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Statistical Analysis of Operational Carbon for Different Building Types in the UAE

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ABSTRACT

The building sector contributes significantly to the greenhouse effect, generating significant carbon dioxide (CO_2) emissions throughout the life cycle of buildings. Traditional methods for assessing emissions, such as software evaluation and site inspection, are time-consuming and do not adequately account for variability and uncertainty in emission data. This research aims to investigate and analyze the statistical characteristics of the operational carbon produced from different types of buildings in the context of the United Arab Emirates (UAE). The investigation focused on residential, commercial and educational buildings and their heating, ventilation, air conditioning (HVAC) systems, walls and window systems. All scenarios were statistically evaluated through linear-regression analysis, correlation analysis, Probability Mass Functions (PMFs) and Cumulative Distribution Functions (CDFs). The results of linear-regression analysis revealed an average accuracy (R^2) of 0.958. The results of correlation analysis indicated that upgrading the HVAC system in residential and commercial buildings reduced the operational carbon, while in educational buildings, upgrading the window systems reduced the operational carbon. Finally, the PMF and CDF analyses indicated that upgrading the HVAC system in residential and commercial buildings was the optimal option, which reduced the carbon percentage by 28.56% and 28.48%, respectively. However, upgrading the window system was the optimal option for educational buildings, reducing the carbon percentage by 75.80%.

Keywords: Operational carbon, Linear regression, Correlation analysis, Probability mass functions, Cumulative distribution functions.

INTRODUCTION

Global-climate change is significantly impacted by greenhouse gas emissions from human activities, notably those associated with the building sector (Prato, 2008; Rabiei et al., 2022). This sector, recognized as a primary consumer of natural resources and energy, is responsible for a substantial portion of air pollution and carbon dioxide (CO_2) emissions (Javadinejad et al., 2019; You et al., 2011). The importance of life-cycle assessment for evaluating the environmental footprint of buildings has been increasingly recognized (Asdrubali et al., 2013; Cho and Chae, 2016; Nayana and Kavitha, 2017; Zhang and Wang, 2016). Building life cycles encompass embodied carbon emissions from material manufacturing, transportation and construction (Kang et al., 2015). Meanwhile, operational-carbon emissions from building uses include heating, ventilation, air conditioning (HVAC), lighting and other electricity-dependent activities. Previous research has shown that operational carbon represents the highest percentage in the life cycle of buildings. Consequently, the operational carbon needs to be reduced using different technology and policy aspects, such as improving the HVAC performance, upgrading the building-envelope system and adopting new building designs.

Several studies have investigated environmental impacts and mitigation strategies for buildings (Chau et al., 2015). Gan et al. (2017) analyzed high-rise buildings' carbon emissions, considering the life-cycle phases from material selection to construction, while Xu et al. (2014) established a model to decompose CO_2 emissions into five factors and identified CO_2 emission sources from various sectors and regions. Moreover, Su et al. (2014) developed a systematic method to estimate the city-level emissions of CO_2 in China. They found that the major cities in southwestern China are characterized by small CO_2 emissions. Acquaye et al. (2011) stated that understanding embodied carbon's statistical characteristics could help create an effective policy and promote environmental decision-making during the design process by providing architects and contractors with detailed details. A probabilistic analysis must be used to meaningfully evaluate the embodied carbon, where uncertainties and variables are inherent and the study of statistical characteristics needs to take precedence to preserve value for the simulated input variables (Acquaye et al., 2011). Kang et al. (2015) detailed the statistical characteristics of carbon emissions from building materials. The research focused on analyzing reinforced-concrete buildings and nine representative building materials. The statistical characteristics of carbon emission were defined by descriptive statistical analysis, correlation analysis and a goodness-of-fit test. Additionally, the results demonstrate the necessity and reasonability of the probabilistic carbon-emission estimation approach by providing statistical details on the carbon-emission data and variations between the deterministic and probability values.

Research Gap and Objectives

Previous studies have highlighted the importance of life-cycle assessment in evaluating the environmental impact of buildings. However, most research has focused on embodied carbon, with less attention given to operational carbon, despite its significant impact on the life-cycle carbon of buildings. Operational-carbon reduction strategies, including enhancements in HVAC performance, building envelope upgrades and innovative building designs, have been explored to a limited extent. However, these strategies often lack a comprehensive analysis of the statistical characteristics of operational-carbon emissions across different building types, structural systems and construction materials.

In the United Arab Emirates (UAE), the building sector is the third largest contributor to carbon emissions, accounting for approximately 28% of the annual emissions. It is also the largest energy consumer, using about 48% of the total energy (Radhi, 2009). This concern is heightened by projections indicating a potential 25% increase in building CO_2 emissions by 2050, driven by the UAE's rapid urbanization (Brockerhoff, 2016). Despite current efforts to mitigate carbon emissions throughout the life cycle of buildings, there remains a substantial gap in understanding and effectively reducing operational carbon, which accounts for a significant portion of a building's life-cycle emissions.

Therefore, this research aims to identify and analyze the statistical characteristics of the operational carbon produced from different types of buildings in the context of the UAE. The developed approach was based on a statistical analysis of the different suggested scenarios using actual data. The proposed approach was broadly applicable to similar building types. Moreover, statistical analysis was performed for the most common building types in the UAE (villa, building and education) and three alternative retrofit scenarios (HVAC, walls and windows). The main statistical analyses considered are: linear regression, correlation, probability mass functions (PMFs) and cumulative distribution functions (CDFs).

METHODS AND TECHNIQUES

This research followed a systematic methodology to analyze the statistical characteristics of the operational carbon of buildings in the UAE. The methodology included several steps, as illustrated in Figure 1.

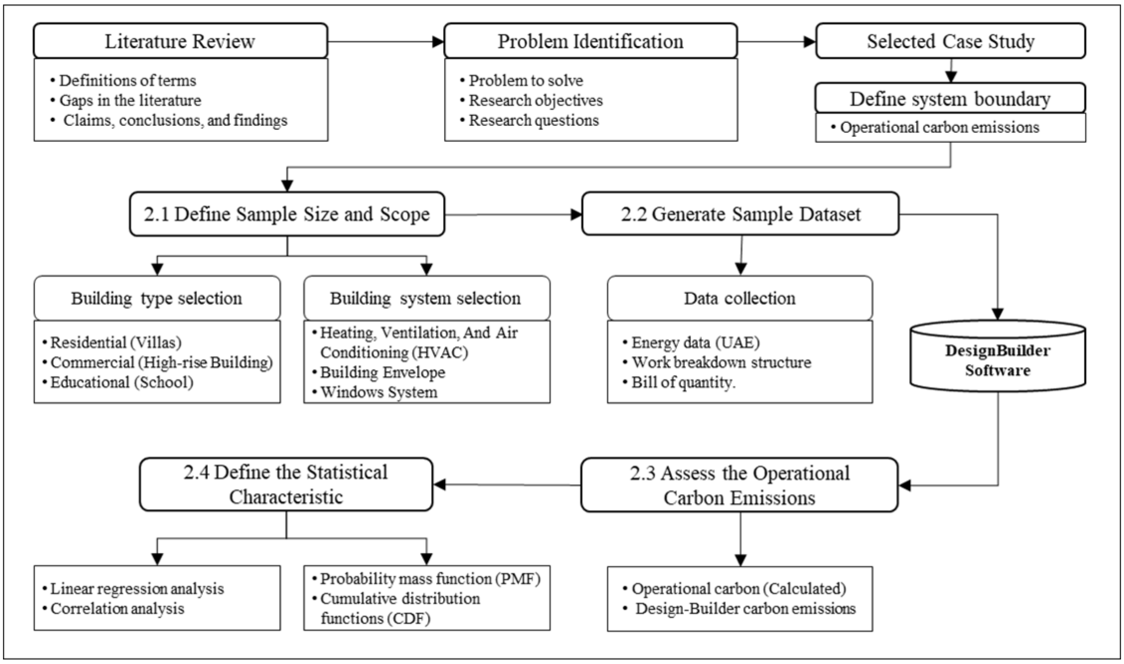


Figure (1): Research methodology framework

A comprehensive literature review was conducted to establish a foundation for this research. This included identifying definitions of key terms, recognizing gaps in the existing literature and obtaining significant claims, conclusions and findings relevant to operational-carbon emissions in building construction. After the literature review, the research problem was identified and the specific gaps to be addressed were outlined. Moreover, objectives and questions were established to guide the research. Case studies were employed, selecting a representative sample of building types within the UAE to assess operational-carbon emissions. In addition, the system boundary was defined to focus exclusively on operational-carbon emissions, excluding other life-cycle phases.

The sample size and scope were determined by selecting various buildings, including residential villas, commercial high-rise buildings and educational institutions. Simultaneously, key building systems for retrofitting, including HVAC systems, building envelope and window systems, were selected for analysis. A database of 36 distinct samples reflective of these selections was compiled to facilitate the analysis. A dataset was generated through data collection, which included gathering energy data specific to the UAE, work breakdown structure (WBS) and bill of quantities (BOQ) from construction projects. The collected data was input into DesignBuilder software, an advanced tool to simulate building-energy use and calculate operational-carbon emissions. In addition, manual calculations were used to estimate operational-carbon emissions.

A linear-regression analysis was used to investigate the relationship between actual and DesignBuilder estimated carbon emissions, assessing operational-carbon accuracy over three years (2017-2019) of each building type's 36 monthly energy-consumption samples. This method evaluates the correlation between actual and DesignBuilder carbon, allowing for an analysis of operational carbon across different building types and systems. The correlation analysis assessed the correlation with operational carbon between all selected building types and the building system. Finally, both PMF and CDF analyses were used to understand the emission-data distribution and predict the potential energy savings that different systems could achieve.

Sample Size and Scope

Building-type Selection

The classification of building types in the UAE reflects the diverse functional requirements and energy-usage patterns inherent in each category. As demonstrated in Figure 2, buildings are categorized into six distinct types: residential, commercial, educational, governmental, entertainment and health buildings. These classifications are instrumental in understanding and predicting operational-carbon emissions, as each type of building has unique design specifications, occupancy patterns and functional needs that significantly influence their material composition and energy-consumption profiles. For instance, residential buildings are designed with comfort and domestic utility in mind, potentially prioritizing energy-intensive HVAC systems. Commercial structures may emphasize energy-management systems to handle extensive electronic equipment and lighting requirements. Educational buildings often accommodate fluctuating occupancy and require versatile energy solutions for various activities. Governmental buildings may enforce strict energy-efficiency standards, while entertainment and health facilities could have irregular-usage patterns with high peak demands. In operational-carbon estimation, the variance in construction materials and energy demands across these building types underscores the importance of type-specific analysis. Such differentiation ensures that strategies for reducing carbon footprints are appropriately tailored to each building category's unique characteristics and needs.

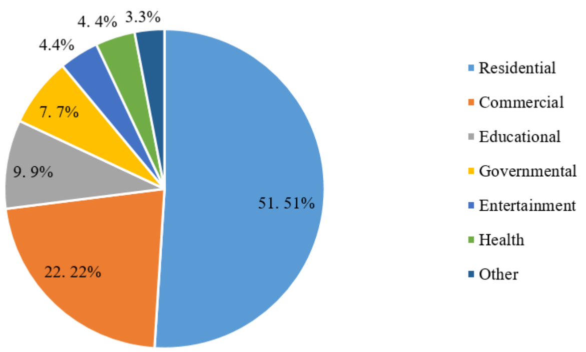


Figure (2): Distribution according to building type in the UAE (2019)

In this study, a targeted selection **of** building types, including residential (villas), commercial (high-rise buildings) and educational (schools), was made to capture a representative scope of the built environment in the UAE. Details on the specifics of these building types are illustrated and delineated in Table 1. The rationale behind focusing on these three categories is twofold. Firstly, it facilitates an in-depth exploration of each building type as a discrete entity, allowing for a nuanced understanding of their operational carbon footprints. Each type presents a different set of variables regarding design, use, occupancy and energy consumption, thereby necessitating a distinct approach to analyze their carbon emissions. Secondly, by examining these diverse building categories, the research can apply a comparative analysis to discern patterns and variances in energy usage and carbon emissions across building types.

Building-system Selection

Previous studies that evaluated operational energy or carbon constrained their analysis to overall building-energy consumption without factoring in the distinct impacts of various building systems. This research broadens the scope by investigating the effects of specific building systems on operational-carbon emissions. The study identifies three primary systems based on their significant influence on operational carbon: the HVAC system, the building envelope and the window system. These systems were chosen due to their substantial roles in energy consumption and their potential for carbon-emission reduction through design and technology interventions. An in-depth analysis was conducted on the current configurations of these systems within the buildings and on proposed retrofit scenarios aimed at reducing operational carbon. The existing systems provide a baseline for comparison, while the proposed scenarios offer insight into the potential benefits of retrofitting and upgrading building systems. Table 2 presents a detailed comparison, delineating the specifications of the existing systems alongside the proposed modifications for each building type under consideration. This side-by-side layout allows for a clear visualization of the potential improvements. It serves as a reference for the projected impact that these changes may have on reducing the operational-carbon footprint of the buildings.

Generating Sample Dataset

Energy Consumption According to Building Type

This research compiled a comprehensive dataset from the energy-consumption records of various types of buildings within the UAE, ensuring a wide-ranging sample that reflects the diverse building stock. The dataset was carefully chosen to include buildings with similar functions and features, enabling a reliable comparison. Energy consumptions were normalized to a common unit of watt-hours per square meter to standardize the comparison across buildings of differing sizes and functionalities. Figure 3 shows the average monthly energy consumption for the selected building types in 2019 (Appendix A and Appendix B show the average monthly energy consumption for 2016 and 2017). It directly compares energy-use intensity across various building sizes and types. In addition, both WBS and BOQ were used to derive construction-related data, significantly enhancing the analysis by integrating specific construction details into evaluating energy-consumption patterns.

Table 1. Overview of three common types of buildings in the UAE (sample)

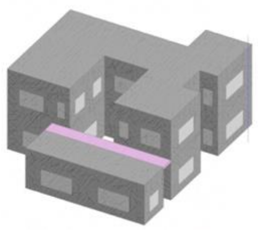
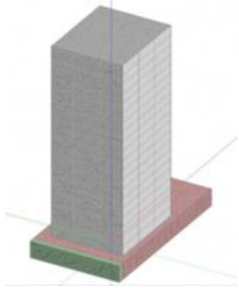
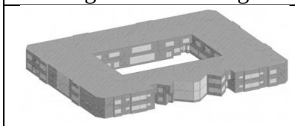
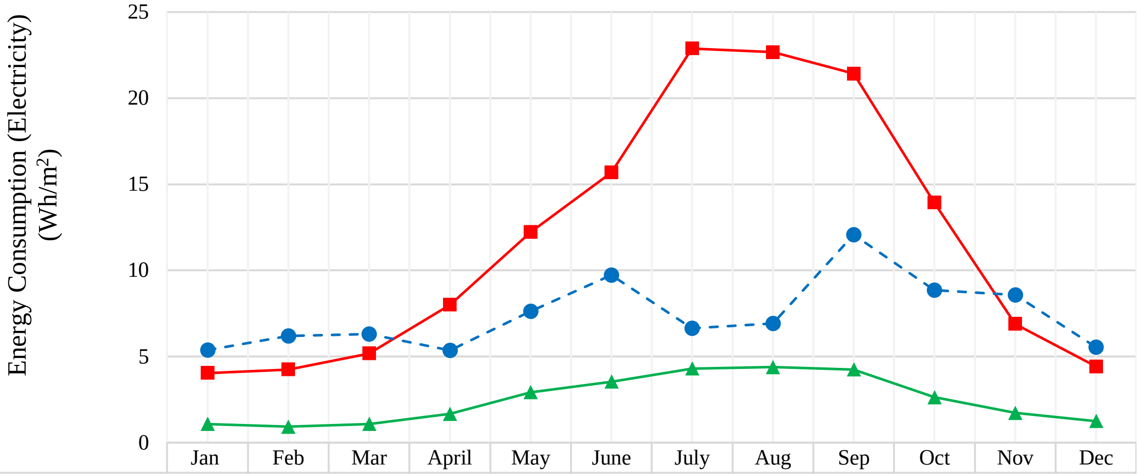
Type	Description	# Floors	Total Height (m)	Floor Area (m^2)	Total Area (m^2)
 Villa	• Brick-Concrete Block • Double Glass Aluminum Windows • Plaster Coat-Inside and Outside	2	6	225	450
 High-Rise Building	• Reinforced Cement Concrete Structure • Double Glazed Windows • Plaster Coat -Inside and Outside	15	33	1,090	11,970
 School	• Reinforced Concrete Structure • Aluminum-Polyester Powder Coated • Double Glazed Windows • Plaster Coat-Inside and Outside	2	11.2	5,238	15,664

Table 2. Description of proposed retrofit scenarios for building systems

Type \ System		HVAC	Building Envelope	Window System
Residential (Villas)	Existing System	CAV (constant air volume), Air-cooled Chiller (COP=3.40)	200 mm concrete block with 20 mm cement paster (U= 0.950 W/m^2 K)	Double-glazed (air)
	Proposed System	Change to new chiller (more efficient) to VAV (COP = 3.7)	Insulated wall (40 mm XPS Extruded Polystyrene) with light color exterior	Triple-glazed (Argon)
Commercial (High-rise Building)	Existing System	CAV (constant air volume), Air-cooled Chiller (COP=3.40)	90 mm aerated concrete block with 20 mm cement paster (U= 0.944 W/m^2 K)	Double-glazed 13 mm Argon Fill (U= 2.511 W/m^2-K)
	Proposed System	Change to new chiller (more efficient) to VAV (COP = 3.66)	Insulated wall (40 mm XPS Extruded Polystyrene) with light color exterior (U= 0.480 W/m^2 K)	Double-glazed tint windows 10 mm Air (U= 1.760 W/m^2-K)

Educational (School)	Existing System	Single-layer louver diffuser and returner-CFM (143,646) Rooftop HVAC Packaged Units (RTU)	Dark color (brown) exterior wall- with insulation (U = 0.400)	Single-glazed (U= 3 W/m^2 K) low reflectance
	Proposed System	Change to new chiller (more efficient) with different capacity and add single line diffuser & returner-CFM (179,557)	Aluminum composite panels sold (Alupex) 4 mm (U = 0.514)	Clear tint window film (U= 2.4 W/m^2 K) higher reflectance



	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Residential	4.04	4.24	5.18	8.00	12.22	15.69	22.89	22.67	21.42	13.93	6.89	4.42
Commercial	1.08	0.92	1.09	1.67	2.93	3.54	4.30	4.39	4.25	2.63	1.72	1.25
Educational	5.37	6.20	6.30	5.35	7.63	9.72	6.64	6.93	12.07	8.85	8.58	5.54

Figure (3): Average monthly energy consumption for the selected building types (2019)

The dataset was then used to automate a comprehensive model using DesignBuilder software. The input data included construction details from the WBS and the BOQ (materials, structural systems, energy system), building activity and building geometry. DesignBuilder software served as a tool for simulating the energy consumption for each type of building based on its specific inputs and architectural specifications. The simulated data generated was then meticulously compared with the actual energy-consumption data to verify the software's predictive accuracy (Figure 4). The average accuracy of the models was 91.78%, 97.96% and 89.70% for residential buildings, commercial buildings and educational buildings, respectively. After verifying the results, the comprehensive model can generate an energy analysis for any type. The software outputs included the annual energy consumption (electricity), indoor environment, life-cycle cost (construction and operational) and operational and construction embodied carbon.

Energy Consumption According to the Building System

Following the verification of the DesignBuilder simulations, the models were employed to simulate the energy consumption of various retrofitting scenarios applied to the selected building systems, including HVAC, wall cladding and windows. The models' input data was adjusted to reflect the specifics of each system individually, enabling an assessment of the impact of changes on energy consumption. This approach allowed for a detailed evaluation of how retrofitting different components of the building's envelope and systems influences overall energy consumption. The research will analyze the energy reduction and efficiency gains attributable to each retrofit scenario by substituting the original inputs with data relating to the upgraded systems. Moreover, this assessment provided insights into the potential benefits of targeted retrofitting measures on the energy performance of buildings, highlighting the importance of strategic upgrades in achieving energy-efficiency and -sustainability goals.

Figure 5 shows the total energy consumption for the retrofitting scenarios applied to the selected building systems over the study period (2017-2019).

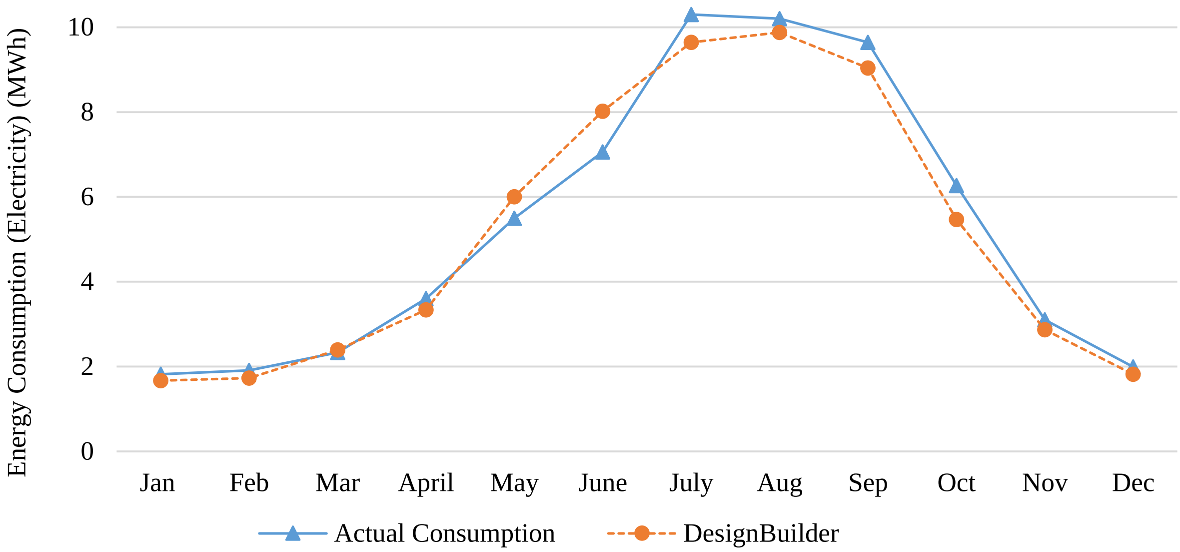


Figure (4): Sample of model verifying of residential buildings (2019)

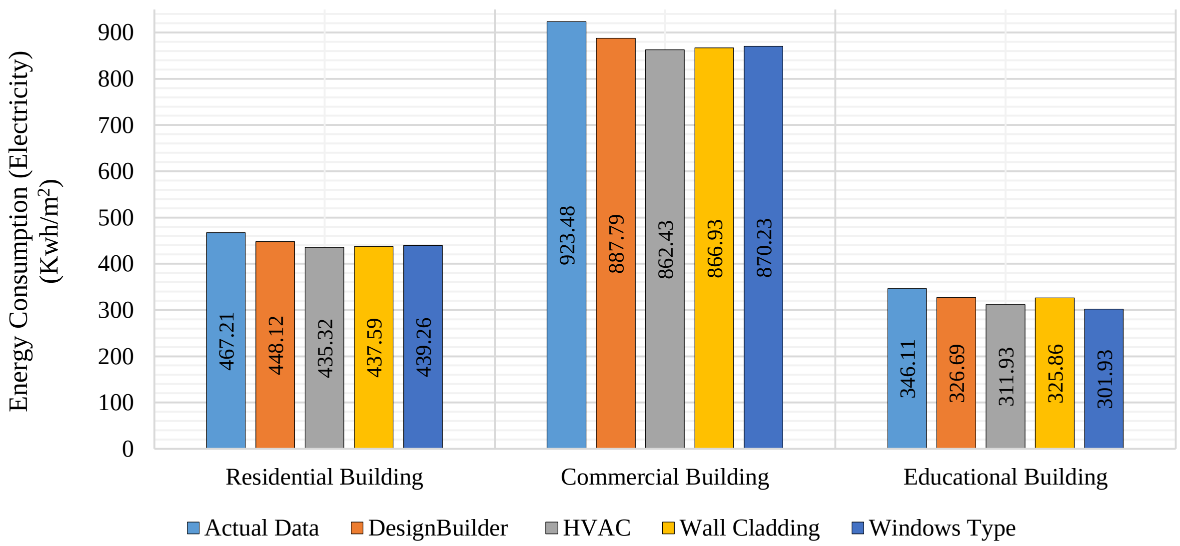


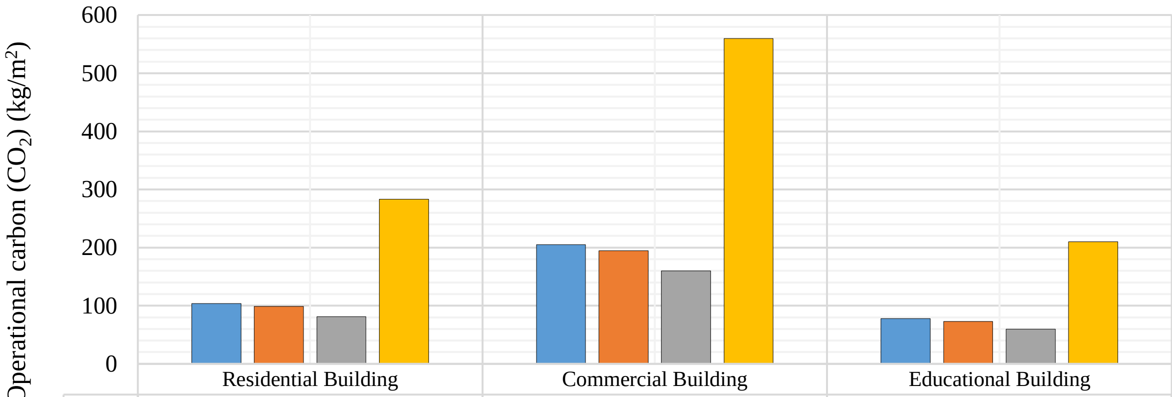
Figure (5): Total energy consumption for the selected building systems

Assessing the Operational-carbon Emissions Calculated Embodied Carbon

The operational carbon is CO_2 emission due to the energy used in a building by residents to maintain a comfortable level through using different equipment and systems during their lifetime. The operational phase accounts for the major amount of CO_2 emission from buildings during their life cycles. Operational carbon varies significantly due to the different levels of comfort required, climatic conditions and the number of operating hours. Typically, the sources of energy that contribute to the operational carbon are electricity, natural gas, fuel oil, propane and wood. Operational carbon due to the use of the building either annually or through the whole building life cycle can be expressed as:

$$C_o = \left(E_i \times f_{e,i} \times Y\right) \quad (1)$$

where $C_{O.}$ is the CO_2 emissions of one material at the operation phase (kg CO_2); E_i is the annual consumption of energy type i (kWh, l); $f_{e,i}$ is the carbon-emission unit rate of energy type i (kg CO_2/kWh, kg CO_2/l, … etc.); Y is the life span of the building (years). In addition, actual energy consumption from energy bills was used to calculate the operational carbon. These values are typically expressed in kilograms of CO_2 per unit of material (e.g. per kilogram, per square meter) or per unit of activity (e.g. per kilometer for transportation). Figure 6 illustrates the average calculated operational carbon of the actual scenario over the study period. The commercial buildings primarily contribute to operational-carbon emissions, totaling 559.63 kg CO_2/m^2.



	Residential Building	Commercial Building	Educational Building
2017	103.47	205.22	77.58
2018	98.50	194.74	72.67
2019	81.15	159.66	59.49
Total	283.13	559.63	209.74

2017 2018 2019 Total

Figure (6): Calculated operational-carbon emissions

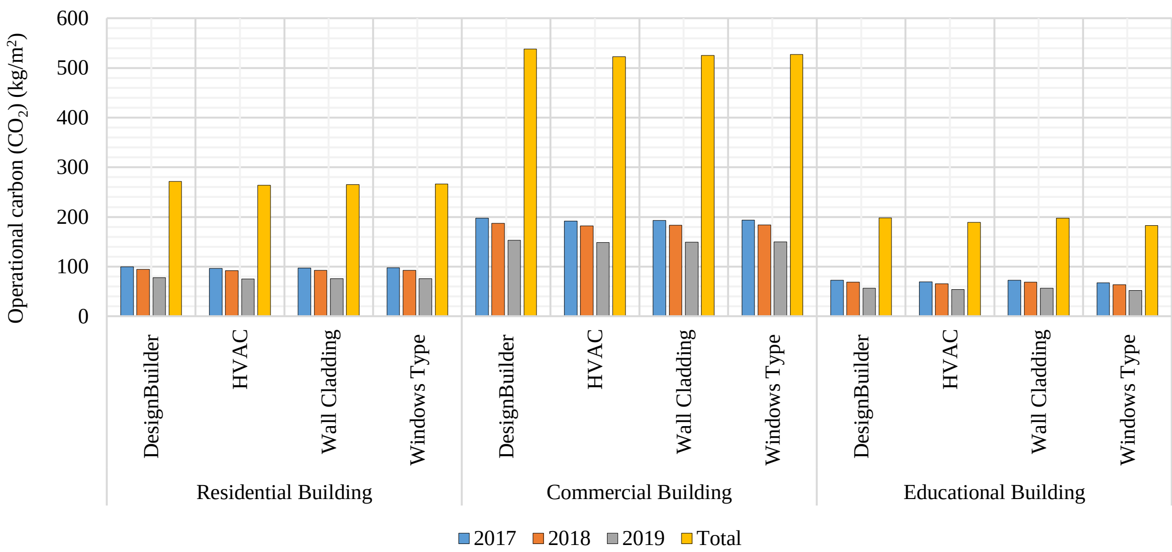


Figure (7): Operational-carbon emissions extracted from DesignBuilder

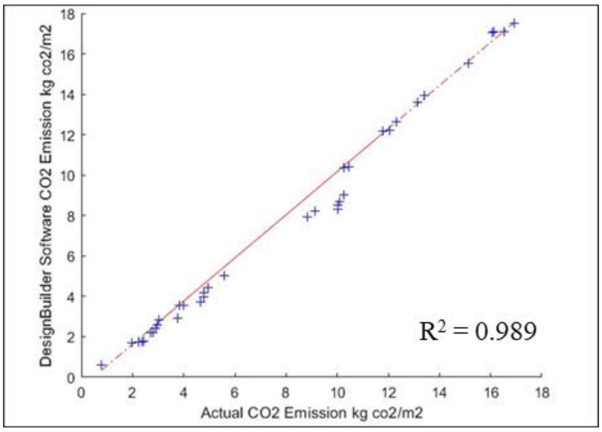
DesignBuilder Embodied Carbon

DesignBuilder offers capabilities for assessing carbon and its functions for evaluating operational energy and embodied carbon (Baek et al., 2013; Rodrigues and Freire, 2014). By integrating carbon-emission analysis, DesignBuilder allows architects, engineers and construction professionals to make informed decisions that can significantly reduce a building's total-carbon emissions. The software uses databases of materials and construction processes to estimate the operational carbon of different building components, such as structural materials, insulation, windows and finishes. This research used software to test the three retrofit building systems, assessing their impacts on operational-carbon emissions. By quantifying the carbon reduction of different retrofit-building systems, DesignBuilder supports selecting energy-efficiency and - sustainability investments. Figure 7 shows the operational-carbon emissions of the three building systems over the study period.

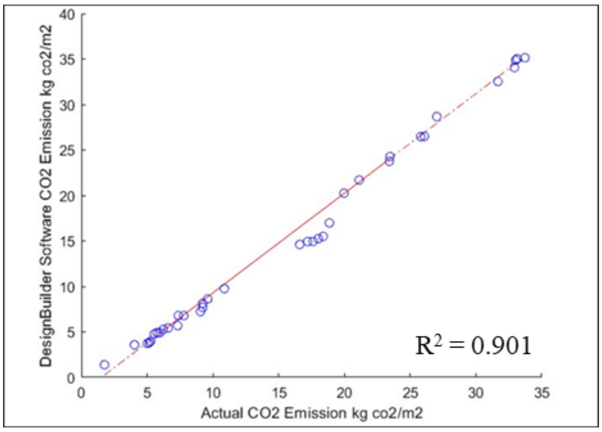
Defining the Statistical Characteristics

Linear-reegression Analysis

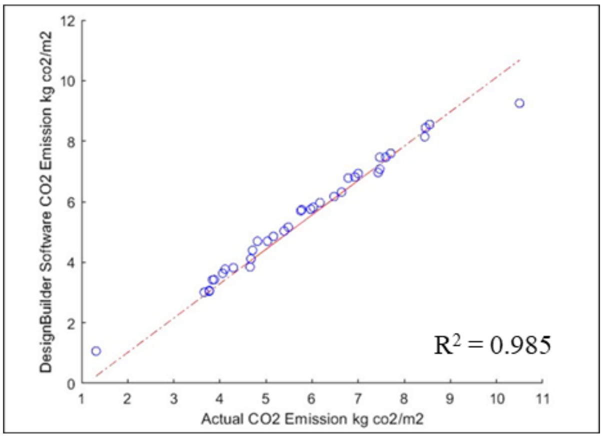
Following the assessment of the operational carbon of building types and systems, linear-regression analysis was performed to investigate the relationship between actual and DesignBuilder estimated-carbon emissions, assessing operational-carbon accuracy over three years (2017-2019) of each building type's 36 monthly energy consumption samples (Bahrami and Marandi, 2018). Figure 8 presents the outcomes of these analysis efforts for each respective building type. The reliability of the DesignBuilder estimations was quantified by evaluating 36 distinct samples of consumption data for each building type, which provided a substantial dataset for assessing the precision of the operational-carbon estimations made by the software. The linear-regression analysis revealed a high level of accuracy in the operational-carbon predictions generated by DesignBuilder, as evidenced by an average R^2 (coefficient of determination) value of 0.958, indicating that the model explains 95.8% of the variance in actual energy consumption for the three-building type. Furthermore, the average root-mean-square error (RMSE) stood at 0.810, signifying a close match between the predicted and actual energy-usage figures, thus underscoring the reliability of the DesignBuilder simulations in estimating the operational-carbon emissions within the context of the UAE's built environment.



a) Residential (Villas)



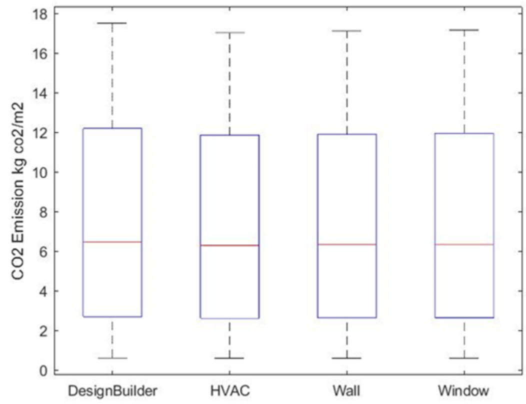
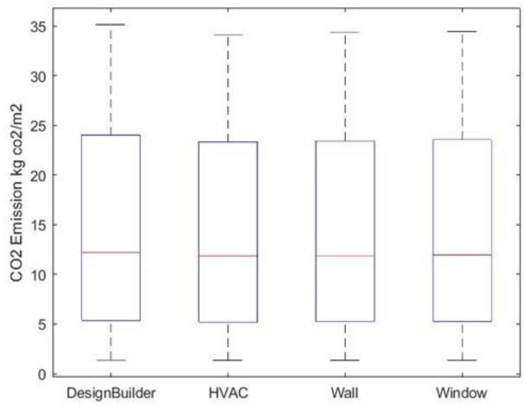
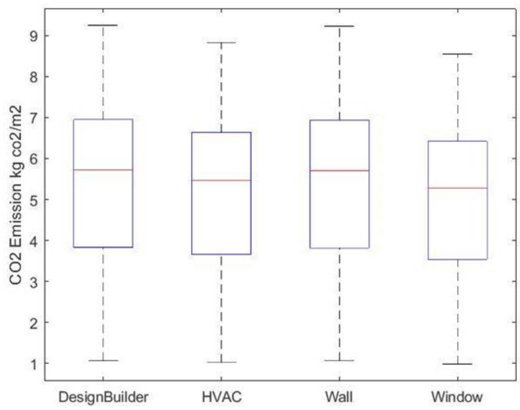
b) Commercial (High-Rise Building)



c) Educational (School)

Figure (8): Linear-regression analysis for operational carbon (MATLAB)

Table 3. Box plot for the suggested scenario (MATLAB)

	Design Builder	HVAC	Walls	Windows	Box plot
	(kg CO_2/m^2)				
Residential Building					
Minimum	0.62	**0.60**	0.61	0.61	
Q1 (25%)	2.70	**2.66**	2.64	2.65	
Median	6.49	**6.30**	6.33	6.37	
Q3 (75%)	12.20	**11.85**	11.92	11.96	
Maximum	17.51	**17.01**	17.10	17.17	
Commercial Building					
Minimum	1.39	**1.35**	1.35	1.36	
Q1 (25%)	5.35	**5.20**	5.23	5.25	
Median	12.19	**11.84**	11.90	11.95	
Q3 (75%)	24.02	**23.33**	23.45	23.54	
Maximum	35.14	**34.14**	1.35	34.45	
Educational Building					
Minimum	1.063	1.015	1.060	**0.982**	
Q1 (25%)	3.830	3.658	3.820	**3.540**	
Median	5.718	5.459	5.703	**5.285**	
Q3 (75%)	6.947	6.633	6.929	**6.420**	
Maximum	9.252	8.834	9.229	**8.551**	

Correlation Analysis

The correlation analysis carried out in this study offered valuable insights into the operational carbon across various building types and systems in the UAE over three years. The data underscored the positive impact of retrofitting building systems, highlighting their potential to decrease energy consumption substantially and, by extension, carbon emissions. Table 3 offers a comprehensive statistical distribution of the collected data, including key metrics, such as quartiles and averages, which depict the distribution and central tendencies of the dataset.

A significant finding from the analysis was the impact of HVAC-system upgrades on carbon reduction in residential and commercial buildings. The median operational carbon for residential buildings decreased from 6.49 $kgCO_2/m^2$ to 6.30 $kgCO_2/m^2$. Similarly, commercial buildings experienced a median reduction from 12.19 $kgCO_2/m^2$ to 11.84 $kgCO_2/m^2$. These figures emphasize the efficacy of HVAC-system improvements in diminishing carbon emissions in these buildings. However, for educational buildings, the analysis identified window upgrades as the most impactful intervention for carbon-emission reduction. After changes were implemented, the median operational carbon for educational buildings fell from 6.95 $kgCO_2/m^2$ to 6.42 $kgCO_2/m^2$, suggesting that window-system improvements could be the most beneficial strategy for these facilities.

Overall, the study's results advocate for tailored approaches to carbon reduction based on building type and function. It is recommended that HVAC-system upgrades for residential and commercial buildings achieve significant decreases in carbon emissions. For educational buildings, on the other hand, it is recommended to replace windows to achieve maximum carbon-emission reduction. This tailored strategy enhances the sustainability of the built environment and contributes to the broader goal of mitigating climate change by reducing the carbon footprint of buildings in the UAE.

Probability Mass Functions and Cumulative Distribution Functions

The final analysis stage focused on predicting and quantifying the cumulative annual energy savings for the selected building types, using both PMF and CDF methodologies. PMF analysis provided a discrete probability distribution of energy savings, offering insights into the likelihood of specific saving outcomes. CDF analysis offered a cumulative perspective, illustrating the probability that the variable of interest, such as energy saving in this case, would take a value less than or equal to a threshold. Together, these functions enabled a comprehensive understanding of energy-saving distributions within the studied systems. Figure 9 encapsulates these findings, presenting the percentage of energy saving every month. The data revealed a consistent trend in energy savings across residential and commercial buildings when modifications to HVAC systems were implemented, showcasing similar carbon-reduction percentages. The HVAC-system enhancements for residential buildings, led to a 28.56% reduction in carbon emissions, while commercial buildings saw a 28.48% decrease. Wall modifications also yielded notable energy savings, with residential buildings achieving a 23.49% reduction and commercial buildings a 23.99% decrease. Window changes resulted in the minimum energy reduction, albeit still significant, with reductions of 19.77% for residential buildings and 19.85% for commercial buildings. These figures underscore the effectiveness of HVAC-system improvements as the most influential factor in reducing energy consumption and carbon emissions within these building types.

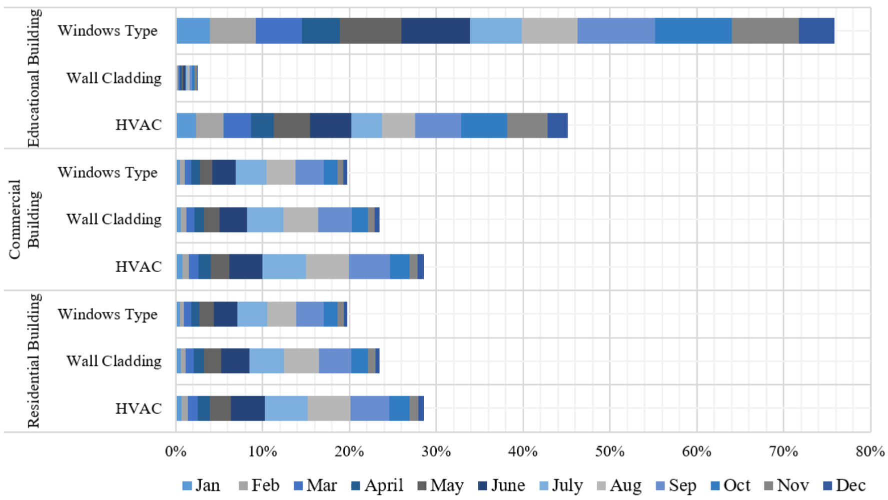


Figure (9): Cumulative percentage of carbon reduction (kg CO_2/m^2)

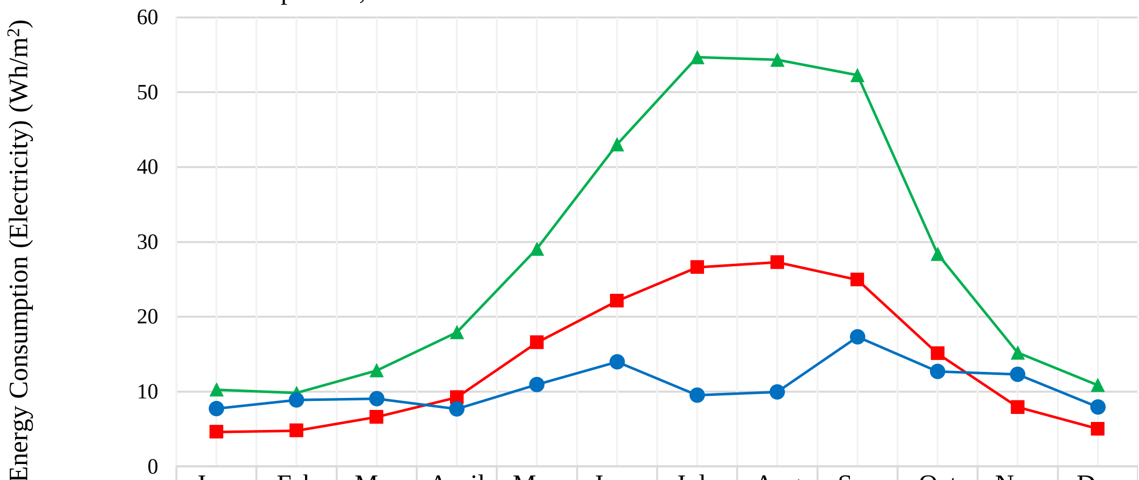
Conversely, educational buildings displayed a distinct pattern of energy savings, with window-system improvements leading to the most substantial reduction in carbon emissions, at a remarkable 75.80%. The HVAC system followed with a 45.45% reduction, while modifications to the wall type were less impactful, contributing to only a 2.55% decrease. These insights highlight the importance of system-specific interventions tailored to building types to maximize energy savings and carbon-emission reductions. While HVAC improvements are pivotal for residential and commercial buildings, educational buildings benefit significantly more from enhancements to window systems, suggesting a need for a customized approach in sustainability strategies for different building categories.

CONCLUSIONS

This research investigated the statistical characteristics of operational carbon from three types of buildings in the UAE: residential, commercial and educational as well as three building systems: HVAC, walls and window type. All scenarios were statistically evaluated through linear-regression analysis, correlation analysis, PMF and CDF methodologies.

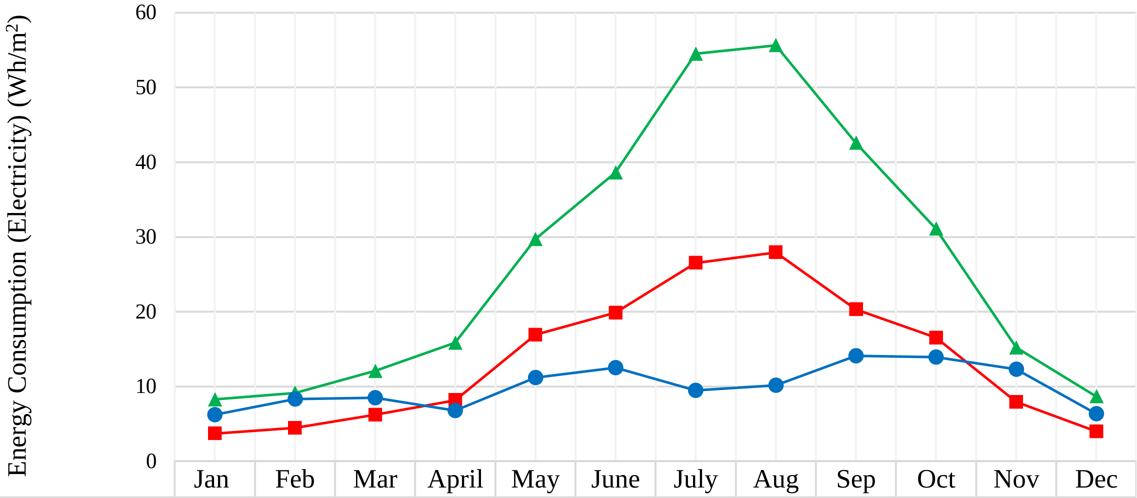
Linear-regression analysis investigated the relationship between actual and DesignBuilder carbon emissions. The results revealed an average accuracy (R^2) of 0.958, indicating that the model explains 95.8% of the variance in actual emissions. In comparison, correlation analysis evaluated the relationship between the building type and the building system. The results indicated that upgrading the HVAC system in residential and commercial buildings reduced the operational carbon, where the median decreased from 6.49 kgCO_2/m^2 to 6.30 kgCO_2/m^2 in residential buildings and from 12.19 kgCO_2/m^2 to 11.84 kgCO_2/m^2 in commercial buildings. In educational buildings, upgrading the window system reduced the operational carbon, where the median decreased from 6.95 kgCO_2/m^2 to 6.42 kgCO_2/m^2. Finally, PMF and CDF analyses were used to predict and quantify the cumulative annual carbon reduction for the three building types. The analyses indicated that upgrading the HVAC system reduced the carbon percentage of residential, commercial and educational buildings by 28.56%, 28.48% and 45.45%, respectively. However, upgrading the wall cladding reduced the carbon percentages by 23.99%, 23.99% and 2.55%, respectively. Finally, upgrading the window system reduced the carbon percentages by 19.77%, 19.85% and 75.80%, respectively. This variation in carbon-reduction percentages was due to the difference in the existing condition of each building type.

The limitations of this research were the availability of the actual data for each building type. In addition, the scope was also limited to specific building types and retrofitting strategies. Future research can explore more building types and investigate innovative retrofitting scenarios alongside adopting renewable-energy sources.



	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Residential	4.60	4.78	6.60	9.23	16.55	22.13	26.60	27.28	24.95	15.09	7.92	5.01
Commercial	10.26	9.80	12.84	17.92	29.07	43.03	54.66	54.33	52.26	28.39	15.21	10.87
Educational	7.71	8.90	9.05	7.68	10.95	13.96	9.52	9.94	17.32	12.71	12.32	7.95

Appendix (A): Average monthly energy consumption (2017)



	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Residential	3.71	4.46	6.21	8.16	16.91	19.86	26.52	27.93	20.32	16.54	7.92	4.00
Commercial	8.28	9.15	12.08	15.84	29.70	38.63	54.49	55.63	42.57	31.11	15.21	8.67
Educational	6.22	8.30	8.51	6.79	11.19	12.53	9.50	10.18	14.11	13.93	12.32	6.34

Appendix (B): Average monthly energy consumption (2018)

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