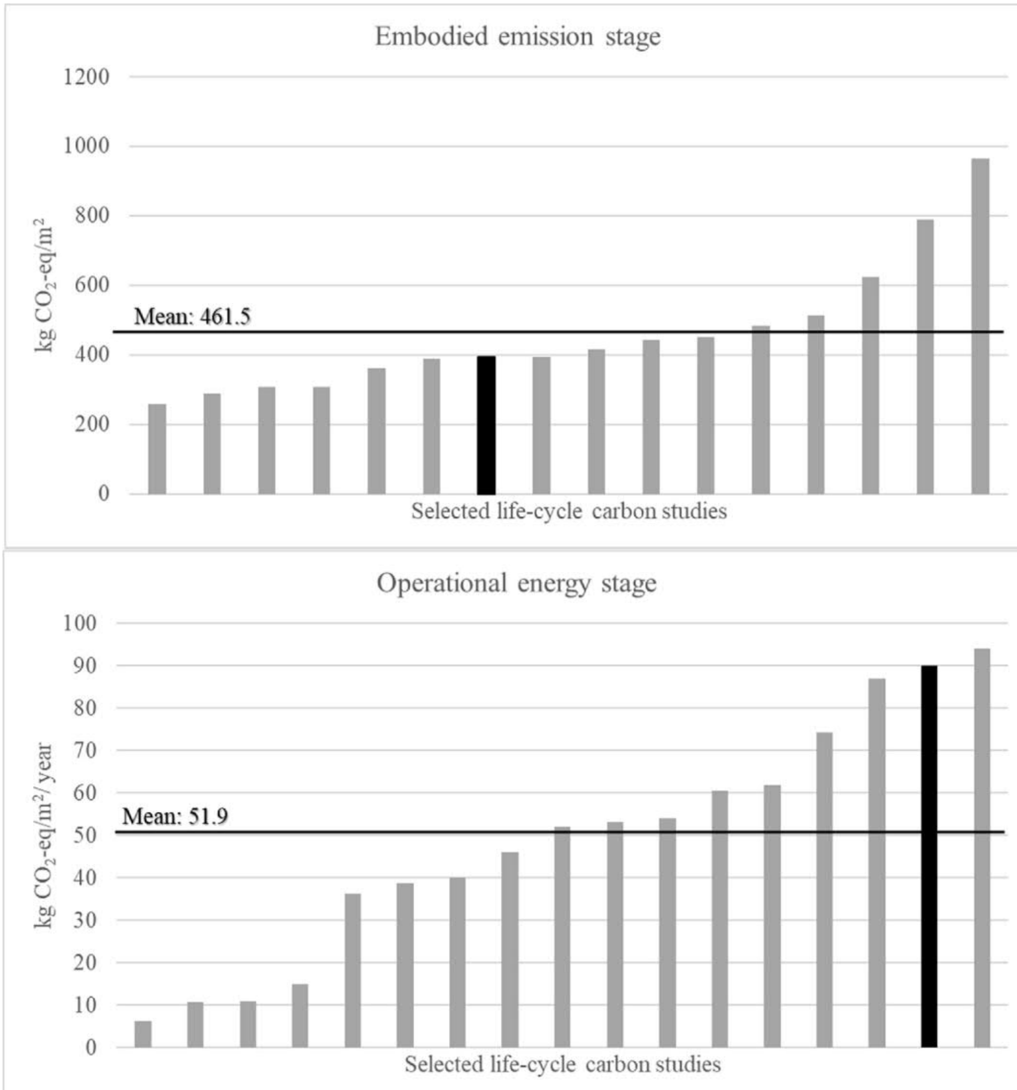

Fig. 5. Comparison of the embodied carbon emissions and operational energy carbon emissions of Rinker Hall with other studies that used a process-based detailed assessment. Adapted from (Fenner et al., 2018).

emissions. The tenant transportation (CIS 3) represents the second major carbon emitter with around 24% of the total emissions. The embodied emissions (CIS 1) corresponds to roughly 6% of the total emissions in this study. The main significance of this study was to illustrate the weight of CIS 3 in the total carbon emissions of a building, a scope that lacks research in the LCA of buildings. This study shows that the mobility emissions for Rinker Hall is not as high as suggested by other studies, but could be significantly higher for new buildings, where operational energy emissions is contin- uously reducing.

The increasing shift towards carbon neutrality in the built environment demands changes in the existing carbon foot-printing methods. Low-carbon building design, human behavioral changes, and strategic urban planning are essential elements in helping to reduce the carbon footprint of the built environment. This paper reinforces the idea that commuting, building energy consumption, and building material production should be targeted as the triple bottom line of carbon footprint assessment for buildings and highly encouraged by green building certification standards.

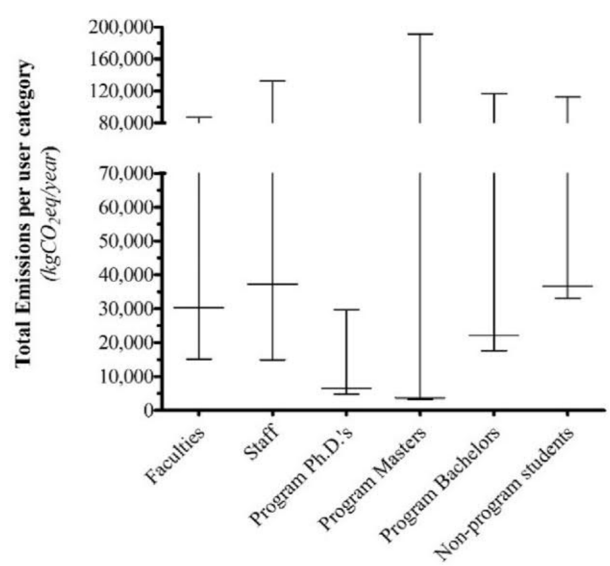

Fig. 6. Emissions per capita from daily commuting of tenants of Rinker Hall.

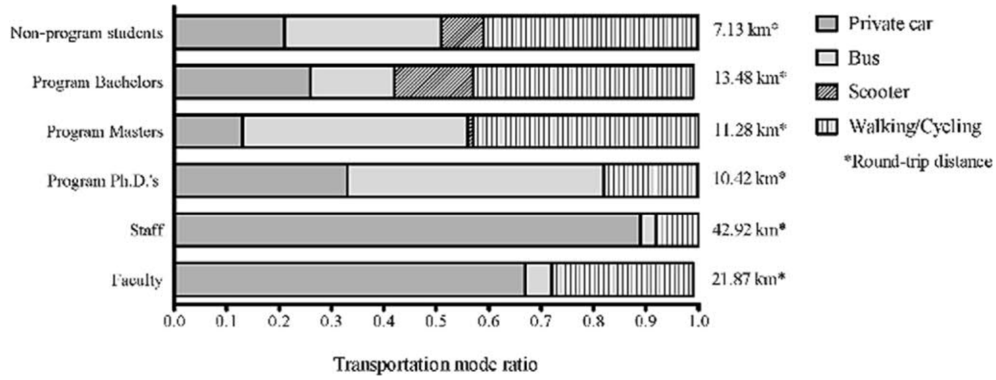

Fig. 7. Transportation mode ratio and average round-trip distance for each user category.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Andriel Evandro Fenner: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. Charles Joseph Kibert: Conceptualization, Methodology, Validation, Writing - review & editing, Supervision. Jiaxuan Li: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing. Mohamad Ahmadzade Razkenari: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. Hamed Hakim: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Data curation, Visualization. Xiaoshu Lu: Validation, Writing - review & editing. Maryam Kouhirostami: Writing - review & editing. Mahya Sam: Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122081.

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