Estimating the carbon contribution of the construction and operation of parking spaces in the City of Vancouver

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Executive Summary

CO_2 emissions have become one of the most important issues globally, and their reduction can facilitate the mitigation of climate change. In this context, many countries and cities aim to reduce their emissions and implement legislation for different sectors of society. Moreover, the transportation sector is usually targeted due to its large contribution to emissions and impact on global warming and human health. However, there are very few papers in the literature that aim to evaluate the impact of the construction and operation of parking spaces, one of the main infrastructures in the sector.

This paper has aimed to evaluate the CO_2 emissions of underground parking spaces in the City of Vancouver in the province of British Columbia, Canada. The analysis used a Life-Cycle approach, considering the construction and operation scenarios using data from Vancouver as well as literature data (construction phase), along with electricity and methane heating (operational phase). Furthermore, two sensitivity analyses were conducted, focusing on material transportation to the sites and vehicle parking within the parking garages.

The results show that the construction phase has an important contribution to CO_2 emissions, varying from 5 tonnes of CO_2 Eq[1] per parking space to 85 tonnes of CO_2 – Eq/parking space. The results are highly impacted by the size of the parking garage, and more importantly by the ratio of the area per parking space (square metres per parking space). Furthermore, when the ratios are similar, the number of levels of parking garages also play an important role in CO_2 emissions.

For the operation phase, on the other hand, only the ratio was important, and the main contributor to emissions from operations was the ventilation, followed by lighting and heating. The impact varied from 16 kg CO_2 – Eq/ parking space per year to 147 kg CO_2 – Eq/ parking space per year and all the results followed the space/parking space ratio. Hence, the CO_2 emissions are directly proportional to the ratio.

In conclusion, the results indicate that the implementation of parking minimums in the City of Vancouver needs to consider the design of the parking garage in its entirety. In this regard, the number of parking spaces, the space/parking space ratio and the number of levels in underground parking garages should all be included in the parking by-law to ensure that CO_2 emissions are decreased and the design is enhanced.

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[1] Carbon dioxide equivalent is the number of metric tonnes of emissions that have the same warming potential as one metric tonne of CO_2.

Introduction

Transportation is an important sector for current human society and it is an integral part of people's day-to-day lives. The transportation sector encompasses materials and goods transportation, as well as human transportation (Mao et al., 2020), being one of the most important elements of urban logistics (Mao et al., 2020). Furthermore, transportation has a significant environmental impact in urban areas (Alves et al., 2019) such as Vancouver.

The transportation sector requires multiple infrastructures to maintain its functionality, these infrastructures range from vehicle manufacturing to roads and parking spaces (Chester et al., 2010). While transportation is an essential part in urban economies (Alves et al., 2019), its infrastructure has a substantial impact on the environment, and both direct and indirect impacts can be identified in the sector (Wang et al., 2018).

While the definition of direct and indirect impacts can vary according to the stakeholder and the objective of the analysis, direct impacts and emissions in transportation systems are typically defined as the emissions related to fuel and energy use during the operational phase (Ministry of Environment and Climate Change Strategy in British Columbia, 2020). Indirect emissions, on the other hand, refer to the emissions due to the construction or manufacturing of necessary goods and energy (Ecometrica, 2013).

Qi et al. (2018) mention that the CO_2 (carbon dioxide) equivalent for transportation systems due to direct and indirect emissions is the second highest contributor to urban emissions, only topped by energy consumption (73% of total CO_2-Eq). Similarly, Solaymani (2019) indicates transportation as the second most important emissions in the urban environment, accounting for 23% of total CO_2 emissions. Cities, on the other hand, are responsible for 80% of total emissions and vehicles cruising for parking cause 30% of daily traffic congestion (Mangiaracina et al., 2017).

El-Fadel & Sbayti (2001) studied the noise and air impacts of parking, taking into account the construction of the parking spaces. The authors considered parking solutions for Beirut (Lebanon), and their assessment showed that the construction phase represents an important contribution to the environmental impacts. Furthermore, the authors also quantified the impacts of mitigation strategies (fuel improvement, vehicle inspection, air quality monitoring, proper logistics and maintenance, limiting site working, and quiet machinery). However, the study shows that these strategies did not help to decrease the environmental impacts significantly.

On the other hand, Chester et al. (2010) analyzed the infrastructure of parking spaces to understand the environmental impacts of vehicle travel. The authors analyzed both energy and emissions for 5 scenarios, considering different construction techniques, paid parking spaces, and solutions such as on-street parking. In their study, the consideration of the construction of parking spaces in the analysis increases the energy consumption and emissions by a significant amount, 1.7 MJ/passenger-km and CO_2 emissions by 17 kg/passenger-km, respectively.

Finally, Filyppova et al. (2021) investigated the environmental impacts associated with road transportation. The authors considered vehicle emissions, the administrative and the organizational planning of traffic in cities, along with automatic parking systems and various construction methods. Their results highlight that the construction of parking spaces has a substantial contribution to CO_2 emissions, representing almost twice the operational vehicle emissions.

Hence, the literature indicates that the construction of parking spaces has a significant impact on air emissions and CO_2 equivalent. However, very few studies consider infrastructure and there were no studies identified that account for underground parking. Moreover, no study considered any cities in Canada, and the studies did not aim to become the basis for CO_2 management at a municipal level. In this context, the city of Vancouver has 631,486 inhabitants (City of Vancouver, 2016) and 270,000 passenger vehicles registered (Korstrom, 2017), which indicates that the impacts associated with parking spaces in Vancouver could be substantial.

While the population of Vancouver is increasing, the percentage of people that own a vehicle is decreasing (Korstrom, 2017). Furthermore, Metro Vancouver (2019) highlights that the need for parking spaces in Vancouver is lower than the built capacity, and their study indicates that 18%-

35% of the parking spaces are not generally utilized. These two aspects open the city to the possibility of reducing parking spaces, aiming to decrease CO_2 emissions in the city, to reach the City's goal of reducing emissions by 50% by 2030 (City of Vancouver, 2017).

In this context, this report aims to summarize the literature concerning CO_2 emissions from parking space infrastructure as well as analyze the CO_2 emissions for parking spaces in multi-storey developments located in downtown Vancouver. The following specific objectives were performed in the present contribution:

1. Literature review focused on understanding different CO_2 emissions estimation techniques
2. Identification of CO_2 emissions from parking spaces as described in the literature, as well as the main processes contributing to the emissions.
3. An estimate of CO_2 emissions for the construction and operation of underground parking garages in the City of Vancouver
4. A short guideline to enhance future CO_2 calculations and the potential for implementation of CO_2 fees.

Background

The Importance of Quantifying CO_2 Emissions

According to the IPCC (2022), limiting the global temperature increase to 1.5 degrees will still lead to increased risk, especially in sea level areas. Furthermore, climate change impacts have increased the morbidity and mortality of human populations in North America and caused important impacts in the economic sector, disrupting the supply and demand chain (IPCC, 2022). Finally, climate change is caused by excessive greenhouse gas emissions, such as methane, nitrous oxides, synthetic compounds and CO_2 (EPA, 2020).

The evaluation of climate change is often carried out using CO_2 equivalent. This is due to the fact that CO_2 is an inert compound that does not react in the atmosphere, contrary to methane and other GHG emissions (Shaya et al., 2018). Furthermore, CO_2 can be removed through biological sequestration, mineralization, or direct air capture and filtering (World Resources Institute, 2020). However, mineralization and biological pathways are limited, especially considering current degradation of ecosystems and air capture, and filtering requires energy and a high investment. Hence, the assessment of CO_2 emissions and the mitigation of these impacts is crucial for future sustainability.

While the effects of CO_2 emissions and the importance of mitigating strategies have been long documented in the literature (Whalley & Wigle, 1991), few countries are strongly committed to reducing CO_2 emissions and the emission goals determined by United Nations (UN) are far from being reached. Furthermore, transportation represents 20% of global CO_2 emissions, reaching almost 40% in Canada (The World Bank, 2014). The construction sector, on the other hand, represents 40% of the total global CO_2 emissions (IEA, 2019).

In this context, direct and indirect emissions from the transportation and construction sectors need to be evaluated in order to identify opportunities to mitigate these impacts and to provide insight for future policies to reduce CO_2 emissions. Figure 1 shows the different types of emissions found in the transportation sector.

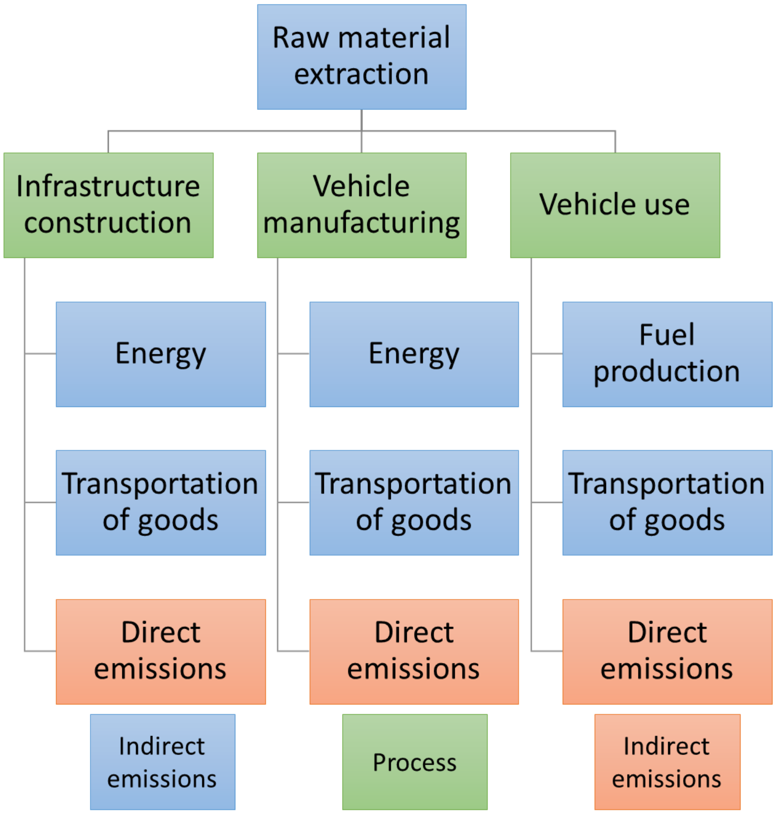

Figure 1 - Breakdown of direct and indirect emissions in the transportation sector

CO_2 Emissions Quantification Methodologies

CO_2 emissions can be monitored directly, estimated or calculated for various systems and processes. For instance, direct CO_2 emissions can be monitored through the use of different devices (Preston et al., 2005), which increases the reliability of results. However, monitoring devices increase the cost of identifying CO_2 emissions and these techniques might require the use of dispersion models and source-models to identify the sources in the urban management context, depending on the type of monitoring implemented (de Ferreyro Monticelli et al., 2021). In this context, while the monitoring devices are highly important for public health, the creation of public strategies will require the identification of sources to enhance mitigation, such as modeling identification or emissions monitoring in the source.

Another relevant point is that emissions can be estimated through a regional-oriented methodology (Nemitz et al., 2002), in a sector-oriented manner (Gunter & Wöber, 2021), or in a site-specific manner (Chester et al., 2010). Each method has its own advantages and disadvantages and can be used to support different decision-making processes and conclusions. Regional-oriented methodologies can be used for health or global environmental impact assessments, when the main goal is to merely describe the effects and possible outcomes. Sector-oriented investigations can be used for high-level decision making and the development of mitigation strategies. Similarly, site specific methodologies will provide the foundation for decision-making (now in a more specific manner) and the development of mitigation strategies, with the advantage of providing data with lower uncertainty.

Carbon emissions can be estimated or calculated using various methodologies. For instance, CO_2 emissions can be estimated through a simple methodology considering production-based, raw material-specific emission factors (Campbell et al., 2020). This method is highly effective for production sites and can be used for the transportation sector as well (EPA, 2022). Nevertheless, the method typically evaluates the CO_2 emissions of vehicle use, disregarding the indirect emissions of the sector.

In this context, Tian et al. (2016) researched the emissions and energy efficiency of commercial trucks in China. The authors implemented a simple methodology, considering fuel consumption and a constant speed. Then, the authors used an emission factor (23 kg of CO_2/fuel) to estimate the overall CO_2 emissions of vehicle use. Similar to most studies in the literature, the study disregarded infrastructure emissions.

Furthermore, Machine Learning has also been applied to calculate CO_2 emissions associated with the transportation sector. For instance, Li et al. (2022) developed a framework to calculate CO_2 emissions associated with the transportation sector considering three machine learning algorithms (ordinary least squares regression (OLS), support vector machine (SVM), and gradient boosting regression (GBR)). The authors combined socioeconomic and transportation factors in the features of their calculation, and cross-examined their model by using statistical metrics such as R^2. The work showed that the GBR algorithm combining Socioeconomic and transportation data had the best performance, with the highest linear correlation (R^2=0.9943).

Sundo et al. (2016) highlight that the transportation sector is one of the major contributors to CO_2 emissions globally. In their study, the authors considered a new mathematical approach using the Origin-Destination (O-D) strategy to calculate the energy demand and CO_2 emissions considering inter-regional passenger and freight flow data. The authors disregarded the infrastructure of the transportation sector, and estimated a total of 36,410.43 ktoe (thousand tonnes of oil equivalent) of CO_2 emissions in 2050, considering only inter-regional public buses and freight road transportation.

Another methodology identified in the literature is the Logarithmic Mean Divisia Index (LDMI), investigated in the work of W. W. Wang et al. (2011). This work considered the analysis of the factors that influence CO_2 emissions rates in China. The authors calculated an increase from 80 Mt of CO_2 in 1985 to 890 Mt in 2009, with a 10% annual growth rate. The authors also disregarded the infrastructure of transportation systems, but found that highway emissions are the highest percentage in the total calculated.

Other methods that can be used are: the use of carbon content and oxygen concentration to estimate CO_2 emissions, as well as IPCC developed methodologies (Lee et al., 2018). The first analysis considers a mass-balance approach to investigate the emissions, the second relies on estimations of CO_2 and Greenhouse gas emissions, which are then transformed into a CO_2 - Eq (CO_2 equivalent) indicator. While the first method is well applied for fuels with a defined composition and could be used for vehicle use, it adds uncertainty to studies considering construction materials for infrastructure and raw materials in general, which have different compositions.

Parking Spaces Emissions Estimates

El-Fadel & Sbayti (2001) considered the analysis of parking spaces in the City of Beirut (Lebanon). The authors identified vehicle-induced pollutant and noise emission impacts in the parking area, and considered the infrastructure construction as well. The authors applied a method to determine the baseline conditions, and assess the impacts and mitigate the potential impacts, using impact factors and CALLINE, an atmospheric dispersion model for transportation. The scenarios varied from a baseline scenario (no parking) to two scenarios that consider parking (scenarios 3 and 4). The results indicate that scenario 3 (712 parking spaces) would increase CO_2 emissions by 13% when compared to the baseline scenario, while scenario 4 (2000 parking spaces) increased CO_2 emissions by 35%.

Similarly, Chester et al. (2010) studied parking infrastructure in the United States to evaluate the environmental impacts and costs of automobile travel. The authors considered 5 scenarios: a) 105 million for-pay parking spaces, b) paid spaces and 1 square foot for commercial estimates, c) urban on-street parking, d) Considering a 3.4 to 1 space per vehicle ration, and e) 8-1 spaces per vehicle. The results show that the addition of infrastructure could increase the CO_2 emissions 17 g/person.km, emphasizing the importance of the analysis of the infrastructure in the transportation sector.

Finally, Filyppova et al. (2021) studied the application of “green” logistics to the transportation system considering a broader application to multiple cities. The article aimed to assess the planning behind transportation in urban areas, considering the infrastructure of vehicle operations. More specifically, the authors aimed to evaluate parking lot development in large cities, considering the environmental impacts of these facilities. Their results indicate that the construction of automated parking garages is highly effective in decreasing the environmental impacts of different vehicle manufacturers, due to the decrease of emissions in the vehicle parking when compared to conventional parking spaces.

Parking Spaces Management in Urban Areas

Organizing and managing parking spaces is one of the keys for Urban sustainability because parking prices and availability will affect the rates of private vehicle ownership and use (Kirschner & Lanzendorf, 2020). However, changing parking management and policies is challenging due to the opposition from users (Kirschner & Lanzendorf, 2020). Kirschner & Lanzendorf (2020) highlight that the following policies can be implemented in neighborhoods to enhance parking spaces performance: 1) maximum parking requirements; 2) physical detachment of residences and parking; 3) residential parking permits and limiting available parking space; 4) performance-based pricing; and 5) parking as demand management strategy. Table 1 shows the requirements for each policy implementation.

Table 1- Parking management strategies and requirements

Policy	Requirements
Maximum parking requirements	1- Implementation of maximum parking by-laws 2- Reduction or removal or parking minimums
Physical detachment of residence and parking	1- Creation of community garages 2- Obligation of separation
Residential parking permits	1- Stricter requirements to issue permits 2- Transforming on street parking into off street parking
Performance based pricing	1- Introduction of parking fees varying according to location, day and time 2- Changes to parking fines
Demand oriented management	1- Alternative means of transportation 2- Reuse of former parking spaces 3- Clear communication of goals 4- Mobility plan for urban spaces 5- Introduction of digital developments with policies to prevent spillover effects and increase parking convenience

Adapted from: Kirschner & Lanzendorf (2020)

Furthermore, the increase in use of vehicle parking in urban areas due to economic growth causes an important concern for parking space management in cities, and parking has become one of the main concerns in the transportation sector globally (Parmar et al., 2020). According to Parmar et al. (2020), understanding parking choice and demand is highly important for parking space management in cities and the selection of a parking space is influenced by social, economic and environmental factors, such as age, income, number of parking spaces available, parking price, accessibility, seeking time and availability of guidance system. Finally, the reduction of vehicle ownership and the implementation of multimodal mobility plans can improve urban transportation (Parmar et al., 2020).

In this context, some studies have applied methodologies to improve parking management. However, the literature lacks comprehensive studies from the urban-management perspective. For instance, Lei & Ouyang (2017) used a dynamic location-dependent parking pricing and reservation to improve the performance of an intelligent parking system. In the system proposed the agency can decide the spatial and temporal distribution of parking prices according to the availability, through the use of online reservation. The authors argue that the driver's experiences can be improved through the reservation service and the parking market could be expanded. Hence, the implementation of dynamic parking pricing and reservation can become technical feasibility and socioeconomically appealing.

Similarly, Vera-Gómez et al. (2016) proposed a low-cost and minimally intrusive system to manage parking spaces for public and controlled zones. The system proposed is a wireless network considering sensors that can access roads into and out these areas. The sensors detect the passage of vehicles and are able to quantify parking availability. This information can then be communicated to drivers to facilitate their search for a parking space and to authorities to facilitate parking management. The authors highlight that one of the causes for excessive amount of time spent on the road in private road transport is the time looking for parking spaces.

Parking Spaces Construction Techniques and Operational Inputs

According to Drive Smart BC (s.d), parking lots are classified as private property and are also considered highways under the Motor Vehicle Act. The speed limit for parking lots in British Columbia (BC) is 20km/h, and parking lot designs are typically conducted in a way that will guarantee maximum space for parking, rather than the safety of pedestrians. In 2016, the city of Vancouver had 270,000 registered vehicles (Korstrom, 2017), which require the construction, operation, and maintenance of parking spaces.

Furthermore, the presence of an integrated garage in a house is a primordial selection factor for some home buyers in Canada (Kaynak & Meidan, 1980). House value, quality and location are also highly important house selection criteria in Canada (Kaynak & Meidan, 1980). Nevertheless, present studies indicate that shared private parking spaces can become a solution for densely populated cities (Lai et al., 2021).

Hence, many developers of multi-family buildings will incorporate parking spaces in their design to attract buyers. The number of parking spaces needed to be constructed is determined by the City of Vancouver parking by-law (City of Vancouver, 2019), which highlights both minimum and maximum requirements for parking spaces in different land uses. Table 2 provides an example of accessible and standard parking space requirements for multiple dwelling buildings.

Table 2- Parking specifications in the City of Vancouver

Requirement	Multiple dwelling or live-work use
Accessible parking	Minimum: one accessible parking space for each building with seven residential units. If the building has more than seven domiciliary units, the number 0.034 spaces per apartment will be the norm.
Parking spaces	Minimum: one parking space per 140m^2 or one space per dwelling unit Maximum: 0.5 space per unit that is less than 50m^2, 2 parking spaces per unit that has more than 189m^2 and no more than 0.65 for a unit between 50 and 189 m^2

Source: (City of Vancouver, 2019)

Furthermore, the environmental impacts of parking spaces are dependent on the specifics of the construction techniques, operational details, and the particular requirements of the site. For instance, the operation of parking spaces often includes: emissions due to vehicle cruising, lighting, heating, and ventilation depending on location and parking type. The construction, on the other hand, will include material extraction, manufacturing and transportation, and the construction technique and material selection will highly influence the construction environmental impacts and emissions.

According to METCALFE (s.d), parking lots are the areas designated for parking, they are marked in the ground using yellow or white lines. Parking garages, on the other hand, are parking structures and can be classified into single-level parking garages, multilevel or multi-storey parking garages, underground parking spaces, automated parking garages, carports, and curbside parking. A more detailed definition of the aforementioned is found below:

A. Carports are defined as covered places that are near driveways that allow multiple vehicles to be parked. This type of parking space typically uses one wall from the house and aims to protect the vehicle from the weather (METCALFE, s.d).
B. Automated parking garages: garages that use an automated parking system.
C. Automated parking systems: these systems move the vehicles from the entry area to a free parking space inside the garage. These systems do not require any workers to help in the process (METCALFE, s.d).
D. Semi-automated parking systems: these systems use mechanical machinery to move the vehicles to their parking spaces. However, they are required to be attended by a worker or the driver (METCALFE, s.d).

In Vancouver, parking spaces are typically built underground, due to space restrictions, and use the cast-in-place concrete technique. In the cast-in-place technique the walls and slabs of buildings are cast on site. The main material for this type of construction is reinforced concrete (rebar), which has a high environmental impact. According to (Knoeri et al., 2013), CO_2 emissions from the production of concrete are 24-36 $kgCO_2\text{-Eq}/m^3$ (kilograms of carbon dioxide equivalent per cubic meter), while steel production creates 1,270-2,125 $kgCO_2\text{-Eq}/m^3$ (Liang et al., 2020). Furthermore, the below-ground construction technique requires excavation as well as the reinforcement of the structure and foundation.

Multi-Storey Developments in Downtown Vancouver

According to the City of Vancouver (2022a), Vancouver zoning considers urban planning, sustainability and the development of the city. Furthermore, Vancouver has become a symbol around the word and the term “Vancouverism” has been coined to refer to urban planning that respects the natural environment while considering the urban dynamics needed for economic growth. In this context, the city is known for tall slim towers that increase the urban density and are separated by low-rise buildings to enhance the lighting, air, and views of infrastructure. Vancouver is also known for its parks, walkable streets and public spaces, considering various sustainable forms of transit (City of Vancouver, 2022a). Furthermore, a very important aspect of Vancouver urbanization is that most Vancouver citizens want to maintain views from the city and they are not willing to compromise on losing views of the ocean or mountains (City of Vancouver, 2022b).

Furthermore, the municipal government of Vancouver aims to develop a downtown area that will consist of mixed-income communities with affordable housing, local serving commerce, social services and cultural activities (City of Vancouver, 2020). The development of affordable housing is vital for the City of Vancouver, as 2,223 people are living in the streets according to the census of 2019, representing a 23% increase when compared to the data from 2005.

Furthermore, the affordability crisis is spreading from housing to retail and industrial spaces in Vancouver, which is leading businesses, including cultural organizations and artists, to leave the city. Finally, the lack of affordable places is leading to a loss of local grocery stores, which will lead to longer distances travelled for to buy groceries and access employment, leading to an increased demand for vehicles and parking. Vancouver aims to secure 3,000 rental market units by the year 2043, as well as upgrading 4,400 social housing and 2,200 SRO units. Furthermore, the city aims to retain 2,800 small businesses and create 3,500 employment opportunities (City of Vancouver, 2020).

Furthermore, Vancouver has implemented metered parking in many areas of the city. In this context, the government aims to increase the public parking space turnover and improve the traffic flow in busy areas (City of Vancouver, 2022c). Hence, the parking spaces provided by residential and commercial buildings might become highly required and their implementation and construction need to be evaluated. In this context, this work evaluated 6 developments located in the downtown area of Vancouver. Table 3 shows each of these buildings, their addresses and main uses.

Table 3- Multi-storey developments in downtown Vancouver

Address	Main uses/characteristics
1190 Burrard St rezoning application	139 social housing units, commercial uses at grade, social service center, and 276 bike spaces
1133 Melville Street	Public building, 257 underground parking spaces
443 Seymour Street	Office spaces and commercial retail, 8 levels of underground parking containing 201 parking spaces, 5 passenger spaces, 6 Class A loading spaces, 2 Class B loading spaces, and 246 bicycle spaces
720 Beatty St	Two commercial buildings including a 17 storey office building with retail in the ground floor, a 5 storey entertainment pavilion, four levels of underground parking
1166 W Pender Street	Commercial retail space in the ground floor, twenty-nine levels of office space and one level of amenity space above; and six levels of underground parking with 199 vehicle parking spaces.
508 Drake Street	193 units of social housing, a community space to include a place of worship, early childhood playspace, social spaces and reading rooms and 53 vehicle parking spaces and 226 bicycle parking spaces.

Challenges: Literature Review

While the literature review indicated a variety of methodologies that can be applied to the transportation sector, very few studies considered the analysis of the infrastructure and even less considered the analysis of parking spaces emissions. In this context, the implementation of a life-cycle oriented approach considering the construction and operation could become beneficial to provide important decision-making strategies for parking spaces. The mitigation strategies derived from the evaluation of CO_2 emissions in parking spaces can lead to the reduction of the impacts and the implementation of fees that will decrease the number of parking spaces offered. Hence, reducing the use of single-family vehicles, decreasing even further the CO_2 emissions in urban area (Manville & Shoup, 2010). The main limitations identified in the literature are:

1. Lack of a comprehensive analysis of emissions for underground parking spaces;
2. Few analysis concerning the infrastructure used in the transportation sector;
3. Lack of data regarding materials used for parking space construction.

Methodology: Life Cycle CO_2 emission analysis

The methodology of this work is based on ISO 14040:2006 and 14044:2006[2]. Furthermore, the checklist published by Rebello et al. (2021) was also applied so all the necessary details would be listed.

Goal and Scope

The present analysis has the following aims:

1. Quantify the CO_2 emissions of different parking garages located in the City of Vancouver, considering both the construction and the operation of these facilities.
2. Compare the CO_2 emissions in the different parking garages using both the total CO_2 emissions and the CO_2 emissions per parking space (Functional unit: total parking space kg CO_2-Eq and kg CO_2-Eq/parking space).
3. Understand the impacts of parking minimums and propose some guidelines for its implementation
4. Identify trends and propose guidelines for future parking spaces analysis in the City of Vancouver.

Figure 2 and Figure 3 show the boundaries for the analysis, considered in this study. The construction and the operation of parking garages were considered separately to avoid the consideration of life-span, which might increase the uncertainty in the final results. Using the nomenclature shown in Advancing Net Zero Green Building Council (GBC) Steering Committee (2019), this work included A1 (raw materials supply), A3 (manufacturing) for the product stage, A5 (construction process) in the construction process, and B6 (Operational energy use) for the operation in the main analysis. The analysis was conducted as an attributional Life Cycle

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[2] ISO 14040:2006 describes the principles and framework for life cycle assessment (LCA), while ISO 14044:2006 specifies requirements and provides guidelines for life cycle assessment (LCA).

Assessment, due to the type of data available and goals of the study. No allocation method was necessary.

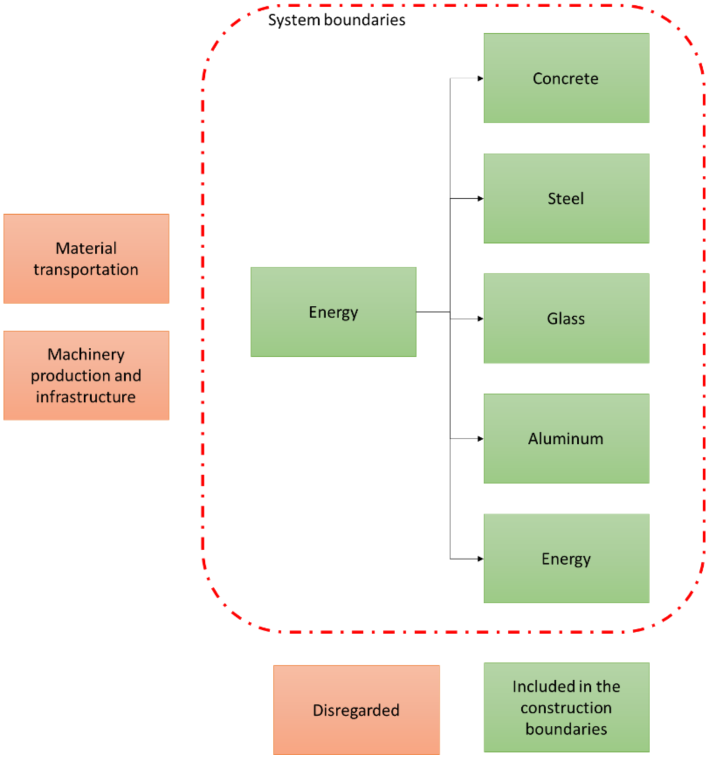


Figure 2 - Construction Life Cycle Assessment boundaries

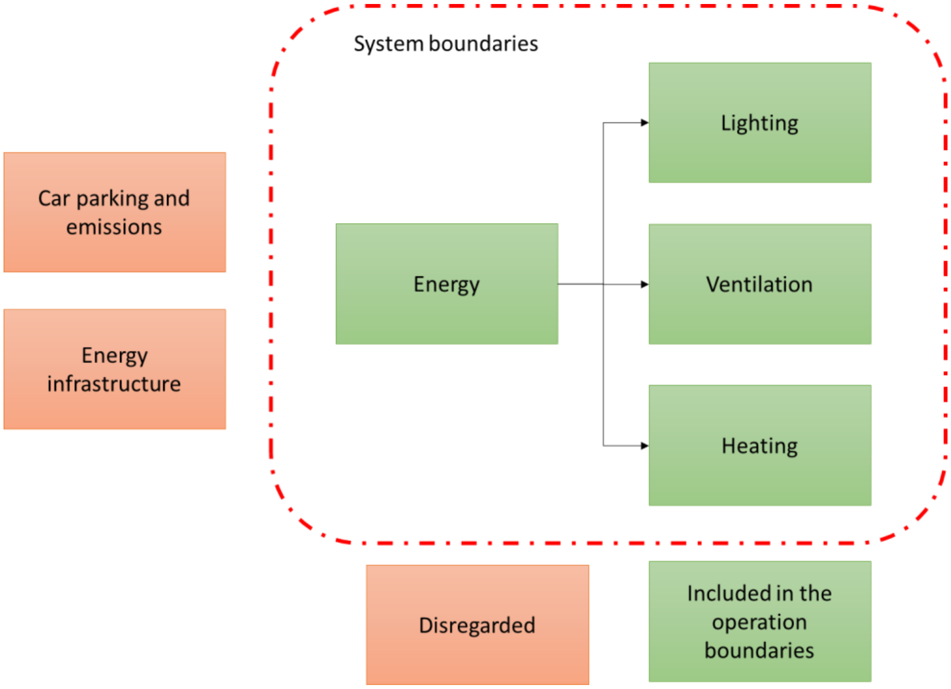


Figure 3- Operation Life Cycle Assessment boundaries

Table 4 shows the buildings used in the calculations, the size of their parking spaces, the total number of parking spaces, the number of levels underground and the space per parking ratio.

Table 4 – Parking spaces selected for the analysis, size, parking space count and parking ratio

Address	Total parking (m^2)	Total parking (number of spaces)	Parking levels (underground levels)	m^2/parking Ratio
1190 Burrard St	3412.98	34	3	100.38
1133 MELVILLE STREET	11326.36	257	4	44.07
443 SEYMOUR STREET	13892.25	206	8	67.44
720 BEATTY STREET	13752.00	189	4	72.76
1166 W PENDER STREET	10371.60	199	6	52.12
508 DRAKE STREET	1602.42	53	4	30.23

Life Cycle Inventory

While data was an important shortcoming of the present contribution, a few strategies were conducted to minimize the impact of the lack of data. For instance, the paid database Ecoinvent was not available for the analysis, and a combination of free databases was used. The Agrybalyse 1.2 was selected for materials and Needs 1.8 was selected for the energy processes. The energy matrix was adapted considering the matrix for British Columbia, Canada. All processes missing (concrete, glass, oil, energy, aluminum, hydropower energy and British Columbia electricity matrix) were created from scratch.

Due to limitations in the databases freely available, most of the databases for the construction materials had to be created based in the data available in the literature. The limitations of the database also extended to the energy matrix and the lack of certain energy sources, which were all included through a careful examination of available data.

Data Quality Assessment

Because this work used many databases and background data, a data quality assessment was conducted. The data quality assessment aims to grade the data used to give the reader and the results a simple interpretation of the uncertainty imbedded in the results. Because the data quality assessment proposed by Weidema & Wesnæs (1996) is the main technique applied in the literature, it was selected for the present contribution. In their method, 5 parameters are evaluated (reliability, completeness, temporal correlation, geographical correlation, further technological correlation) and each parameter is scored from 1-5, 1 representing the best score. Reliability and Completeness are typically perceived as a data characteristic in the literature, and it might not change if the goal of the study is changed. Temporal, geographical and further technological correlation, on the other hand, are highly related to the study goals. The following provide a short definition of each data quality parameter according to Weidema & Wesnæs (1996), the scoring system can be found the reference.

I. Reliability: evaluates if data is based on measurements and if the data was verified.
II. Completeness: refers to the data representativeness.

III. Temporal correlation: refers to the relative date of data collection and the goal of the study, it varies according to the selected data quality parameters. In the present contribution, 2020 was used as the year of reference.

IV. Geographical correlation: refers to where the data was collected and how the data collected can be exported to the region under study. In the present report, the region selected is the city of Vancouver located in the British Columbia province (Canada).

V. Technological correlation: refers to how the technology of the data available is representative of the technology under study in the goal of the study. In the present study conventional materials and technologies were selected due to the following: they represent the majority of the materials used in the construction industry, and the data availability for these types of materials is more predominant.

Material and energy data

A. Energy Mix

The British Columbia (Canada) electricity matrix is shown in Table 5.

Table 5- British Columbia electricity matrix

British Columbia		
Electricity type	**quantity**	**unit**
Hydro	87.00	%
Biomass	5.00	%
Natural gas	4.00	%
Petroleum	0.50	%
wind	2.60	%
solar	0.10	%

Source: Canada Energy Regulator, 2019

Because some processes are not available in the database and their contribution are relatively small in British Columbia's electricity matrix the biomass energy was substituted using a wood process and petroleum was substituted with coal. Hydropower, on the other hand represents almost 90% of the matrix and was created from scratch to ensure lower uncertainty and a better final result (Table 6). For the operational phase, the hydropower does not consider the construction of the facility and the CO_2 emissions are 0.9g/kWh.

Table 6- Hydropower database

Hydropower			Reference	Data quality				
Process	quantity	Unit		R*	C*	TC*	GC*	TCC*
Electricity	140	kWh/kWh	(Pang et al., 2015)	2	3	2	3	2
Lubricant oil	6	kg/kWh		2	3	2	3	2
Water Flow	6800000	m3/kWh		2	3	2	3	2
Carbon dioxide	0.0282	Kg/kWh		2	3	2	3	2

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Oil energy was also constructed from the literature, and the data used is shown in Table 7.

Table 7- Oil energy database

Oil			References	Data quality				
Process	quantity	unit		R*	C*	TC*	GC*	TCC*
Energy consumption	0.001349	kwh	(Liu et al., 2020)	2	4	1	3	3
Steam	0.368229	g		2	4	1	3	3
CO2	1.082473	g		2	4	1	3	3
CO	0.017245	g		2	4	1	3	3
Nox	0.003678	g		2	4	1	3	3
SO2	0.001696	g		2	4	1	3	3
VOC	0.007667	g		2	4	1	3	3
PM2.5	0.000382	g		2	4	1	3	3
PM10	0.000406	g		2	4	1	3	3
NH3	0.010318	g		2	4	1	3	3

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Diesel used for energy purposes was also created using the literature data, and the database is showcased in Table 8.

Table 8- Diesel database

Diesel			References	Data quality				
Process	quantity	unit		R*	C*	TC*	GC*	TCC*
Energy consumption	0.05	MJ	(Furuholt, 1995)	2	5	5	3	4
CO2	3.3	g		2	5	5	3	4
CO	0.64	mg		2	5	5	3	4
Nox	16	mg		2	5	5	3	4
SO2	7.1	mg		2	5	5	3	4
VOC	63	mg		2	5	5	3	4

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

B. Construction Materials

In the construction phase, some construction materials databases, such as concrete, aluminum and glass were also built from scratch. Table 9 shows the aggregated data for concrete, considering both the data (Sjunnesson, 2005) and Howden (s.d) concrete traces.

Table 9- Concrete database

						Data quality		
Process	**Minimum**	**Maximum**	**unit**	R*	C*	TC*	GC*	TCC*
Coal	1.90E-01	2.85E-01	MJ	2	5	5	3	3
Coke	0.051	0.0765	MJ	2	5	5	3	3
Diesel	0.0095	0.7545	MJ	2	5	5	3	3
electricity	7.22E-02	1.20E+00	MJ	2	5	5	3	3
oil	6.56E-03	3.75E-04	MJ	2	5	5	3	3
biomass	3.58E-05	4.13E-05	MJ	2	5	5	3	3
natural gas	7.15E-06	8.25E-06	MJ	2	5	5	3	3
Emissions		**Emissions**				**Emissions**		
CO2	0.072166	1.08E-01	kg	2	5	5	3	3
CO	9.13E-07	1.09E-06	kg	2	5	5	3	3
Nox	7.57E-05	1.11E-04	kg	2	5	5	3	3
Sox	1.06E-05	1.52E-05	kg	2	5	5	3	3
CH4	0.000261	3.91E-04	kg	2	5	5	3	3
HC	5.68E-07	6.80E-07	kg	2	5	5	3	3

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Table 10 shows the database for aluminum and Table 11 shows the database for glass.

Table 10- Aluminum database

minimum		maximum		Reference	Data quality				
Process	quantity	quantity	unit		R*	C*	TC*	GC*	TCC*
Energy	15.5	161.44	MJ	(Martínez-Rocamora et al., 2016)	2	3	5	3	2
CO2	0.726	9.827	kg CO2		2	3	5	3	2

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Table 11 – Glass database

Minimum		Maximum		Reference	Data quality				
Process	quantity	quantity	unit		R*	C*	TC*	GC*	TCC*
Electricity	0.0629	0.0851	kWh	(Humbert et al., 2009)	2	5	5	3	3
Steam	0.952	1.288	kg		2	5	5	3	3
Water	10.2	13.8	kg		2	5	5	3	3

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Construction and operation indicators

A. Construction indicators

The construction analysis was performed using two scenarios: one considers the use of data available from Vancouver buildings, and one considers data extracted from literature. All indicators were adapted from whole building studies, as no study concerning only underground parking was available in the literature or for the city of Vancouver.

The first scenario considers a range of data extracted from Vancouver's buildings that were not included in the study to decrease the geographical uncertainty and improve the data quality scores. Table 12 shows the database for the Vancouver data as found. The data was then divided into minimum and maximum to provide a range of results, for the materials that are not used in both constructions, the minimum is considered 0 to provide a comprehensive range of results.

Table 12- Vancouver indicators: construction

Building A					Data quality		
Material	**Quantity**	**Unit**	R*	C*	TC*	GC*	TCC*
Concrete	1,154.91	kg/m^2	2	5	2	1	2
Glass	5.16	kg/m^2	2	5	2	1	2
Galvanized steel	2.60	kg/ m^2	2	5	2	1	2
Energy	841.55	kWh/ m^2	2	5	2	1	2
Building B					**Data quality**		
Material	**Quantity**	**Unit**	R*	C*	TC*	GC*	TCC*
Concrete	1,240.15	kg/ m^2	2	5	1	1	2
Steel	0.25	kg/ m^2	2	5	1	1	2
Glass	1.72	kg/ m^2	2	5	1	1	2
Aluminum	3.75	kg/ m^2	2	5	1	1	2
Energy	1,064.38	kWh/ m^2	2	5	1	1	2

*R: reliability, C: completeness, TC: temporal correlation, TCC: Technological correlation

The literature data, on the other hand was also considered because it contained data regarding excavation (an important aspect of underground parking) and other machinery related to concrete casting on site and pumping. Table 13 shows the literature data collected for the indicators of the construction phase.

Table 13- Literature data: construction

		Literature data			Data quality				
Material	Minimum	Maximum	Unit	Reference	R *	C *	TC *	GC *	TCC *
Cast in place concrete	841.52	1630.40	kg/m^2	(Eliassen et al., 2019)	2	5	1	4	3
prefrabicated concrete	17.43	95.45	kg/ m^2	(Eliassen et al., 2019)	2	5	1	4	3
Concrete	858.95	1725.86	kg/ m^2	-	2	5	1	4	3
Steel	6.08	8.42	kg/ m^2	(Eliassen et al., 2019)	2	5	1	4	3
Excavation	4.43	24.56	kWh/ m^3	(Marrero et al., 2020)	2	5	1	4	3
Concrete machinery	204.24	277.08	kgCO$_2$/ton of concrete	(X. J. Li & Zheng, 2020)	2	5	1	4	3
Concrete pumping machinery	125.18	130.39	KGCO$_2$/ m^3 of concrete	(X. J. Li & Zheng, 2020)	2	5	1	4	3

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

B. Operational indicators

The operational CO_2 emissions were calculated considering two scenarios: a scenario with electric heating, using the British Columbia electricity matrix and a scenario with natural gas as the heating source. Table 14 shows the indicators used in the analysis.

Table 14- Operation database

	Literature				Data quality				
Process	**minimum**	**maximum**	**unit**	**Reference**	R *	C *	TC *	GC *	TCC *
energy needed for heating	0.025	0.034	kWh/m^2.year	(Energy Star, 2013)	1	1	5	2	2
Energy for lighting	49.283	66.677	kWh/m^2.year	(Energy Star, 2013)	1	1	5	2	2
Energy for ventilation	10.965	14.835	kWh/m^2.year	(Energy Star, 2013)	1	1	5	2	2

*R: reliability, C: completeness, TC: temporal correlation, GC: geographicalcorrelation, TCC: Technological correlation

Life Cycle Assessment

The Life Cycle Assessment was conducted using the IPCC 2021 Global Warming Potential indicator. The indicator was calculated for each individual component of the construction and operation and then calculated separately for all parking spaces included in this analysis. The calculations included two scenarios in the construction phase: one using Vancouver data and one using Literature data, and two scenarios for the operational phase: considering electricity heating and methane heating.

Life Cycle Interpretation: sensitivity

Because there was no data available regarding the transportation of construction materials and vehicle cruising inside the parking spaces, two sensitivity analysis were conducted. In both sensisitivity analysis, the comparison aimed to understand how far materials and cruising could be performed to keep the best alternative as the best alternative. The distances were calculated using Equation 1-2.

$$Emissions_{higher} = Emissions_{lower} + transport_{emission} * distance_{transport} \qquad (Eq.1)$$

$$distance_{transport} = \frac{Emissions_{higher} - Emissions_{lower}}{transport_{emission}} \qquad (Eq.2)$$

In which $Emissions_{higher}$ represents the parking space emissions with the highest CO$_2$ emissions and $Emissions_{lower}$ represents the emissions from the lowest environmental impact parking garage. The comparison uses two parking space pairs, considering the lowest emissions as the Emissions lower and all other alternatives take turn as the higher emissions alternative.

Findings

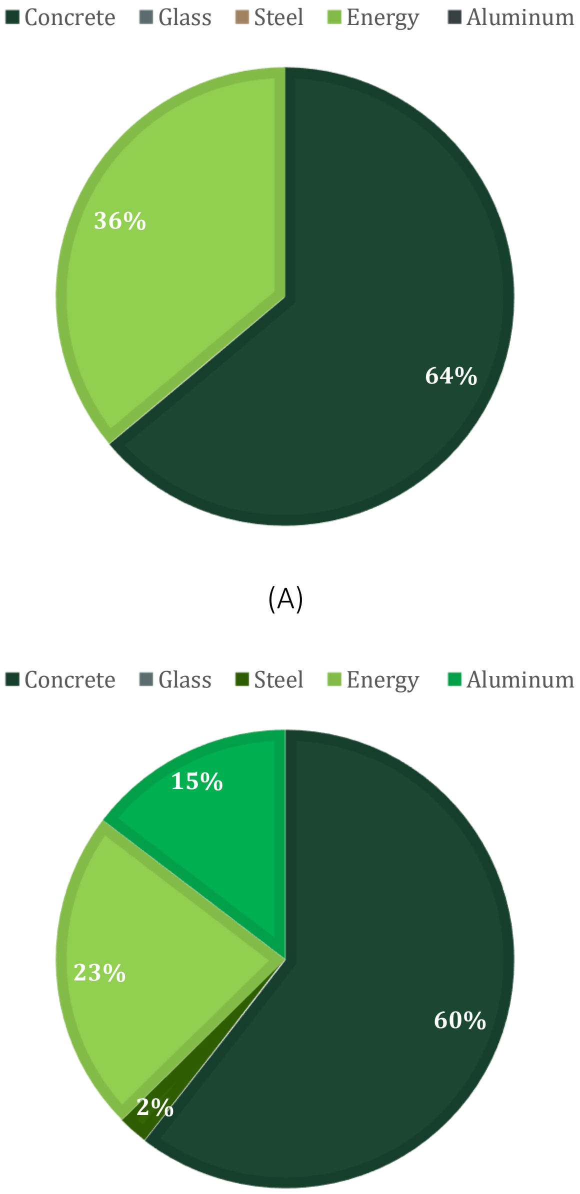
In this paper the results are divided into construction and operation. This is performed to avoid the uncertainty of the life-span consideration. In this case, the construction was considered in full, and the operation is considered for one year.

Construction

The construction impacts and distribution varied according to the data source used in the analysis. For instance, Vancouver data presented the same behavior for all buildings. On the other hand, the literature data presented different behaviors for different buildings.

A. Vancouver data

Considering Vancouver data, the CO_2 emissions varied from 166.93 to 334.55 kg CO_2-Eq/m^2 in all underground parking garages due to the calculations performed. Furthermore, the same behavior was identified in the impact distribution for the different scenarios (Figure 4). Hence, the minimum impact was mainly caused by concrete (64%) and energy (36%), while the maximum impact was divided by concrete (60%), energy (23%), aluminum (15%), and steel (2%).



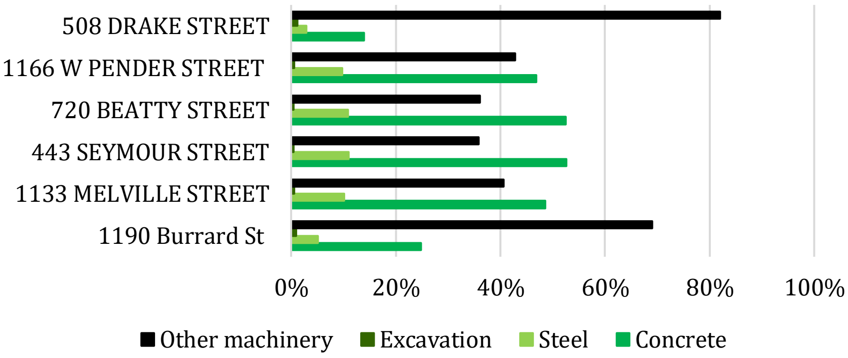
(A)

(B)

Figure 4- Distribution of calculated CO_2 emissions using Vancouver data: minimum (A) and maximum (B)

B. Literature data

Considering the literature data, the results varied according to the building analyzed. For instance, all underground parking garages with more than 100 parking spots had concrete as their main contributor. Parking garages with lower capacities, on the other hand, had the use of machinery to pump and mix the concrete on site as their main contributor. These results highlight the importance of the incorporation of the machinery use as well as the materials. Figure 5 shows the comparison for the contributions in the different parking garages. Furthermore, the literature data had different indicators per m^2 for each parking space, due to the method used to calculate the results. In this context, the CO_2-Eq varied from 150.72 kg CO_2 – Eq (minimum emissions of 443 Seymour Street) to 1385.80 kg of CO_2 – Eq (maximum of 508 Drake Street).



(A)

(B)

Figure 5- Distribution of Calculated CO_2 emissions using the literature data

The excavation and the use of steel were the processes that impacted the least in the analysis, which might be an indicator that underground and above ground parking spaces would have similar results.

C. Total construction emissions and indicators

When considering the entire parking garage, the calculated CO_2 emissions varied from 267.49 tonnes of CO_2 – Eq (508 DRAKE STREET) to 7,061.68 tonnes of CO_2 – Eq (443 SEYMOUR STREET). This variation was mainly due to the size of the parking garages and the excavation for the parking garage. Figure 6 shows the results for the total emissions for each parking garage, using both Vancouver data and Literature data.

This paper also analyzed the CO_2 emissions per parking space, to showcase that the design of parking garages matters in the final environmental impacts and that future studies should also consider parking space design optimization (Figure 7). The impact per parking space varied from 5 tonnes to 84 tonnes.

An important observation in Figure 7 is that the ratio between parking size and parking spots is highly important for the final environmental impact. For instance, the lowest environmental impact was identified in the 508 DRAKE STREET parking garage, which has a 30.23 m^2 floor area/ parking space ratio[3]. The highest environmental impact, on the other hand is identified in 1190 Burrard Street, with a ratio of 100.38 m^2/parking space. While most of the other parking garages followed the ratio behavior, 443 SEYMOUR STREET and 720 BEATTY STREET did not, and the ratio for the Seymour Street building was 67.43 m^2/parking space and the ratio for the Beatty Street building was 72.76 m^2/parking space, but the environmental impact calculated with the Literature was a little higher at the Seymour Street building. These results are due to the number of underground levels constructed, and indicate that the optimization of CO_2 emissions in parking spaces first

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[3] This means that an average of 30.23m^2 of floor area is built in the underground parking garage to accommodate each parking space

should address the m^2/parking ratio and then consider the design of fewer underground parking levels.

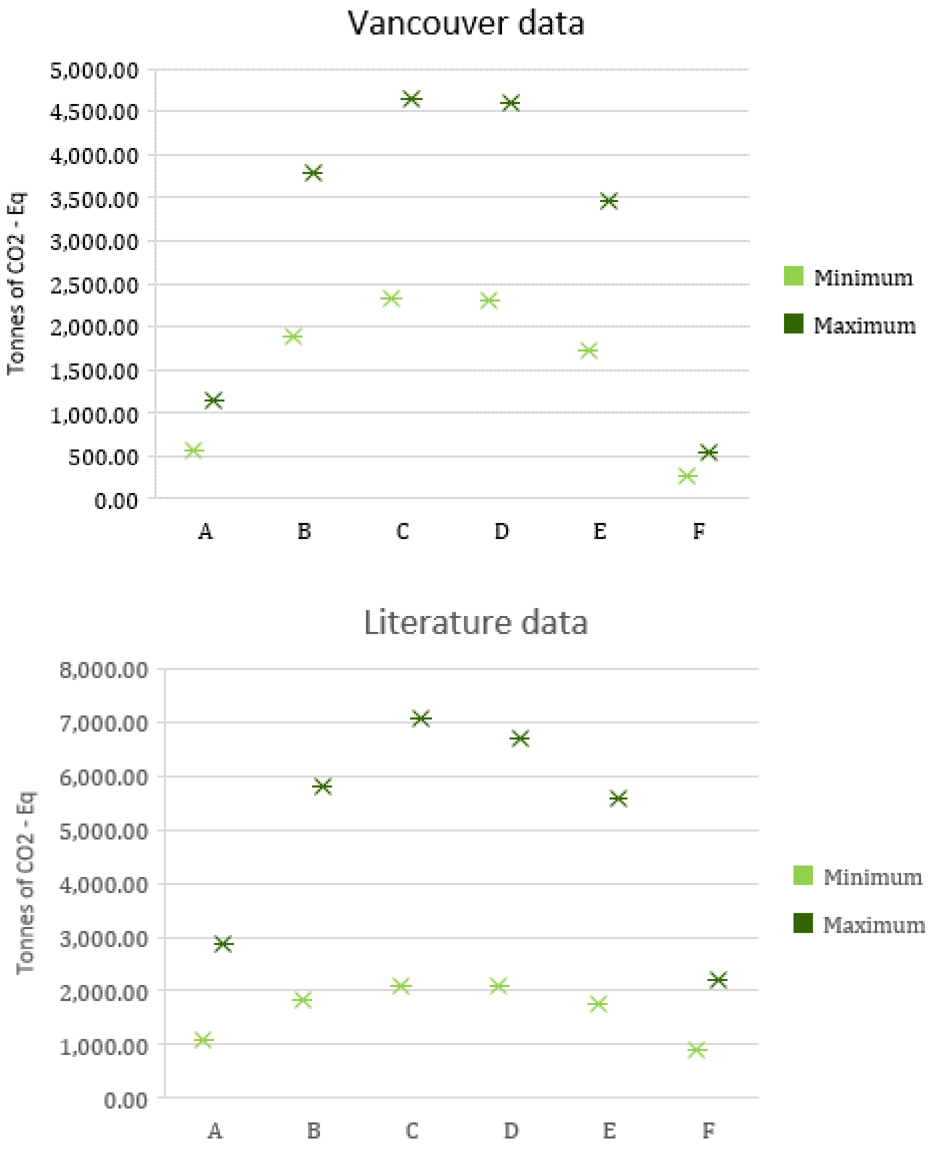

Figure 6 – Total construction CO_2 emissions using Vancouver data and Literature data

A=1190 Burrard Street, B=1133 Melville Street, C=443 Seymour Street, D=720 Beatty Street, E=1166 W Pender Street, F= 508 Drake Street

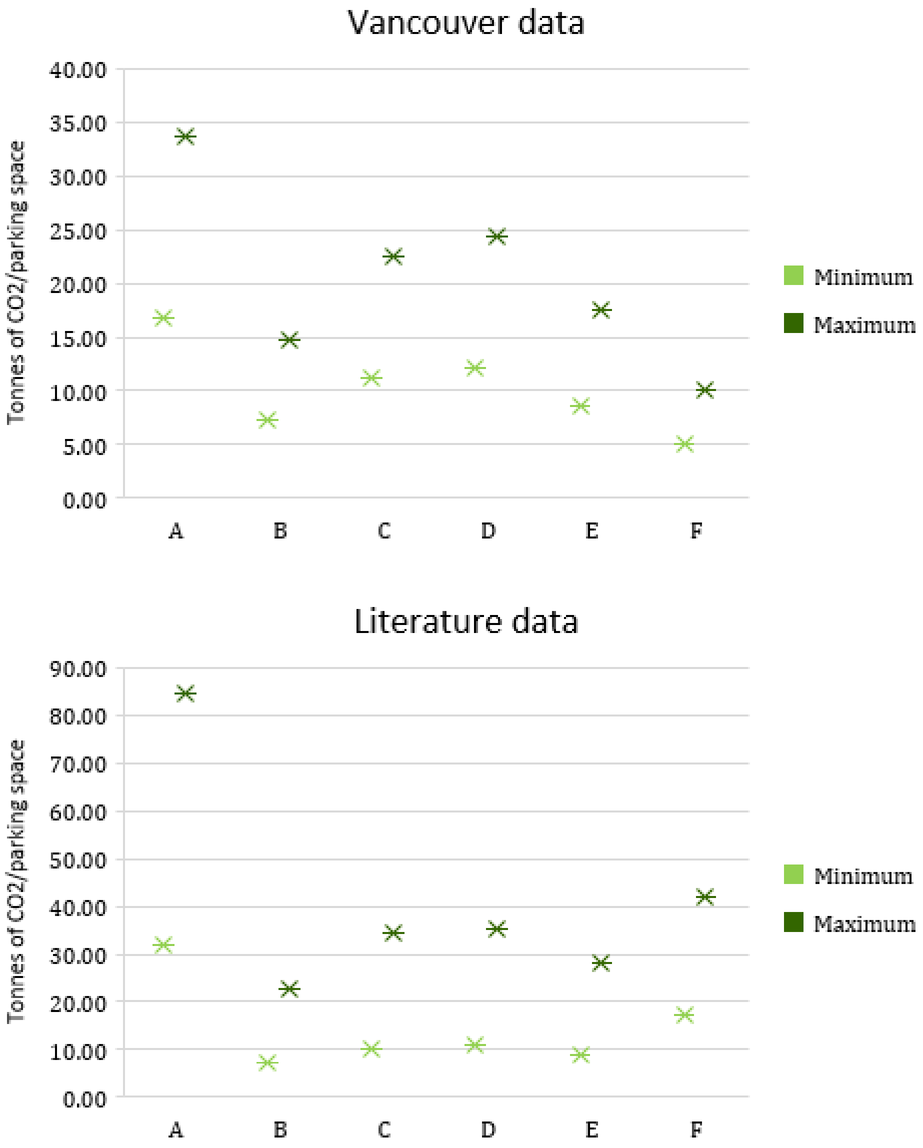

Figure 7 - CO_2 emissions per parking space

A=1190 Burrard Street, B=1133 Melville Street, C=443 Seymour Street, D=720 Beatty Street, E=1166 W Pender Street, F= 508 Drake Street

Operation

In the operation phase, all buildings had a similar behavior and the ventilation represented most of the environmental impact calculated. The operation phase counted both an electricity heating and methane heating scenario and the differences between the scenarios were insignificant. Ventilation was highly significant (95-97%) in the minimum scenario, and represented up to 50% of the total impact in the maximum scenario (Figure 8).

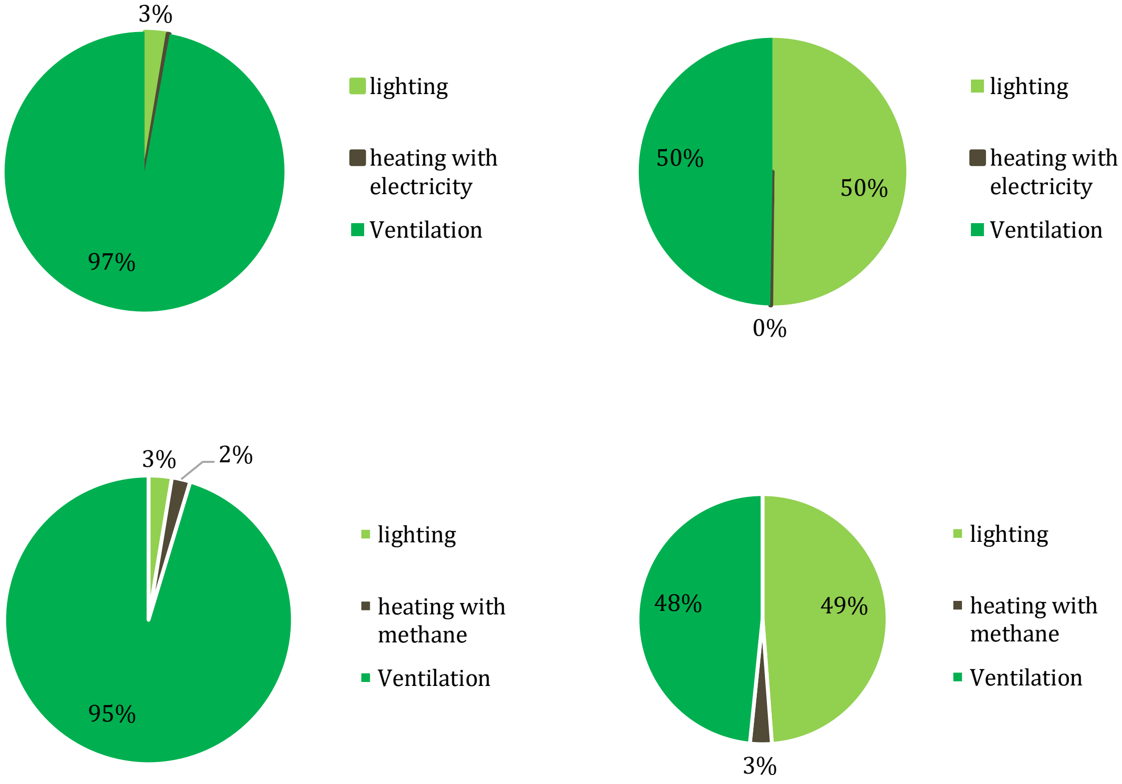

Figure 8- Behavior identified for the operational phase of parking spaces, considering the minimum (left) and maximum (right)

When comparing the total environmental impact of the parking spaces under study, the 508 Drake street parking garage had the lowest environmental impact (867 kg CO_2-Eq/year), in the methane heating scenario. The highest impact, on the other hand, was identified in 443 Seymour Street, in the electricity heating scenario (20364 kg CO_2-Eq/year). Figure 9 shows the comparisons for each parking space.

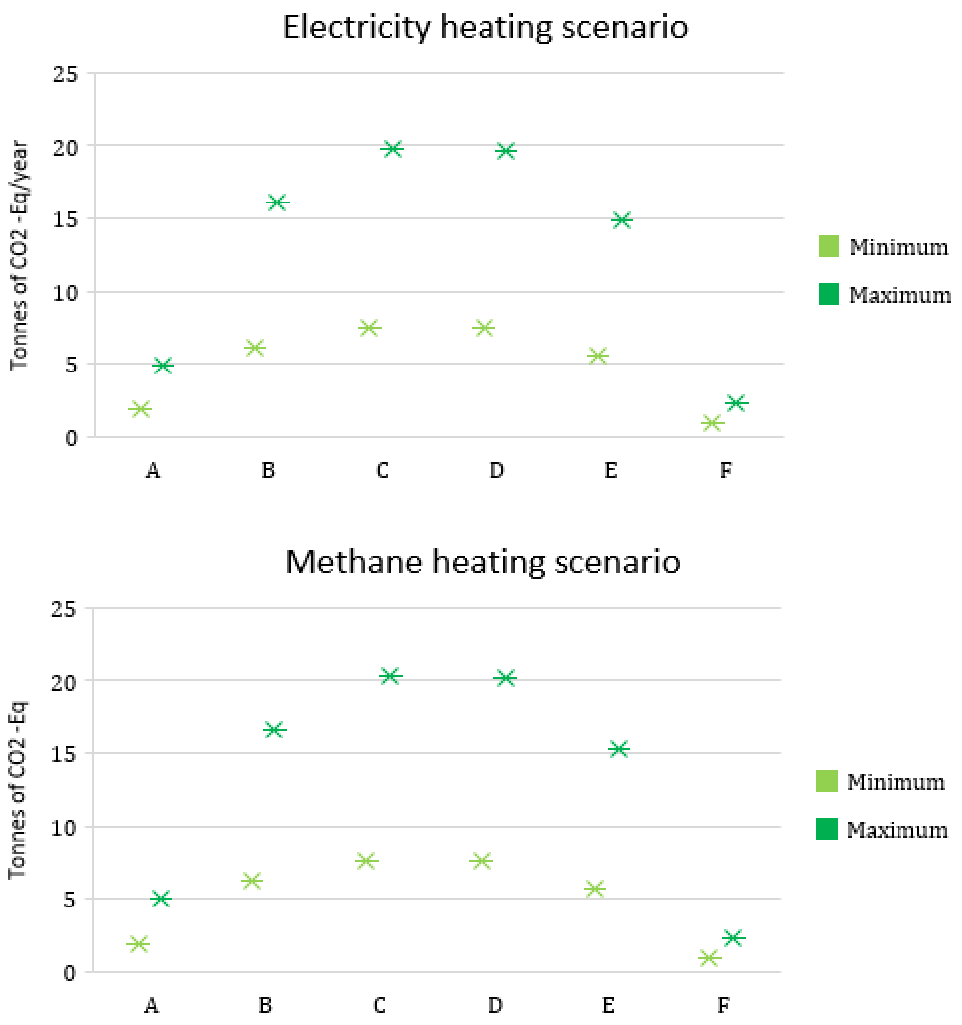

Figure 9 – Total operation CO_2 emissions per year

A=1190 Burrard Street, B=1133 Melville Street, C=443 Seymour Street, D=720 Beatty Street, E=1166 W Pender Street, F= 508 Drake Street

The comparison between kg CO_2-Eq per parking space is also shown in the figure 10. In this comparison, the CO_2 emissions followed the m^2/parking ratio for all the alternatives, and the results are consistent with the expected. Hence, optimizing the spatial distribution and space ration in parking garages is highly important for the final environmental impacts. Emphasizing the need to optimize the design of parking spaces.

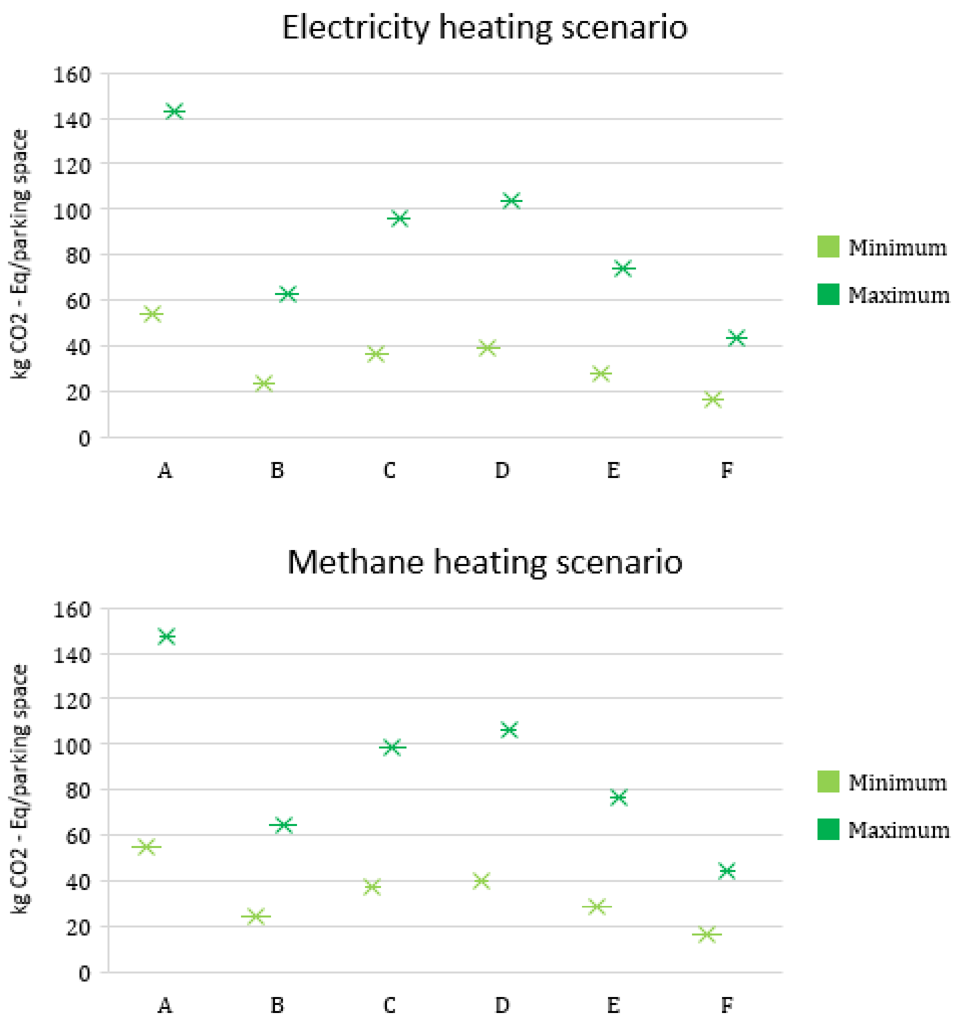

Figure 10 – Yearly operation CO$_2$ emissions per parking spaces

A=1190 Burrard Street, B=1133 Melville Street, C=443 Seymour Street, D=720 Beatty Street, E=1166 W Pender Street, F= 508 Drake Street

Sensitivity

In the construction, a 32 tonne truck creates 0.77559 kg of CO$_2$ per km travelled. The comparison shows that the distance travelled can vary from 0.39 million km to 6.34 million km, depending on the scenario. Figure 11 shows the comparison between the buildings with the lowest CO$_2$ impact (508 Drake street parking space).

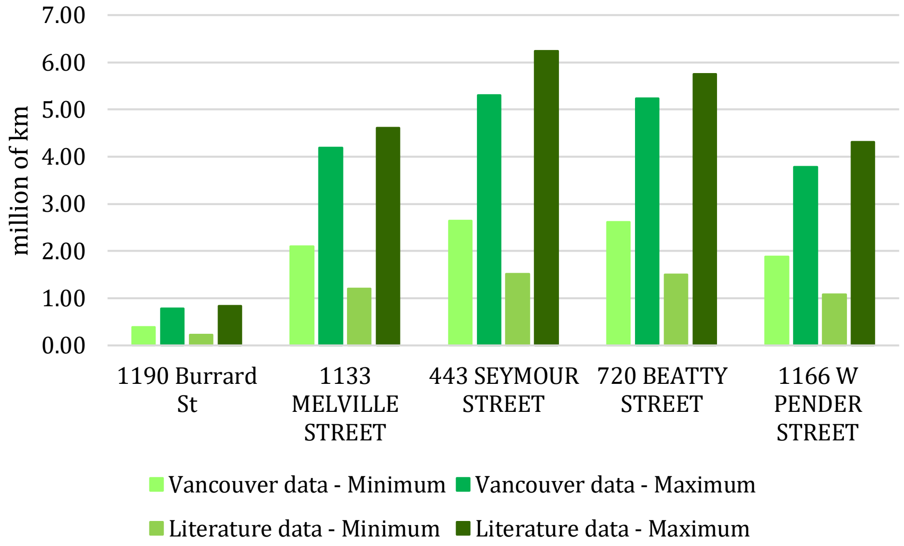

Figure 11 – Materials transportation sensitivity analysis

For the operational sensitivity, on the other hand, the distances that vehicle could cruise inside the parking space also varied highly (Figure 12). The vehicle cruising considered 0.35404 kg CO$_2$ – Eq/km.

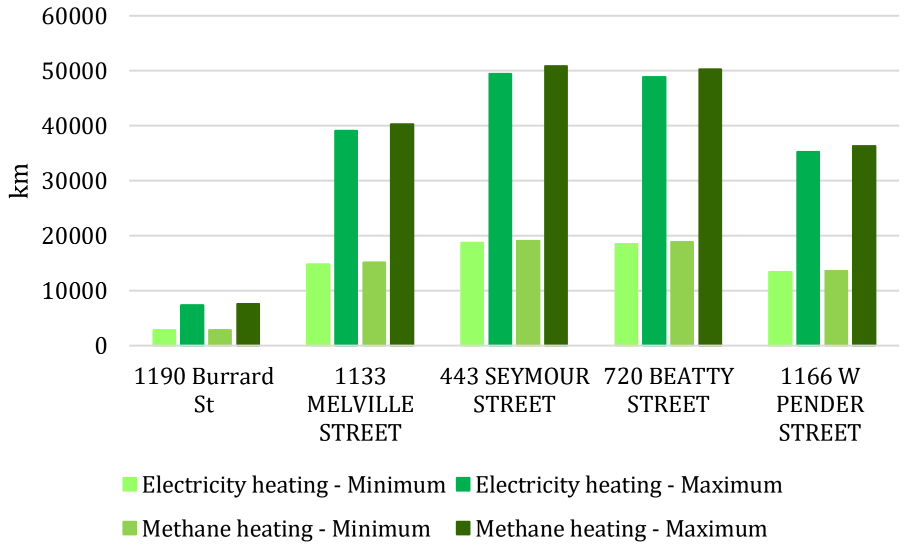

Figure 12 – Distance travelled in the parking space: operation sensitivity

Parking minimums implementation

Because the impact of construction is the main impact as per the calculations, the analysis of parking minimums implementations is also calculated below considering the construction phase. In this regard, this work calculates the impact of: 1- Decreasing the number of parking spaces, 2- Decreasing the parking space ratio (m^2/parking space), 3- Decreasing the number of parking levels.

A. Decreasing the number of parking spaces: for the decreasing of parking space number, two scenarios were considered: minimum (5 tonnes CO_2- Eq/parking space) and maximum (85 tonnes CO_2- Eq /parking space). In this context, a decrease of 10 parking spaces can reduce emissions from as low as 50 tonnes CO_2 – Eq to as high as 8500 tonnes CO_2 – Eq.

B. Decreasing parking space ratio: reducing the parking ratio from 100 m^2/parking space to 50 m^2/parking space, with only one level of parking and 100 parking spaces. In this analysis, the results showed emissions decreased by 39% in the minimum scenario and 52% in the maximum scenario. Using Vancouver data, on the other hand, the environmental impact doubles for both the minimum and the maximum scenario.

C. Decreasing the number of parking levels: considering two scenarios using 2 and 4 parking levels, the results show that a 2% difference was identified for the maximum results. This indicates that the parking ratio and size are the most important information to include in the parking minimums.

CO_2 emissions comparisons

To enhance the understanding of the results, this section aims to compare the CO_2 emissions from construction of parking spaces to emissions from transportation and eating a Canadian diet.

A. Comparison with transportation: the minimum construction impact of one parking space is almost equivalent to a year of operation in a passenger vehicle, and the maximum impact from construction is equivalent to the operation of a passenger vehicle for almost 19 years (EPA, 2022). These results showcase the importance of reducing parking in cities, and decreasing the parking ratios.

B. The minimum CO_2 emissions calculated for the construction of one parking space is equivalent to the impact of feeding a vegan or vegetarian for 5 days, and an omnivore for

2 days (Veeramani et al., 2017). The maximum impact would feed a vegan or vegetarian for almost 3 months and an omnivore for approximately 5 weeks (Veeramani et al., 2017).

Study limitations

While this study aimed to analyze the CO_2 emissions of different underground parking spaces in Vancouver, the study faced many limitations during the development. These limitations, and the strategies used to decrease their impacts are listed below.

A. Lack of access to paid Life Cycle Assessment databases, this issue was reduced through the combination of two free databases and the inclusion of data from the literature and creation of basic processes from scratch, using data from the literature.

B. Lack of specific data for each parking space, an issue that was reduced through the use of data from other Vancouver parking spaces (Vancouver data), and data from the literature (literature data). Hence, the results were presented in two ranges of minimum and maximum impacts, for the considered materials and boundaries.

C. Lack of data regarding material transportation, parking space utilization and types of vehicle, an issue that was minimized through the consideration of two sensitivity analysis considering the transportation of materials and vehicle emissions inside the parking space.

D. Due to the lack of data, some materials and processes were disregarded, we expect that future analysis will be able to conduct a complete CO_2 calculation.

E. The natural heating gas scenario considered simple data found in the literature, and while the results indicate that the differences are not very important considering natural gas and the electricity matrix of British Columbia. Future studies should strive to consider gas losses during the process, as well as the construction or operation of the natural gas energy scenario.

Future studies

While this report is part of various studies to determine future parking minimums in Vancouver, it does not showcase all the information needed to reduce CO_2 emissions from parking spaces in the City of Vancouver. The following studies are also needed:

A. Optimization studies regarding the locations of the parking spaces, to ensure the implementation of parking minimums will consider different zones and the parking demand of these different zones.
B. Demand studies to understand future demands across different neighborhoods and different social-economic aspects.
C. Studies to gather data for Vancouver buildings, considering material composition, to develop specific databases.
D. Future studies of Life Cycle Assessment for parking spaces, considering data with less uncertainty.
E. Uncertainty analysis considering the data quality.

Recommendations: implementing Life Cycle Assessment and data acquisition

This section aims to provide a few guidelines for the implementation of Life Cycle Assessment in buildings from Vancouver, focusing on parking spaces. The proposed guidelines aim to facilitate the implementation of Life Cycle Assessment, considering the complexity of each data and proposing a dynamic data collection to help stakeholders throughout time. The described phases include all data showed in previous phases. Figure 13 shows the different phases and how the implementation of the data acquisition can be conducted.

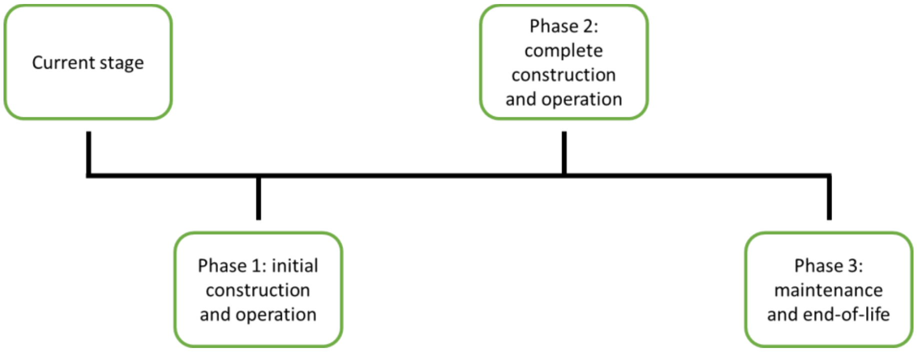

Figure 13- Data acquisition timeline

Data collection: phase 1 (next two years)

The primary data collection should focus on building materials and operation. The list below showcases the main data required for future Life Cycle Assessment studies:

I. Materials: concrete, steel, glass, wood, aluminum. The materials data should be described either in a ratio or in total. Both volume and mass can be used, but it is highly important that the data also describes the type of material (e.g. type of concrete). Ideally the data should be separated by level or function of the space (e.g. concrete use in the parking space, concrete use in the domiciliary area, concrete use in the business area or concrete use in the first floor).

II. Energy: type and consumption during the operational phase. Ideally this data would be divided through the different categories (e.g. lighting, ventilation, heating, A.C), because the division can assist decision-makers to change and improve the building performance.

Data collection: phase 2 (2024-2027)

The second phase aims to enhance the evaluation of the operation and construction life-cycle stages.

I. Transportation: inclusion of the transportation of materials, that has to be evaluated either using the distances (simpler approach) or the amount of fuel used in the transportation stage.
II. Emissions: inclusion of estimates or data about the emissions that are related to the direct operation of the building (e.g. emissions from cooking, emissions from vehicles travelling in the parking space).
III. Waste: inclusion of the materials in the construction phase that were discarded during the construction process. The inclusion of waste aims to provide a more comprehensive calculation, that will be more reliable and stimulate good management techniques during the construction.
IV. Life-Span: the inclusion of the design life-span or a life-span considering similar constructions aims to facilitate the combination of the construction emissions with the operation emissions,

Data collection: phase 3

The third phase aims to include the maintenance and end of life of the building.

I. Maintenance: inclusion of material substitution. In this phase, ideally the materials should also be considered by sector or level in the building.
II. End-of-Life: inclusion of the disposal of the materials, transportation to disposal site and type of treatment used for the construction materials.

Final remarks

This paper aimed to calculate the CO_2 emissions of underground parking spaces in Vancouver (British Columbia – Canada). The study used the Life Cycle Assessment technique and evaluated the construction and operation of parking spaces, considering the entire construction period and one year of operation, respectively.

The results indicate that the construction phase represents an important contribution to CO_2 emissions from parking spaces, varying from 5 tonnes of CO_2-Eq per parking space to 85 tons of CO_2 per parking space. In the construction phase, the ratio of floor area per parking space is the main contributor to the final CO_2 emissions. The number of levels in the parking garage can also become important if the ratios (m^2/parking space) are similar. In the operation estimates, the ratio (m^2/parking space) is also the most important aspect of the CO_2 emissions and varies from 16 kg CO_2-Eq/parking space per year to 147 kg CO_2-Eq/parking space per year.

In this context, this work indicates that the implementation of parking minimums might require the implementation of parking ratios within the parking by-law, to ensure that CO_2 emissions are decreased. In this regard, the design of the underground parking garage is more important than just the number of parking spaces constructed and needs to be taken into consideration. Another important aspect in the analysis is the number of parking levels, with the aim to reduce the total number of levels, as the excavation process for parking garages is an important contributor to GHG emissions with similar space/parking space ratios.

Nevertheless, it is important to acknowledge that the present study faced important limitations regarding the data used and the databases applied and that these limitations might influence the results. In this context, future studies should aim to gather and apply site-specific data, reducing the uncertainty. Data quality should also be used to estimate the data uncertainty and results variations according to uncertainty.

In conclusion, this paper shows that the construction and operation of parking spaces are an important contributors towards CO_2 emissions in urban areas. However, the implementation of parking minimums should consider the floor area to parking space ratio and the number of levels in a parking garage. The operation of parking garages does not highly contribute to the environmental impacts, and even when considering a 50 year life-span, the impact would vary from 0.8 tonnes/parking space to 7.5 tonnes/parking space.

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