

SPATIO-TEMPORAL LIFE CYCLE ANALYSIS FOR ENHANCED CARBON EMISSION MANAGEMENT IN BUILDING CONSTRUCTION

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ABSTRACT: The building sector significantly contributes to carbon emissions, mainly due to the extensive use of concrete in residential construction. Rapid urban development in residential areas has intensified these emissions, necessitating effective management strategies. Despite its importance, the life cycle environmental impacts of residential building construction remain underexplored in urban sustainability planning. Therefore, this research develops a geographic information system (GIS)-based framework, integrated with spatio-temporal life cycle analysis (LCA), to quantify and manage carbon emissions from residential buildings during both construction and operation phases. Using high-resolution satellite imagery and building attribute data, the framework identifies CO₂ emission hotspots and evaluates retrofitting measures for emission reduction. A case study in Ajman, United Arab Emirates (UAE), demonstrates the framework's application. Over 30,000 buildings were classified based on structural attributes, material use, and energy consumption. Carbon intensity factors for construction and operation phases revealed emissions reaching 890 kg CO₂/m² and 150 kg CO₂/m², respectively. The analysis identified emission hotspots in densely developed urban districts driven by material production, transportation, and high cooling energy demands. Retrofitting scenarios, including heating, ventilation, and air conditioning (HVAC) upgrades, improved insulation, and solar shading, showed significant potential for emission reductions in these areas. The results highlight the importance of spatio-temporal carbon management in urban planning. Future work will expand the framework by incorporating diverse building types, cost analysis, and multi-year assessments to understand long-term carbon trends better and optimize sustainable urban development strategies.

1. INTRODUCTION

Over the last decade, rapid urbanization has transformed cities worldwide, driven by economic, social, and cultural changes (Li et al. 2019). While climate change is a pressing global concern requiring top-down solutions through international treaties, urban areas and cities are at the head of addressing its effects (Wang et al. 2018). Urbanization-related land-use activities and the spatial characteristics of infrastructure expansion significantly influence global greenhouse gas (GHG) emissions (Marcotullio et al. 2016). Among the primary components of urbanization, the residential building construction sector is a major consumer of natural resources and a key contributor to environmental impacts (de Klijn-Chevalerias & Javed 2017). Residential buildings account for approximately 22–25% of global energy consumption and about 17–20%

of global CO₂ emissions (Delmastro & Chen 2023). Emissions associated with residential buildings arise from multiple sources, including material production, transportation, equipment energy use during construction, building operation (cooling, lighting, and heating), and end-of-life disposal (Hosny et al. 2024; Mao et al. 2013). A substantial body of literature has emerged that integrates life cycle assessment (LCA) with geographic information systems (GIS) to assess carbon emissions across different spatial and temporal scales. For instance, Roh and Tae (2017) developed a dynamic LCA-based assessment system that continuously evaluates emissions across the building life cycle phases in South Korea. Similarly, Gan et al. (2017) applied LCA to high-rise residential buildings, factoring in supply chain impacts, recycling potential, and construction processes. Numerous other case studies have examined CO₂ emissions for various residential typologies, including detached housing (Cuéllar-Franca & Azapagic 2012; Hosny et al. 2021), high-rise buildings (Xiao et al. 2018), and urban housing stocks (Abu Dabous et al. 2022), highlighting both global diversity and methodological convergence.

Importantly, several studies have gone beyond isolated case analysis to explore city-scale spatio-temporal emissions mapping. For example, Liu et al. (2019) proposed a spatially explicit carbon budget model for Wuhan, China, integrating land cover classification and carbon coefficients to create high-resolution emission maps over time. Wang et al. (2020) developed a GIS-based methodology to estimate carbon emissions using open datasets, demonstrating the role of GIS in visualizing and managing urban energy-related emissions. These works underscore the growing use of GIS–LCA coupling to support urban planning and policy decisions. Despite these advances, three key gaps persist in the existing literature. First, much of the current work is based on case-specific models with narrow material or structural assumptions, limiting generalizability across varied building types and city-wide contexts. Second, while several studies leverage GIS for spatial visualization, fewer have applied spatial analytics, such as kernel density estimation, to identify emission hotspots. Third, the integration of economic considerations, especially within retrofitting scenarios, remains underexplored, leaving a gap in actionable, decision support tools for planners. This research addresses these gaps by developing a GIS-integrated, spatio-temporal life cycle assessment framework specifically tailored to residential buildings at the city scale. The novelty of this study lies in the development of a GIS-integrated, spatio-temporal life cycle assessment framework specifically tailored to residential buildings. Unlike previous studies that focus on static or single-building assessments, this framework identifies spatial CO₂ emission hotspots and evaluates the impact of retrofitting scenarios at a city scale. The approach is adaptable, data-driven, and scalable, offering urban planners a practical tool to support low-carbon development strategies

2. METHODOLOGY

Figure 1 illustrates the step-by-step process of the framework used for spatio-temporal carbon emission analysis. The process begins with determining the study area, where the geographical boundaries and relevant building data are defined. Next, two concurrent steps are performed: developing a CO₂ estimation model and preparing a GIS database. The CO₂ estimation model calculates carbon emissions based on factors related to building construction, materials, and operational systems, while the GIS database organizes spatial data on building attributes such as type, floors, and footprint area. Following this, the CO₂ density map is generated by integrating the carbon emission data into the GIS platform. This map highlights carbon emission hotspots, which are areas with a high concentration of CO₂ emissions. Once these hotspots are identified, the next phase involves recommending enhancement techniques, which focuses on identifying and evaluating mitigation strategies such as retrofitting measures to reduce carbon emissions. The final output of the framework is a comprehensive assessment that identifies critical areas for carbon management, supporting decision-makers in implementing effective emission reduction measures.

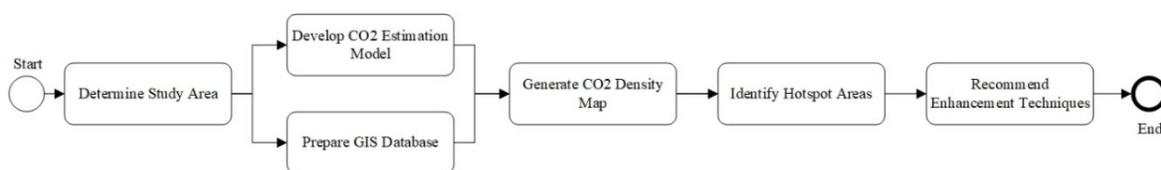


Figure 1: Methodology flowchart

2.1 Determine Study Area

The United Arab Emirates (UAE) has undergone significant urban expansion over the past few decades, leading to a dramatic increase in built-up areas. Like other cities in the UAE, Ajman experienced limited development in the 1960s and early 70s but has since witnessed rapid urban growth, which is expected to continue in the coming years. This urban expansion has resulted in a substantial rise in carbon emissions, mainly from residential building construction and operations. Given its growing population and increasing urban footprint, Ajman presents an ideal case study for evaluating spatio-temporal carbon emissions. In addition, residential buildings make up approximately 79% in 2019 of the total building stock in Ajman, highlighting their dominant role in urban expansion and carbon emissions. As shown in Figure 2, the high proportion of residential structures significantly influences the city's overall energy consumption, CO₂ emissions, and future urban planning strategies. Given this substantial share, the analysis of spatio-temporal CO₂ emissions in residential buildings is crucial for developing sustainable construction and retrofitting policies that align with Ajman's urban growth and environmental goals.

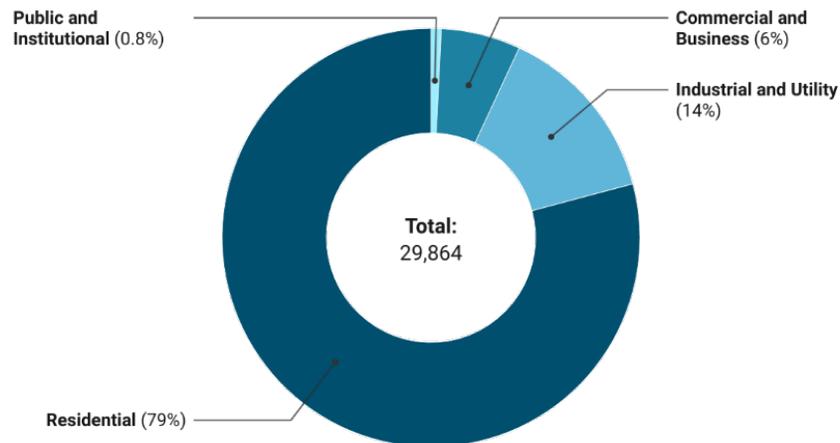


Figure 2: Distribution of building types in Ajman

2.2 Prepare GIS Database

A spatial database of buildings in Ajman was developed as a foundational step in the proposed framework. High-resolution 2019 satellite imagery was used to digitize building footprints within ArcGIS Pro®, resulting in a dataset of over 30,000 buildings across the city. Manual digitization was performed to ensure an accurate representation of the built environment. Each building was assigned key physical attributes, including building type, number of floors, and total floor area (derived by multiplying footprint by floor count). Attribute data was retrieved and validated through 2GIS® open-source data, visual interpretation, and local municipal records. Figure 3 illustrates the spatial distribution of buildings in Ajman, classified into six major sectors: city center, Zorah, northern, mid, southern, and eastern sectors. The dataset serves as a foundation for spatio-temporal CO₂ emissions analysis, enabling a detailed assessment of the environmental impact of urban growth and supporting sustainable urban planning strategies.

In parallel, essential information for life cycle carbon estimation was compiled. For the construction phase, materials and structural systems were identified based on common regional practices, with the predominant system being reinforced concrete frames with masonry infill. Material quantities were estimated per unit area using standard bill of quantities (BoQ) templates, while emission factors were obtained from the OneClick LCA® database, aligned with ISO 14040/44 and EN 15978 standards. For the operational phase, building energy use was estimated based on actual utility data from residential buildings in Ajman, supported by regional consumption benchmarks.

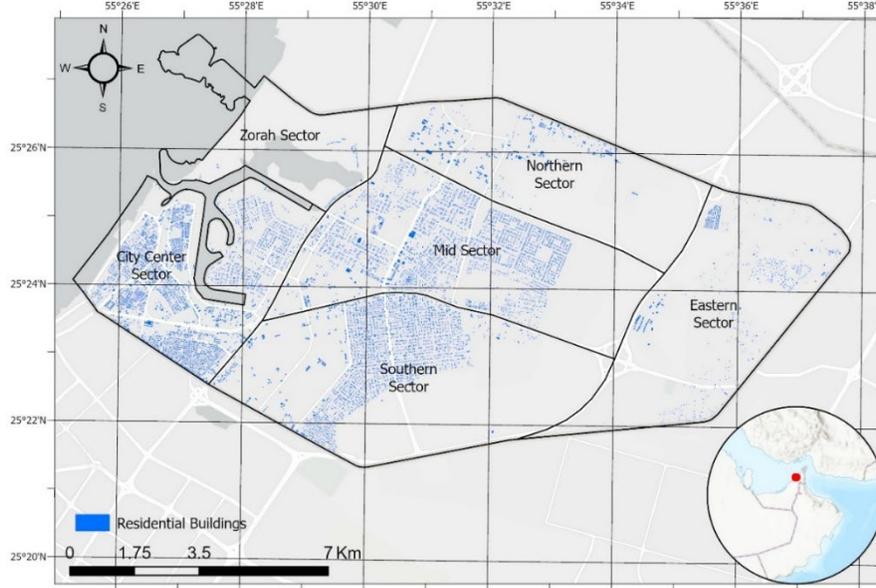


Figure 3: GIS database of buildings in Ajman

2.3 Develop CO₂ Estimation Model

The CO₂ estimation model developed for this framework aims to calculate the carbon intensity factor (IFCO₂) for various residential building types by capturing the full scope of construction and operation emissions using a representative work breakdown structure (WBS) (Azizalrahman & Hasyimi 2019). The model is separated into two main components: building construction (embodied carbon) and building operation (operational carbon). For the construction phase, CO₂ emissions are attributed to raw material extraction and production, material transportation, on-site construction activities, and periodic maintenance. The analysis adheres to the ISO 21931-1 classification and calculates total construction emissions using Eq. 1 (EN ISO 14040, 2006; EN ISO 14044, 2006; D. Li et al., 2016):

$$[1] \sum C_T = C_P + C_C + C_M + C_D$$

Where C_P , C_C , C_M , and C_D represent emissions from material production and transportation, construction, maintenance, and demolition/disposal, respectively. The model applies to the following sub-equations for each component: where Eq. 2 represents material production, Eq. 3 represents construction activities, Eq. 4 represents maintenance, and Eq. 5 represents demolition and disposal.

$$[2] C_P = \frac{(m_i \times f_{m,i}) + \left[\left(\frac{m_i}{T} \right) \times d_i \times f_{t,i} \right]}{A}$$

Here, m_i is the quantity of material i (m², m³, or kg); $f_{m,i}$ is the material's carbon emission factor (kg CO₂/m², kg CO₂/m³ or kg CO₂/kg); T is the transportation capacity (m², m³ or kg); d_i is the transportation distance (km); $f_{t,i}$ is the emission factor for transportation (kg CO₂/km); and A is the building's gross area (m²).

$$[3] C_C = \frac{Q_{c,i} \times U_i \times f_{c,i}}{A}$$

In this equation, $Q_{c,i}$ denotes the quantity of construction activity i (m², m³, or kg); U_i is the fuel or electricity usage rate (1/m³ or kWh/kg); and $f_{c,i}$ is the emission factor for the fuel or electricity consumed (kg CO₂/l or kg CO₂/kwh).

$$[4] C_M = (m_i \times f_{m,i} \times \left(\frac{Y}{R_i} \right))$$

Here, Y is the building lifespan (years), and R_i is the replacement rate for material i (years). The term $\frac{Y}{R_i}$ reflects the frequency of repairs or material replacements.

$$[5] C_D = \frac{(M_d \times f_d) + (Q_d \times f_{d,i}) + \left[\left(\frac{Q_{d,i}}{T} \right) \times d_i \times f_{t,i} \right]}{A}$$

Where M_d is the mass of demolished materials (kg); f_d is the emission factor for landfill operations (kg CO₂/kg), and Q_d represents demolition activities (m², m³ or kg).

On the other hand, the operational phase typically accounts for a significant portion of life cycle emissions driven by electricity, water, gas, and other energy sources needed to operate the building. These emissions are influenced by factors such as comfort levels, climatic conditions, and operating hours. Operational emissions are calculated using Eq. 6 (EN ISO 14044 2006; Li et al. 2016):

$$[6] C_O = (E_i \times f_{e,i} \times Y)$$

Where E_i is the annual energy consumption for type i (kWh, l); $f_{e,i}$ is the emission rate of energy source i (kg CO₂/kWh, kg CO₂/l, etc.), and Y is the building's lifespan (years).

To estimate the IFCO₂ values for each residential building class, a combination of quantitative data and software-based modeling was used. First, physical building characteristics, such as structural system, floor area, material types, and layout, were extracted from GIS records and satellite imagery. Energy consumption data was sourced from actual utility bills and regional consumption benchmarks specific to Ajman. These inputs were fed into the OneClick LCA[®] software, a certified platform for life cycle assessment that follows EN 15978 and ISO 14040/44 standards. Within OneClick[®], a typical residential building model was developed representing average characteristics observed in Ajman, using a reference floor area, typical material assembly (concrete frame with masonry infill), and average construction practices relevant to the region. For the operational carbon, assumptions included an average annual energy consumption of 322 kWh/m², with electricity as the primary energy source and a grid emission factor of 0.42 kg CO₂/kWh. A building lifespan of 50 years was considered for both phases. The analysis revealed that the carbon intensity factor (IFCO₂) for building construction is approximately 890 kg CO₂/m², representing a one-time embodied emission, while the operational-phase IFCO₂ was calculated at 150 kg CO₂/m² per year, accumulating over the building's lifespan. These values are in line with international benchmarks and reflect regional construction practices and energy profiles. It is important to note that while embodied emissions dominate initially, operational emissions often exceed them over time, particularly in climates with high energy demands for cooling. The integration of this LCA output into the GIS platform enabled the spatial mapping of CO₂ emissions, allowing for the identification of hotspots, comparison across districts, and evaluation of retrofitting scenarios based on both environmental and spatial performance. The OneClick[®] was used independently to derive construction and operational IFCO₂ values for representative residential building types. These values were then manually integrated into the GIS platform (ArcGIS Pro[®]) by linking the calculated IFCO₂ with corresponding building records in the spatial database based on building class and attributes. While OneClick and GIS are not directly integrated, this approach allows for effective spatial representation and analysis of lifecycle-based carbon emissions across the study area.

2.4 Generate CO₂ Density Map

Upon developing the GIS database and incorporating building attributes, the total CO₂ emissions for each building in the study area can be computed and analyzed across two distinct categories: embodied carbon emissions and operational carbon emissions. In this study, embodied carbon refers specifically to the emissions generated during the construction phase of buildings, which includes emissions from material production, transportation, construction activities, and associated processes. These are one-time emissions that occur upfront during the building's development. In contrast, operational carbon refers to the ongoing emissions produced during the use of the building, primarily from energy consumption for heating, ventilation, air conditioning (HVAC), lighting, and appliances. To calculate emissions for both categories,

the carbon intensity factor (IFCO₂) for each building is multiplied by its floor area and number of floors, a process automated within the GIS platform (ArcGIS Pro®). To visualize the spatial distribution of emissions, the kernel density function is applied to rasterize the total CO₂ emissions, generating a CO₂ density map of the study area. This function fits a curved surface over each building, with the highest values centered around areas with high cumulative CO₂ emissions, helping to identify emission hotspots within a specified radius. The analysis yields two keymaps: one illustrating the embodied carbon emissions associated with building construction (Figure 4) and another showing the operational carbon emissions resulting from building use (Figure 5). While this study focuses on the year 2019, if temporal data is available, construction-phase maps can be generated for multiple years to enable a spatio-temporal analysis of CO₂ emission trends over time, providing valuable insights for long-term urban sustainability planning.

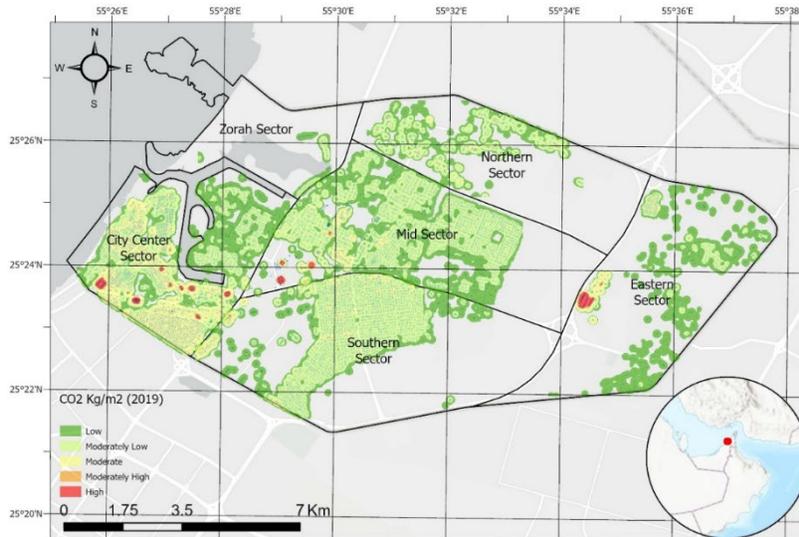


Figure 4: Total CO₂ emission for the building construction (2019)

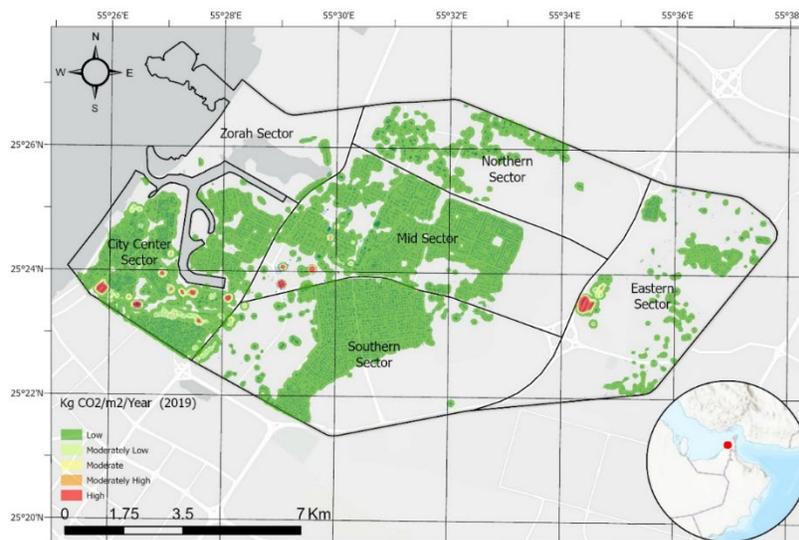


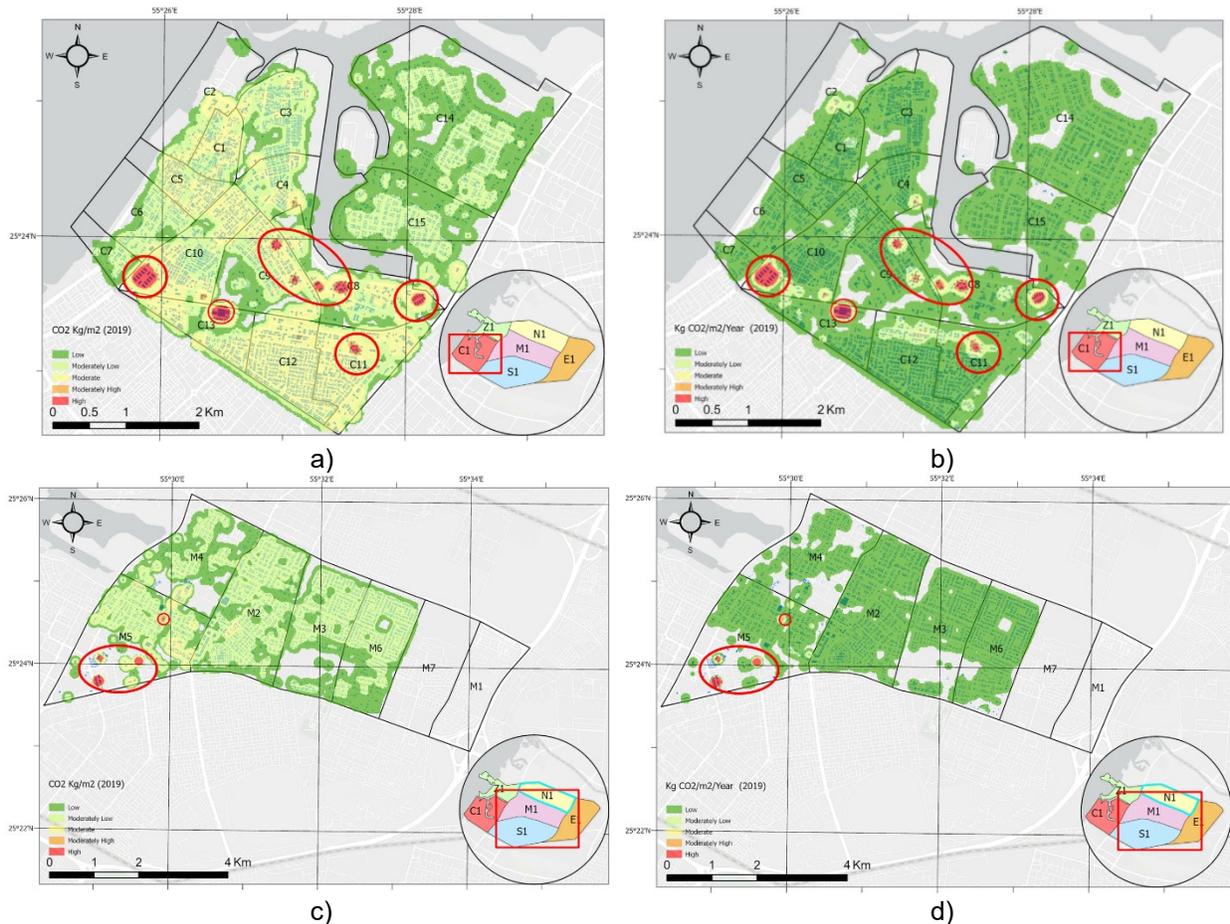
Figure 5: Total CO₂ emission of building operation (2019)

2.5 Identify Hotspot Areas

The analysis of carbon emissions density in Ajman has identified hotspot areas with high cumulative CO₂ emissions, as illustrated in Figure 6. These areas are primarily marked in red, indicating moderately high to high CO₂ emissions levels in both the building construction and building operation phases. The highest

emission intensities are concentrated in sectors with dense urbanization, such as the city center sector, mid sector, and parts of the eastern sector. These regions reflect significant embodied carbon emissions due to a combination of large building footprints, multi-story developments, and extensive material use. In the city center sector, multiple hotspots are concentrated in districts C8, C9, C10, C11, and C13, driven by dense multi-story developments and the high resource consumption associated with construction activities. Similarly, during the operational phase, these districts experience elevated emissions due to significant energy demands for HVAC, lighting, and other services, likely influenced by older, less energy-efficient structures. In the mid sector, district M5 exhibits localized hotspots for both construction and operation emissions, possibly linked to large-scale construction projects and mixed-use facilities with high ongoing energy consumption. The eastern sector shows a construction-phase hotspot in district E1, likely attributed to significant development or industrial projects requiring substantial construction resources. This district also demonstrates a high operational CO₂ emissions hotspot, reflecting continuous energy demands from residential or industrial complexes.

While it is true that areas with higher population or building density tend to exhibit higher carbon emissions, the goal of identifying emission hotspots in this study is not solely based on absolute emission values but on their spatial intensity (emissions per area) and opportunity for impact through intervention. Many of the high-emission zones correspond to residential districts with dense building clusters, which also means they house a significant portion of the population. Retrofitting strategies in these areas, therefore, offer both environmental and social benefits, as they can reduce emissions while also improving living conditions (e.g., through better insulation, energy savings, and indoor comfort) for a large number of residents. Although the study did not explicitly calculate the population per building, the concentration of multi-story and high-occupancy buildings in these zones implies a higher potential impact per retrofitting effort. Future studies may further refine prioritization by combining spatial emission density with population exposure, enabling more equity-focused planning for carbon reduction strategies.



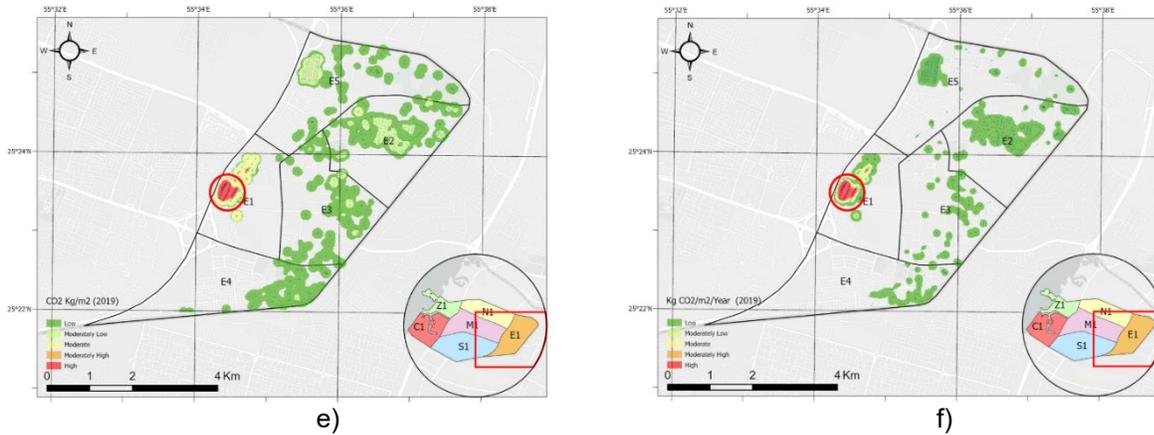


Figure 6: Hotspot areas across Ajman districts: a) building construction CO₂ for city center area, b) building operation CO₂ for city center area, c) building construction CO₂ for mid area, d) building operation CO₂ for mid area, e) building construction CO₂ for east area, f) building operation CO₂ for east area

2.6 Recommend Enhancement Techniques

A deep analysis of the identified CO₂ emission hotspots in Ajman city has revealed that material production and transportation are key contributors to building construction CO₂ emissions, mainly due to the extensive use of concrete, steel, and other high-carbon materials. Additionally, the cooling systems generate a significant part of the CO₂ emissions. The cooling systems consume around 73% of the total consumption (around 322 kWh/m²). This can be justified by the fact that cooling systems in the UAE are generally in demand throughout the entire year. Consequently, both the construction and operational phases require targeted enhancement techniques to mitigate emissions in residential buildings. For the construction phase, adopting low-carbon materials such as recycled aggregates, engineered timber, and high-performance insulation can significantly reduce embodied carbon emissions. Utilizing prefabricated components can optimize material use, improve on-site efficiency, and reduce construction waste. Additionally, local material sources help to minimize emissions from transportation. Implementing construction process optimization technologies, such as carbon capture systems and energy-efficient construction equipment, can further reduce CO₂ emissions. Applying advanced project management practices that integrate life cycle carbon monitoring ensures that sustainable practices are maintained throughout the construction process. For the operation phase, addressing cooling system inefficiencies is essential. Upgrading to energy-efficient HVAC systems and implementing innovative climate control technologies can reduce cooling-related emissions. Retrofitting measures such as improved thermal insulation, double-glazed windows, and solar shading can lower cooling demands by minimizing heat transfer by 14%. Furthermore, integrating renewable energy systems, such as solar photovoltaic (PV) panels and geothermal cooling, can offset energy use from non-renewable sources. Passive cooling design strategies, including green roofs, natural ventilation, and optimized building orientation, can further enhance energy efficiency. Additional measures include energy-efficient lighting and appliances, intelligent energy management systems, and demand-response technology to optimize overall building energy consumption. Enhancing water efficiency through the use of low-flow fixtures and gray water recycling also reduces operational emissions associated with water heating and pumping.

In addition to reducing CO₂ emissions, cost efficiency is a critical factor in determining the most appropriate retrofitting scenarios for each building type. To support effective decision-making, a cost-benefit analysis was conducted for various retrofitting strategies. The analysis considers a discount rate of 10% and the expected lifespan of each retrofitting system. It accounts for initial investment, operation and maintenance costs, and annual benefits, which include both energy savings and the monetary value of reduced CO₂ emissions. For the latter, the social cost of carbon is estimated at \$220 per ton of CO₂, based on the economic impact values proposed by Moore & Diaz (2015). Table 1 presents an illustrative example of the annual cost-benefit analysis for different retrofitting scenarios applied. Among all options, the HVAC scenario demonstrated the highest annual savings of 9,687 USD, alongside an estimated reduction of 27 tons of CO₂ emissions per year, equating to a carbon-related cost saving of approximately 6,007 USD.

Table 1: Cost-benefit analysis of the retrofitting scenarios (sample)

Category	Existent system	Suggested scenario	Saving in CO ₂ Emissions (Ton)	Saving in Environmental Cost (USD)	Savings on Electricity (KWh)	Saving in Electricity Cost (USD)	Total Saving (USD)
HVAC	CAV (constant air volume), Air cooled Chiller (COP=3.40)	The new system (roof mounted package air conditioning system) (COP = 4.0)	27.134	6,007	44,775	3,680	9,687
Wall Cladding	90 mm aerated concrete block with 20 mm cement paster (U = 0.944 W/m ² K)	Insulated wall (80 mm XPS extruded polystyrene) (U = 0.293 W/m ² K)	22.321	4,941	36,832	3,027	7,969
Windows & Shading	Double-glazed 13 mm Argon Fill (U = 2.511 W/m ² -K)	Add proper shading elements (vertical or horizontal) according to building orientation	18.785	4,159	30,998	2,548	6,707

3. SENSITIVITY AND UNCERTAINTY ANALYSIS

As with any modeling-based study, the estimation of carbon emissions involves inherent uncertainties and assumptions, which can influence the results. This section presents a sensitivity analysis to evaluate how variations in key input parameters affect the model's output, specifically total CO₂ emissions from residential buildings. Key sources of uncertainty include the IFCO₂ for materials and energy sources, HVAC system performance, energy consumption estimates, and the building lifespan assumed for operational emissions. These factors were selected based on their influence on both construction- and operation-phase emissions within the proposed framework. A sensitivity analysis was conducted by varying each parameter within a reasonable range and observing the resulting change in total CO₂ emissions. Table 2 summarizes the baseline values, the tested variation range, and the estimated impact on total CO₂ emissions. The results indicate that annual energy consumption and HVAC efficiency are the most influential parameters affecting operational emissions, while concrete emission factors and electricity grid intensity moderately impact the construction and operation phases. Changes in the assumed building lifespan have a relatively lower effect on overall emissions but are still relevant in long-term planning scenarios. This analysis demonstrates the importance of using locally accurate input data and supports the need for context-sensitive modeling when applying the framework in different regions. In future work, a more detailed probabilistic or Monte Carlo-based uncertainty analysis could provide a broader range of confidence for emission estimates.

Table 2: Sensitivity analysis of key model parameters and their relative influence on total CO₂ emissions

Parameter	Baseline Value	Test Range	Impact on Total CO ₂ Emissions (%)
Emission factor – concrete	240 kg CO ₂ /m ³	±10%	±5.2%
HVAC system efficiency	3.0 COP	±15%	±11.4%
Electricity emission factor	0.42 kg CO ₂ /kWh	0.36 – 0.48	±8.6%
Annual energy consumption	322 kWh/m ²	±20%	±13.7%
Building lifespan (operation)	50 years	30 – 70 years	±3.9%

4. CONCLUSION

This research highlights the critical role of spatio-temporal life cycle analysis in enhancing carbon emission management for residential building construction. Through the development of a comprehensive GIS-based framework integrated with LCA, the study provides valuable insights into the distribution and intensity of CO₂ emissions across different urban sectors in Ajman, UAE. The findings emphasize that both the construction and operation phases significantly contribute to carbon emissions, with construction-phase emissions driven by material production and transportation and operational emissions dominated by cooling systems, which account for around 73% of total energy consumption. The research identified CO₂ emission hotspots in key districts through spatial analysis, revealing that emissions are concentrated in areas with

high-density developments and multi-story structures. These results underscore the importance of implementing targeted carbon mitigation strategies, including the use of low-carbon materials, energy-efficient construction techniques, and renewable energy integration. Retrofitting measures such as upgraded HVAC systems, thermal insulation, and solar shading were shown to reduce operational emissions significantly, thereby improving sustainability. By combining spatial and temporal data with carbon emission modeling, the framework enables data-driven decision-making for sustainable urban planning. It supports policymakers and planners in identifying priority areas for emission reduction and retrofitting interventions. Ultimately, this study demonstrates that spatio-temporal carbon management is crucial for reducing the environmental footprint of urban residential development, aligning with global sustainability objectives while meeting local needs for urban expansion and infrastructure growth.

4.1 Limitations and Future Recommendations

While this study presents a robust framework for spatio-temporal carbon emission analysis in residential building construction, several limitations should be acknowledged. Currently, the framework is applied exclusively to residential buildings, which offers focused insight but leaves room for expansion to other building types, such as commercial, industrial, and institutional structures. Incorporating these would enhance the applicability of the framework across broader urban sectors. Additionally, the analysis is based on a single reference year (2019), providing a detailed snapshot in time; however, extending the study across multiple years would enable a deeper understanding of temporal emission trends linked to urban growth. Furthermore, while this research concentrates on environmental performance, integrating cost evaluation in future studies would allow for a more holistic approach, balancing sustainability with economic feasibility. Future research can build on this study by enhancing the framework in three key areas. First, the inclusion of a wider variety of building types will allow for a more comprehensive assessment of carbon emissions across different building classes and land uses. This expansion will provide a clearer understanding of sector-specific challenges and opportunities for carbon mitigation. Second, future studies should incorporate life cycle cost analysis, allowing policymakers to evaluate both the environmental and economic feasibility of proposed mitigation strategies, including retrofitting and material selection. Finally, analyzing multiple timeframes will help identify long-term carbon emission trends and assess how changes in urban growth patterns and building practices influence emissions over time. These enhancements will further strengthen the framework's utility in supporting sustainable urban planning and policy development.

4.2 Scalability and Broader Applicability

Although this framework was applied specifically to Ajman, UAE, its structure is designed to be scalable and adaptable to a variety of geographic contexts. The integration of GIS-based spatial data with life cycle assessment methods allows for flexibility in data input, making the framework applicable to urban areas with varying building types, climates, and development patterns. By adjusting key parameters, such as emission intensity factors, energy consumption profiles, and building classifications, the methodology can be adapted to other regions with different urban dynamics. For example, in regions with colder climates, heating-related emissions may replace cooling as the dominant operational factor. Similarly, cities with extensive vertical development or industrial presence may require modified classifications for hotspot identification. Even if full implementation is not immediately possible, the framework provides a foundational structure for cities to begin integrating spatial emissions analysis into planning processes, with the potential for gradual expansion as local data becomes available. This flexibility makes the framework a valuable starting point for broader application in diverse urban environments seeking to manage and reduce building-related carbon emissions.

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