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DOI
10.1108/F-05-2017-0051

Publication date
2019

Document Version
Final published version

Published in
Facilities

Citation (APA)
Lee, P., Chan, E. H. W., Qian, Q. K., & Lam, P. T. I. (2019). Development of a user-friendly regression model to evaluate carbon emissions of office buildings design in the subtropics. *Facilities*, *37*(11-12), 860-878. https://doi.org/10.1108/F-05-2017-0051

The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/0263-2772.htm

Received 15 May 2017
Revised 31 October 2017
15 June 2018
22 October 2018
Accepted 21 January 2019

Development of a user-friendly regression model to evaluate carbon emissions of office buildings design in the subtropics

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Abstract

Purpose – Design teams have difficulties in assessing building carbon emissions at an early stage, as most building energy simulation tools require a detailed input of building design for estimation. The purpose of this paper is to develop a user-friendly regression model to estimate carbon emissions of the preliminary design of office buildings in the subtropics by way of example. Five sets of building design parameters, including building configuration, building envelope, design space conditions, building system configuration and occupant behaviour, are considered in this study.

Design/methodology/approach – Both EnergyPlus and Monte Carlo simulation were used to predict carbon emissions for different combinations of the design parameters. A total of 100,000 simulations were conducted to ensure a full range of simulation results. Based on the simulation results, a regression model was developed to estimate carbon emissions of office buildings based on preliminary design information.

Findings – The results show that occupant density, annual mean occupancy rate, equipment load, lighting load and chiller coefficient of performance are the top five influential parameters affecting building carbon emissions under the subtropics. Besides, the design parameters of ten office buildings were input into this user-friendly regression model for validation. The results show that the ranking of its simulated carbon emissions for these ten buildings is consistent with the original carbon emissions ranking.

Practical implications – With the use of this developed regression model, design teams can not only have a simple and quick estimation of carbon emissions based on the building design information at the conceptual stage but also explore design options by understanding the level of reduction in carbon emissions if a certain building design parameter is changed. The study also provides recommendations on building design to reduce carbon emissions of office buildings.

Originality/value – Limited research has been conducted to date to investigate how the change of building design affects carbon emissions in the subtropics where four distinct seasons lead to significant variations of outdoor temperature and relative humidity. Previous research also did not emphasise on the impact of high-rise office building designs (e.g. small building footprint, high window-to-wall ratio) on carbon emissions.

The authors gratefully acknowledge the Hong Kong Polytechnic University for providing funding to support this study via the General Research Fund of the Hong Kong SAR Government (Project Account Code: 152006/14E). The third author is thankful for the generous support of Delft Technology Fellowship (2014-2020).

Facilities
Vol. 37 No. 11/12, 2019
pp. 860-878

0263-2772
DOI 10.1108/F-05-2017-0051

This paper adds value by identifying the influential parameters affecting carbon emissions for a high-rise office building design and allows a handy estimate of building carbon emissions under the subtropical conditions. The same approach may be used for other meteorological conditions.

Keywords Office building, Building design, Carbon emission

Paper type Research paper

Nomenclature

Abbreviations

SRC = Standardized regression coefficient;
COP = Coefficient of performance;
FT = Fluorescent tube;
FL = Fluorescent lamp;
EUI = Energy utilization index;
R^2 = Coefficient of determination;
RMSE = Root means square error;
CAV = Constant air volume;
VAV = Variable air volume;
SHGC = Solar heat gain coefficient;
ACH = Air change per hour;
E&M = Electrical and mechanical;
y = The predicted carbon emission;
x_i = The value of a design parameter;
β_i = The regression coefficient of a design parameter;
s_i = The standard deviation of a design parameter; and
s_y = The standard deviation of predicted carbon emission.

1. Introduction

Buildings account for approximately 40 per cent of total energy use and carbon emissions in the world (Bloom and Wheelock, 2011). A research conducted by USA National Research Council (2011) indicated that greenhouse gas emissions from buildings are the key factors to the rise in the surface temperature of earth. Wood and Agogino (2005) pointed out that the final environmental impacts of buildings are highly related to the early phases of building design. Change of design parameters in the early stage of a project involves very little cost but can reap huge benefits. Parmee (2005) stated that designers make the building design decision-based on intuition and past experience. Therefore, it is important for design teams to estimate building carbon emissions before the stage of the detail design and make necessary changes on building design when the level of carbon emission for the proposed building is found to be far above the baseline level (Basbagill *et al.*, 2017). Building energy simulation is one of the common methods to investigate the quantitative relationship between carbon emissions and different building designs (Nguyen *et al.*, 2014). However, because of significant resources, time and technical expertise, this method is not commonly used at the early design stage (Hopfe *et al.*, 2005). In addition, a high degree of technical specification to characterise buildings, such as floor area, building materials and building system configurations, is required to achieve more accurate simulation results. De Souza (2012) discussed the fundamental differences in knowledge of building design and building physics throughout the whole building design. As such, these are reasons hindering the real application of building energy simulation programmes at the early design stage in practice.

Therefore, there is a need to develop a simplified assessment model for evaluating carbon emissions for exploring design options at the early building design stage.

Statistical modelling is a common method to investigate the quantitative relationship between carbon emissions and different building designs. The statistical models are developed based on the correlation between energy use/carbon emissions and building and system configurations. A number of research studies on the statistical models were found. Lam and Hui (1996) found that approximately 90 per cent of the discrepancy in building energy use can be described by the influential parameters, including building construction, HVAC systems and weather. Hygh *et al.* (2012) developed a tool with 27 parameters to predict building energy performance using multi-variate regression model. The results indicated that a linear regression model is regarded as a reliable tool to evaluate building energy performance at the early design stage. Asadi *et al.* (2014) performed an analysis to estimate the impact of different building shapes on its building energy consumption. It is concluded that optimisation of building shape is an effective way to minimise construction costs. However, there is limited research to investigate how the change of building design affects carbon emissions under the subtropics condition. As the feature of subtropical weather has four distinct seasons where the variations of outdoor temperature and relative humidity are significant, more attention should be paid to the impact on energy use owing to different building designs under the subtropics. In addition, pervious research did not emphasise on the impact of high-rise office building designs on carbon emissions. The features of high-rise office buildings (e.g. small building footprint, high window-to-wall ratio) will be taken into account in this study.

The aim of this paper is to develop a simplified assessment model for evaluating carbon emissions for quick exploration of design options at the early building design stage by:

- identifying the influential parameters which significantly affect carbon emissions for office building design under the subtropics; and
- providing solutions for minimising carbon emissions in building design.

In this study, five aspects of building design, including building configuration, building envelope, design space conditions, building system configuration and occupant behaviour, are considered as design parameters affecting carbon emissions for office buildings. Both *EnergyPlus* and Monte Carlo simulation were used to predict carbon emissions for the different combination of these design parameters. To ensure the full range of simulation results, 100,000 simulations were conducted. The simulation results were then used to develop the regression model to estimate the carbon emissions of the office building at the operational stage.

It is noted that considerable performance gaps between model prediction and field observation of building energy use are found in practice. Li *et al.* (2016) discussed the reasons of performance gap as being because of discrepancies in actual manufacturing process, construction and building operation. However, this proposed method is not intended to estimate carbon emissions in great accuracy. The aim of this paper is to demonstrate a simplified assessment model which enables design team to explore design options by predicting building energy performance and carbon emission quickly with certain accuracy when the building is in use.

This paper is structured as follows: Section 2 outlines the methods for developing the simplified regression model to evaluate carbon emissions for office building design. The design parameters affecting carbon emissions for office buildings at the building operation stage are also discussed. Section 3 reports the results of regression model and its accuracy. Section 4 describes the influential design parameters affecting building carbon emissions at the operational stage and demonstrates the application of the regression model. This section also presents recommendations on carbon reduction for office building design. Section 5 outlines the conclusion drawn from this study and provides further research direction on the passive building design parameters.

2. Review on empirical carbon audit

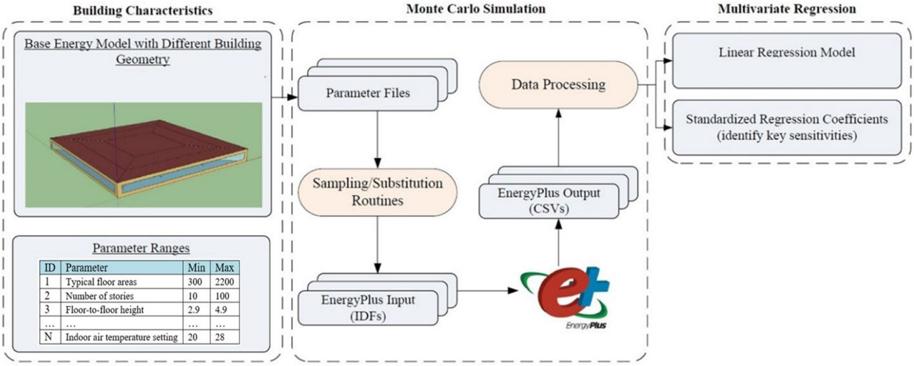
A number of guidelines for empirical carbon audit in different countries and regions have been developed based on the International Standards ISO 14040 series and the Greenhouses Gas (GHG) Protocol (Lai *et al.*, 2012). These guidelines aim to provide building owners/tenants/organisations with guidance to calculate the emissions of six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6). In general, GHG emissions in buildings are often categorised into three scopes (Lai, 2015). To ascertain the GHG emissions, the data and information required include:

- type and quantity of consumed fuel;
- number of planted trees;
- quantities of consumed electricity;
- consumed town gas;
- recycled paper and consumed water; and
- type and quantity of released refrigerants.

At the early building design stage, it is not feasible to obtain or estimate some of the data, such as recycled paper and consumed water, type and quantity of released refrigerants and the number of planted trees. Besides, unlike other types of building such as hotels or hospitals where gas cooking stoves and gas-fired boilers are used, electricity is often the major energy source in office buildings. Therefore, the quantities of electricity consumption, which are estimated based on the preliminary building design (e.g. building configuration, building envelope, design space conditions, building system configuration and occupant behaviour), are the main consideration in this study.

3. Material and methods

Figure 1 outlines the procedures and methods for developing a multiple linear regression to evaluate carbon emissions for office building design under the subtropics. The details of the procedures and methods will be discussed as follows.



ID	Parameter	Min	Max
1	Typical floor areas	300	2200
2	Number of stories	10	100
3	Floor-to-floor height	2.9	4.9
…	…	…	…
N	Indoor air temperature setting	20	28

Figure 1. Procedures and methods for developing a multivariate regression model

3.1 Selection of simulation method

To estimate carbon emissions for various building designs under the subtropical climate, it is necessary to adopt a detailed building energy simulation programme. Building energy simulation programme is a tool to analyse energy performance and thermal comfort in buildings. Each building energy simulation programme applies different mathematical algorithms and empirical models for building energy performance prediction (Underwood and Yik, 2004). To date, there are a number of building energy simulation programmes in the field of building energy, including *EnergyPlus, Ecotect, BDA, IES-VE, ESP-r* and *TRNSYS*. In the study of Crawley *et al.* (2001), a direct comparison was made between notable building energy simulation programmes in terms of their features and capabilities (e.g. modelling features, building envelope and daylighting and validation).

In comparison to other notable building energy simulation programmes, *EnergyPlus* is the most suitable to predict energy use of different building designs in this study. The reasons are summarised as follows:

- Unlike other simulation programmes which are developed by commercial companies, *EnergyPlus* is developed by the Department of Energy (DOE) in the USA (DOE, 2014b).
- Regarding simulation accuracy, validation was performed with ASHRAE Standard 140 (American Society of Heating Refrigerating and Air-Conditioning Engineers., 2007), and many actual building scenarios were used to demonstrate the prediction accuracy of building energy consumption.
- *EnergyPlus* is a free and open-source programme which includes a number of innovative simulation capabilities, such as multi-zone air flow, time-steps of less than an hour and integration of plant and systems with heat balance-based zone simulation (Crawley *et al.*, 2001).
- *EnergyPlus* uses text files for inputs, and this format allows researchers to modify numerous input files automatically using *Excel Visual Basic for Application*.

This feature is particularly important as 100,000 simulations are required to perform with different building designs in this study. Other simulation programmes, such as *Ecotect*, *BDA* and *IES-VE*, focus more on model visualisation and user-friendliness. Apart from that, these are not open-source programmes. Difficulties are found in implementation when a significant number of simulations need to be performed automatically.

3.2 Model development

In this study, open-plan office buildings are used to demonstrate the method for developing a multiple linear regression as the office segment is one of the key contributors to carbon emissions in high-density cities. According to the Hong Kong end-user data (EMSD, 2016), the office segment accounted for 12,791 TJ of electricity use (equivalent to 8.1 per cent of the total electricity use or 10.5 per cent of the electricity use in the commercial sector) in 2014.

To represent the actual carbon emissions for office buildings at the operation stage, a building energy model is developed using *EnergyPlus* (Version 8.5) (US DOE, 2014). *EnergyPlus* is a comprehensive building energy simulation programme. With the use of *EnergyPlus*, building designers can predict building energy use for different central air-conditioning (AC) systems and lighting systems under various building configurations.

In this study, one typical floor is modelled to represent the whole building for the sake of simplicity. As the roof floor of buildings in high-density cities (e.g. Hong Kong) is often used to house the potable water and fire services water tanks, it would be reasonable to assume that these services water tanks absorb heat caused by direct solar heat gain, and such heat transfer to the top floor of buildings is rather limited and can be negligible. Regarding the thermal zoning of office buildings, two major zones, namely, core and perimeter zones, are modelled as this is one of the common zoning methods used in open-plan office buildings.

Other parameters which require *EnergyPlus* simulations will be discussed in the next section, and these parameters are often the design parameters affecting carbon emissions at the building operation stage.

3.3 Design parameters affecting carbon emissions at building operation stage

Unlike other types of building such as hotels or hospitals where gas cooking stoves and gas-fired boilers are used, electricity is often the major energy source in office buildings. Therefore, the amount of electricity consumption can be directly related to the carbon emissions in office buildings. In Hong Kong, there are two power supply companies, which use a different mix of energy sources to generate electricity. These energy sources include coal, natural gas and nuclear from China. To simplify the carbon emission calculation, an average of carbon emission design parameters from two power companies is used, and the value is 0.7 kg CO_2-e/kWh (EPD, 2010).

Based on the literature review (Lam and Hui, 1996; Lam *et al.*, 2008), the design parameters affecting carbon emission for office buildings at building operation stage can be categorised into five aspects, namely, building configuration, building envelope, design space conditions, building system configuration and occupant behaviour. To understand the quantitative relationship between carbon emissions and these design parameters, the possible ranges of its value will be identified. Table I shows the details of each design parameter and its ranges being determined.

3.3.1 Building configuration. The design parameters relating to building configuration consists of:

- typical floor areas;
- number of storeys;
- floor-to-floor heights;
- aspect ratios;
- perimeter zone depths; and
- orientations.

There are different types of building geometry available in office buildings, and rectangular form is the most common type as it is the best geometry to maximise floor usage. Thus, only rectangular plan form with different aspect ratios is considered in this study.

Primeoffice is a property search website providing key office building information in Hong Kong (Primeoffice, 2015). This information includes building floor areas, typical floor layout and number of storeys. The database contains more than 1,500 office building information. Based on the design plans of typical floors, the aspect ratio can be estimated. For other design parameters such as floor-to-floor heights, orientations and perimeter zone depths, the range of its values can be obtained from the literature review and relevant research studies (Lam and Hui, 1996; Lam *et al.*, 2008).

3.3.2 Building envelope. The design parameters relating to building envelop include:

- window-to-wall ratio;
- wall U-value;

Table I. Design parameters and sampling ranges used in Monte Carlo simulation

Parameters	Unit	Minimum	Maximum
Building configuration			
Typical floor areas	m^2	300	2,200
Number of storeys	–	10	100
Floor-to-floor height	m^2	2.9	4.9
Aspect ratio	–	0.5	5
Perimeter zone depth	m^2	1	8
Orientation (rotation)	Degrees	0	180
Building envelope			
Window U-value	W/m^2K	1.1	8.6
Window SHGC		0.2	0.6
Wall U-value	W/m2K	0.624	3.01
Window-to-wall ratio	–	0.1	0.95
Space conditions			
Equipment load	W/m^2	1	31
Infiltration load	ACH	0.05	2.05
Lighting load	W/m^2	2	30
Occupant density	m^2/person	2	16
Annual mean occupancy rate	%	10%	100%
Ventilation rate	l/s/person	5	10
Plant configuration			
Type of water-side system	–	Air-/water-cooled chiller	
Type of air-side system	–	CAV/VAV	
COP of air-cooled chiller	–	1	4
COP of water-cooled chiller	–	3	6
Occupant behaviour			
AC operation hours	Hours	17	23
Indoor air temperature setting	°C	20	28

Notes: 1: CAV = constant air volume; VAV = variable air volume; SHGC = solar heat gain coefficient; COP = coefficient of performance

- window U-value; and
- window solar heat gain coefficient (SHGC).

Energy performance of building envelop depends on a number of design parameters, including materials of window and external wall, as well as the window-to-wall ratio. In general, U-values of window and wall are used to represent the rate of heat transfer through a 1 m^2 area of material for every temperature degree difference under a standardised condition. The lower U-value implies the lower rate of heat transfer per unit area.

SHGC is a parameter measuring how much solar radiation passes through the window. Under the subtropical climate, windows with a low SHGC limit the amount of solar radiation to pass through, reducing the cooling load for the air-conditioned spaces. In general, the SHGC of a window depends on glass materials and its surface. For the window-to-wall ratio, the ratio is often determined with the consideration of daylight, ventilation, views and architectural design. Based on the literature review and general code of practices, the possible range of its value can be estimated (Lam *et al.*, 2008; Lam and Hui, 1996).

3.3.3 Design space conditions. In this study, space conditions refer to the design parameters which affect the energy consumption of building services systems in office buildings as these systems account for approximately 80 per cent of the total energy consumption in office buildings (EMSD, 2016). Based on the literature review (Lam *et al.*, 2008; Lam and Hui, 1996), the design parameters for space conditions include:

- lighting load;
- equipment load;
- infiltration load;
- ventilation rate;
- occupant density; and
- annual mean occupancy rate.

Lighting load is a measure of how much lighting power lamps consume per the unit of area. The variation of lighting load in buildings is attributed to the required illumination level, luminaire arrangement and the types of lamp (e.g. T5, T8, LED lamps). Equipment load in offices often refers to office equipment, including notebooks, printers, fax machines, desk fan and photocopiers. It should be highlighted that several design parameters not only affect energy consumption itself but also indirectly influence energy use for central AC systems. For example, both lighting device and equipment contribute to the internal heat gain of AC systems (American Society of Heating Refrigerating and Air-Conditioning Engineers., 2009).

Infiltration load and ventilation rate are the parameters which affect the amount of fresh air intake to the indoor environment. In general, the more the infiltration load and ventilation rate, the more energy the AC system consumes. In the AC system design, the ventilation rate depends on the number of occupants in buildings (American Society of Heating Refrigerating and Air-Conditioning Engineers., 2009).

Apart from lighting and equipment loads, occupants are one of the key design parameters attributing to the internal heat gains of AC systems. Heat is released from the body surface to indoor environment by radiation, convection and evaporation. As a result, cooling load increases accordingly and ultimately more energy is consumed to maintain a constant indoor air temperature. Besides, occupancy rates in office buildings also vary from time to time, and the impact on building energy use becomes more significant during the periods of economic growth or downturn owing to the significant changes in occupancy rates. In this paper, occupant density is defined as the square metre per person (m^2/person).

The range of values for these design parameters can make reference to the common design practices and local guidelines (e.g. Code of Practice for Energy Efficiency of Building Services installation (Electrical and Mechanical Services Department [EMSD], 2012), as well as the relevant survey results (Dunn and Knight [2005]).

3.3.4 Building system configuration. Under the subtropical climate, central AC systems are often the most important to provide a comfortable indoor environment in office buildings. In general, central AC systems consist of two sub-systems, namely, the air- and water-side systems. For the water-side system, air- and water-cooled chillers are the two types of commonly used chillers. Under the subtropical climate, the energy performance of water-cooled chillers is much better than that of air-cooled chillers (Yik *et al.*, 2001). There are two types of air-side system, namely, constant air volume (CAV) and variable air volume (VAV) systems, in typical office building designs. The selection of the systems depends on the office grading, plant space and office design. Compared to CAV systems, VAV systems are more energy-efficient as the fan speed can be varied by cooling load, and this saves fan energy without compromising on comfort level.

In this study, the combination of different water- and air-side systems will be considered. As the COP of air- and water-cooled chillers is significantly different, the range of COP of chillers will be considered with the different types of chiller. For example, the lowest value of COP for air-cooled chiller will be 1 while that for water-cooled chiller will be 3. In addition, the range of COP for different types of chillers is considered with the latest edition of Code of Practice for Energy Efficiency of Building Services Installation, which lists the minimum COP required for different types of chillers (EMSD, 2015).

3.3.5 Occupant behaviour. In this study, AC operation hours and indoor air temperature setting are the two design parameters for occupant behaviour. The indoor air temperature setting can have a significant impact on the actual energy use of AC systems. In practice, the substantial variations in the indoor air temperature setting are observed in open-plan office buildings. Mui and Wong (2007) conducted a survey to measure the room temperature in typical office buildings and found that the setting of the room temperature has a strong correlation with occupant behaviour. The temperature variations can vary from 19°C to 25.4°C.

For the AC operating hours, the variation of actual operating hours is rather substantial as tenants may request property management companies for longer operating hours to fit their business needs. To determine the changes in AC operating hours, the data from *Primeoffice* was adopted to determine the range of AC operating hours.

3.4 Monte Carlo simulation

To understand the quantitative relationship between carbon emission and the above design parameters, a multiple regression model is developed. A uniform distribution is used to create a full range of possible values for each design parameter using Monte Carlo simulation. Monte Carlo simulation is a mathematical method where the output values are computed based on assumed distributions of randomly generated variables. Such a method is widely used in various fields, including physical sciences, engineering, design, finance and business (Eisenhower *et al.*, 2012). In this study, 100,000 sets of data are created, and these data sets comprise possible combinations of the values for all design parameters. Compared to other research studies, 100,000 iterations are considered to be sufficient to simulate all possible conditions of office building designs (Yi and Chan, 2013).

These 100,000 sets of data were incorporated into *EnergyPlus* for energy-use estimation. To make these calculation processes automatic, *jEPlus* is used in this study (Zhang and Korolija, 2010). *jEPlus* will run each simulation with the respective building energy models in a format of the CSV-style text file, and it allows eight *EnergyPlus* simulations to be performed in each run. Apart from the advantage of simultaneous simulation, *jEPlus* will also consolidate all the simulation results automatically. To obtain the final results for the regression model, eight computers with two quad-core processors were used to complete 100,000 simulation runs. It should be noted that the simulation results are the annual electricity consumption for the respective office buildings. A conversion factor is used to convert electricity consumption to carbon emissions (the value of 0.7kg CO_2-e/kWh is used in this study [EPD, 2010]).

Based on the results of the simulations, multiple linear regression analysis was conducted to evaluate carbon emissions on each of the key design parameters:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_p x_p$$

where, y is the predicted carbon emission, x_i is the value of a design parameter and β_i is the regression coefficient of x_i.

For the sake of validation, only 80 per cent of the results were adopted to develop the regression model, while another 20 per cent of the results were used for the model validation process. Based on the values of standardised regression coefficients (SRCs), the impact of each building design parameters on carbon performance can be estimated.

4. Results

4.1 Regression models and accuracy

The developed regression model for predicting carbon emissions in office buildings are presented in Table II. Regarding the model accuracy, several indicators, namely, the coefficient of determination (R^2), the root mean square error (RMSE), F-test and *t*-statistic are used. The R^2 of the models was 0.863, which is acceptable for regression models in the building energy field. The RMSE and F-test parameters were 24.57 and 26456, respectively. The root mean square error was relatively low. Based on the regression result, 20 regression coefficients were evaluated, and the value of the standardised coefficients can be regarded as an indicator to determine the impact on carbon emissions. The negative coefficient implies that the annual building carbon emissions would increase with a decrease in value of the respective design parameter. As the linear regression coefficients (β_i) are related to the units of x_i, a direct comparison between each design parameter cannot be made (e.g. window U-value does not have the same magnitude order for floor-to-floor height). Therefore, linear regression coefficients were then normalised into SRCs for comparison among design parameters. SRCs can be calculated as follows (multiply each coefficient by the ratio of the estimated standard deviations of x_j to y):

Parameter	SRC	Ranking	VIF
Building configuration			
Typical floor areas	−0.061	8	1.0
Number of storeys	0.028	12	1.0
Floor-to-floor height	0.012	16	1.0
Aspect ratio	0.014	15	1.0
Perimeter zone depth	−0.091	6	1.0
Orientation (rotation)	Excluded	20	1.0
Building envelope			
Window U-value	0.008	18	1.0
Window SHGC	0.022	14	1.0
Window-to-wall ratio	0.025	13	1.0
Wall U-value	−0.006	19	1.0
Design space conditions			
Equipment load	0.275	2	1.0
Infiltration load	Excluded	20	1.0
Lighting load	0.165	4	1.0
Occupant density	−0.203	3	1.0
Annual mean occupancy rate	0.818	1	1.0
Ventilation rate	0.061	9	1.0
Building system configuration			
Type of water-side system	−0.011	17	2.033
Type of air-side system	−0.044	10	1.0
Chiller COP*	−0.140	5	2.033
Occupant behaviour			
AC operation hours	0.071	7	1.0
Space air temperature	−0.030	11	1.0

Note: *Depends on the type of chiller (air-cooled vs water-cooled)

Table II. SRC of each parameter and its ranking

$$U_{SRC}(x_i, y) = \frac{\beta_{i x s_i}}{s_y}$$

where, β_i is the regression coefficient of a design parameter; s_i is the standard deviation of a design parameter; and s_y is the standard deviation of predicted carbon emission.

Regression model validation is an important step in model development. It is not sufficient to only use R^2 as an indicator to determine the accuracy of the model. To increase the confidence in using this regression model, 20 per cent of the data generated by the Monte Carlo method were used for validation. It was found that the mean absolute percentage error was 13.2 per cent on the annual carbon emissions. Although the percentage error is considered relatively large, the prediction accuracy is still acceptable for this study as the main purpose of developing the regression model is to provide a simple and quick estimation of carbon emissions at the conceptual design stage. Once the preliminary design is completed regarding building geometry and building envelope designs, further analysis is recommended using a more detailed building energy simulation method to optimise the other design parameters.

5. Discussion

5.1 Parametric study

The SRC compares the strength of the effect of each individual independent variable to the dependent variable. The higher the absolute value of the SRC, the stronger the impact on the dependent variable. In this study, SRC was adopted to determine the impact on carbon emission with the respective design parameters. With the results of predicted carbon emissions and the input design parameters, the SRCs can be calculated using Statistical Package for the Social Sciences. Table II shows the results of SRCs for office buildings under the subtropical weather. It was found that the top five influential design parameters affecting carbon emissions include:

1. annual mean occupancy rate (SRC: 0.818);
2. equipment load (SRC: 0.275);
3. occupant density (SRC: −0.203);
4. lighting load (SRC: 0.165); and
5. chiller COP (SRC: −0.140).

Among these influential design parameters, the annual mean occupancy rate has the largest impact on carbon emissions in office buildings during the operational stage, followed by the equipment load. The negative coefficient implies that the annual building carbon emissions would increase with the decrease in its value of the respective design parameter. For example, the chiller COP has negative SRC, implying that the carbon emissions increase with a decrease in chiller COP. In this study, the values of SCR being less than 0.1 are regarded as non-influential design parameters, which implies that such parameters have limited impact on actual carbon emissions.

In addition, the multicollinearity condition in the regression model was evaluated in this study. Variance inflation factor (VIF) is a measure of collinearity among independent variables within a multiple linear regression. If the VIF is equal to 1, there is no multicollinearity among the parameters. In general, the issue of multicollinearity can be neglected if the VIF is less than 5 (O'brien, 2007). Table II shows the value of VIF for each parameter. It was found that there is no multicollinearity issue in the developed regression model.

It is noted that based on the regression results, the impact of orientation and infiltration load on carbon emission is very limited. In this study, open-plan office buildings are assumed to be a rectangular shape with different aspect ratios. Therefore, the impact of orientation is rather limited under the sun path diagram of Hong Kong. For the parameter of infiltration load, compared to the required ventilation rate for office buildings, the change of infiltration load is highly insignificant. Therefore, these two parameters have been excluded in the regression model.

5.2 Application of regression model

The SRCs in Table II are used not only to identify the influential design parameters affecting carbon emissions in office buildings but also to estimate carbon emissions for new office buildings with the different combination of the design parameters.

For example, for new buildings, the designer can input the necessary parameters into the simple regression model to estimate carbon emissions during the conceptual design stage. Unlike other detailed simulation methods where all the design drawings and system schematic diagrams should be finalised to obtain an accurate result, this regression model can provide a quick and simple method for designers to predict carbon emissions at the early conceptual design stage. With the results obtained by the regression model, the designers have sufficient information to compare the level of carbon emissions with other similar types of building and make the decision on whether more resources should be put to further reduce carbon emissions by the change of building design.

To further illustrate the benefits of using this simple regression model, ten actual office buildings under the subtropical climate were used. The study of Lam *et al.* (2008) provides values of key design parameters for ten office buildings, including U-value of wall and window, building load, characteristics of HVAC system and system operation pattern. The floor areas of these ten office buildings vary from 12,000 m^2 to 100,000 m^2, and the number of storeys ranges from 11 to 48. The details of building characteristics can be found in Table III.

By inputting the values of those design parameters of the ten office buildings into the regression model, the predicted carbon emissions were calculated, and the results are listed in Table IV. The carbon emission values range from 140.8 CO_2-e/kWh/m^2 to 190.9 CO_2-e/kWh/m^2. In general, the ranking result of ten office buildings is consistent with the actual ranking (which is obtained based on its energy utilisation index [kWh/m^2]). The result indicates that this regression model can provide a simple and quick estimation of carbon emission level at the conceptual design stage.

5.3 Recommendations on reduction in carbon emissions for office buildings

As discussed in Section 4.1, annual mean occupancy rate, equipment load, occupant density, lighting load and chiller COP are the top five influential design parameters. Among them, equipment load, lighting load and chiller COP are the parameters relating to electrical and mechanical systems and equipment. Apart from the annual mean occupancy rate which is unforeseeable at the early design stage, the building owners can have early involvement in the design of these influential parameters.

5.3.1 Chiller coefficient of performance. The COP is a performance indicator for central chillers, and COP can be calculated by total cooling load divided by chiller energy consumption. The results of regression model indicate that the level of carbon emissions in office buildings is highly correlated to actual COP of chillers, instead of the type of chillers. Although most of the building energy codes regulate the minimum level of COP for the particular types of chillers at the standard conditions (e.g. Code of Practice for Energy Efficiency of Building Services Installation in Hong Kong), in practice the chillers are often

Table III.
Input design parameters of ten office buildings located under the subtropical climate

			Building configuration					Building envelope		
ID	Typical floor areas	No. of stories	Floor-to-floor height	Aspect ratio	Perimeter zone depth	Orientation[a] (rotation)	Window U-value	Window SHGC	Window-to-wall ratio	Wall U-value
Bld 1	969.48	25	3.5	2.5	2.7	0	4.8	0.4	0.5	1.4
Bld 2	2,045.77	48	3.5	2.5	2.7	0	3.4	0.25	0.65	1.9
Bld 3	631.8	20	3.5	2.5	2.7	0	5.6	0.9	0.4	1.4
Bld 4	807.86	15	3.5	2.5	2.7	0	5.6	0.65	0.36	1.4
Bld 5	1,297	47	3.6	2.5	2.7	0	3.6	0.25	0.5	1.9
Bld 6	19,125	48	3.5	2.5	2.7	0	3.4	0.25	0.45	1.9
Bld 7	928.81	32	3.5	2.5	2.7	0	5.6	0.45	0.45	1.9
Bld 8	1,302	26	3.5	2.5	2.7	0	5.6	0.55	0.33	1.9
Bld 9	2,100.6	11	3.5	2.5	2.7	0	5.6	0.6	0.4	1.9
Bld 10	2,097.09	21	3.5	2.5	2.7	0	5.6	0.65	0.35	1.9

Note: [a]No data are given for orientation and annual mean occupancy rate. Assumptions were made accordingly

(*continued*)

Table III.

	Design space conditions					Building system configuration			Occupant behaviour	
ID	Equip. load	Infil. load	Lighting load	Occupant density	Annual mean occupancy rate[1]	Type of water-side system	Type of air-side system	Chiller COP	Space air temp.	AC operation hours
Bld 1	28.8	0.6	25	6	0.8	WC chillers	VAV	4.1	23	10
Bld 2	37.2	0.6	25	6	0.8	WC chillers	VAV	4.1	23	12
Bld 3	15.8	0.6	24	8	0.8	WC chillers	VAV	4.1	24	10
Bld 4	13.7	0.6	24	8	0.8	AC chillers	VAV	2.7	24	10
Bld 5	25.8	0.6	24	7	0.8	WC chillers	VAV	4.2	23	12
Bld 6	25.8	0.6	25	7.5	0.8	WC chillers	VAV	4.1	23	12
Bld 7	21.3	0.6	24	8	0.8	AC chillers	VAV	3.1	24	11
Bld 8	22.5	0.6	25	7.5	0.8	AC chillers	VAV	3.2	23	11
Bld 9	18.6	0.6	22	7	0.8	AC chillers	CAV	2.9	23	10
Bld 10	18.9	0.6	22	8	0.8	AC chillers	CAV	3.3	25.5	11

operating at the non-standard conditions. Substantial deviations between the design and actual operating conditions are often observed in real situations. Some of the reasons are attributed to the poor system operation and control by building operators. Therefore, system operators should work closely with system service providers to ensure that the newly installed chillers are operating at the optimal conditions.

5.3.2 Equipment load. Equipment load for AC system means the heat release from electric equipment to the indoor environment. In general, the most common equipment for office premises includes computers, printers and photocopiers. To ensure that the building owners/tenants can purchase office equipment with high energy efficiency, the government should extend the current "energy efficiency labelling scheme" to office equipment, including computers, laser printers and photocopiers. With the energy labels, the building owners/tenants can easily purchase the energy-efficient office equipment and estimate the impact on carbon emissions because of the reduction of equipment load when the existing office equipment is replaced with the new one. In addition, facility management companies should strictly enforce good practices of equipment operation. For example, users should not

Table IV.
Comparison between the regression results and actual results for ten office buildings

	Regression model		Actual office building energy use data	
	kg CO_2-e/m^2/annum	Ranking	kWh/m^2/annum	Ranking
Bld 1	169	9	325	7
Bld 2	190.9	10	370	10
Bld 3	140.8	1	224	1
Bld 4	146.3	$\overline{3}$	250	$\overline{3}$
Bld 5	161.4	$\overline{7}$	325	$\overline{8}$
Bld 6	145.7	*2*	295	*5*
Bld 7	160.2	6	322	6
Bld 8	165.1	$\overline{8}$	326	$\overline{9}$
Bld 9	157.2	*5*	260	*4*
Bld 10	154.2	*4*	225	*2*

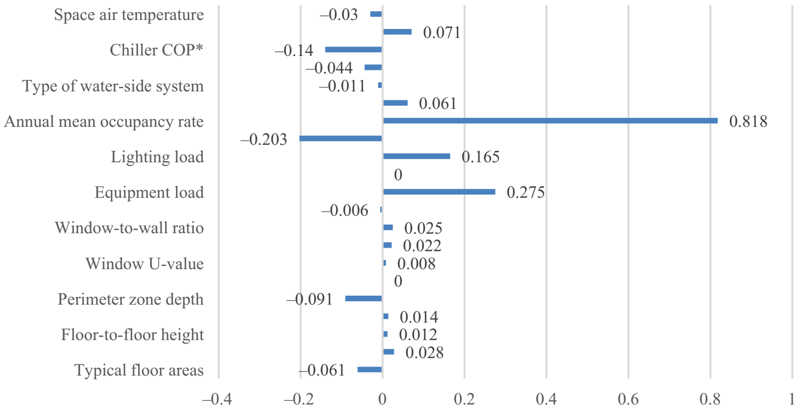


Figure 2.
Effect of building design parameters on annual carbon emission under the subtropical climate

leave the computer on standby mode for too long, and computers should be completely shut off when the workers leave offices.

5.3.3 Lighting load. Lighting load refers to the total lighting equipment power per area. Similar to the equipment load, replacement of existing florescent tubes (FT) with more energy-efficient FT can contribute to a reduction in lighting load. In practice, most of the existing buildings are still using T8 FTs. A large potential of carbon reduction because of the lighting replacement is expected as T5 FTs are higher than T8 FT in luminous efficacy. As such, each luminaire can be installed with wider distances and less power consumption. With the use of this model, the building owner can estimate the level of carbon emissions reduction when existing T8 FLs are replaced with T5 FLs.

5.3.4 Occupant density. Number of occupants is another parameter contributing the internal heat gains for AC systems. In this paper, occupant density is defined as m^2/person. Owing to the high rent, building owners tend to decrease the occupant density to accommodate more staff in offices. However, studies show that occupant density is closely related to the occupants' health and ultimately affects productivity. Therefore, building owners should pay attention to occupant density when the office is under renovation. In general, the occupancy density for typical offices is 13 m^2/person. When the occupant density is slightly changed from 13 to 15 m^2/person, the carbon emissions will be reduced 0.4 kg CO_2-e/m^2.

In addition, from the perspective of central AC systems, occupant density is one of the important parameters as it strongly relates to the amount of fresh air required to maintain a comfortable indoor environment. When the amount of fresh air required increases, more energy use is needed to cool down to the set point temperature of air-handling system, especially for the subtropics conditions where outdoor air is hot and humid. Therefore, owing to the dominance of energy use for central AC system in the subtropics conditions, the parameters which are more related to energy use in central AC system will be the significant factors affecting building energy use, and this masks the impact of other architectural-related parameters such as window U-values and orientation.

5.4 Other observations from the study

Table II shows the results of standardised regression coefficients for each design parameter of office buildings under the subtropical weather. We have discussed the top five influential design parameters affecting carbon emissions. However, attention should also be drawn on the non-influential design parameters identified in this study. It was found that in comparison with other parameters, the design parameter relating to building envelop, including window U-value, window-to-wall ratio and wall U-value, have limited impact on actual carbon emissions of office buildings. It is suggested that under the subtropical climate, building facade retrofit on existing office buildings may not be the most effective solution to reduce carbon emissions. As a result, more resources should be allocated to the more influential parameters first to effectively reduce the carbon emissions in office buildings, especially for existing office buildings.

In addition, further attention should also be paid on the parameters belonging to passive building design approach, such as "depth of the perimeter zone", "window-to-wall ratio" and "typical floor areas". Although in Table II these passive building design parameters are ranked lower, being less influential to carbon emissions, compared to the E&M-related design parameters, they do contribute towards reducing carbon emissions. They deserve serious consideration from a different perspective as they are the building designs that cannot be easily improved after the completion of the building. If the building life cycle is assumed to be 50 years in a typical office building, the impact on carbon emissions attributed from the passive building design parameters is also very significant. Thus, carbon emissions reduction should not rely on active building designs alone to reduce impact. To build more environmentally sustainable buildings, a balance between passive energy building with architectural aesthetics and active engineering on carbon emissions should be made.

6. Conclusions

The work described in this paper presents the development of a regression model to estimate carbon emissions for office building design at a conceptual stage under the subtropics. The present study considers five parameters of building design, including building configuration, building envelope, design space conditions, building system configuration and occupant behaviour. A regression model was then developed using simulation results to estimate the carbon emissions of an office building at the operational stage. The SRCs were adopted to determine the impact on carbon emission with the respective design parameters. Such information provides valuable carbon-related insight at the early design stage. The results indicate that annual mean occupancy rate, equipment load, occupant density, lighting load and chiller COP are the top five influential design parameters affecting building carbon emissions under the subtropical climate.

In addition, the design parameters of ten real office buildings were used to demonstrate the actual application. It is found that the ranking results are in general consistent with the actual ranking results of those ten office buildings under the subtropical climate. This also suggests that this linear regression model provides a simple and quick estimation of carbon emissions based on the conceptual building design information, which can help explore different design options. Apart from that, the model also enables designers to understand the level of reduction in carbon emissions if certain building design parameters change accordingly, which may incur little cost in the early design stage. It should be noted that the regression model can also be used independently with the full-scale carbon emission simulation model, once created. Although Hong Kong is used as an illustration, the proposed method is not only applicable for the subtropical climate zone. For *EnergyPlus*, most of the weather files, such as the USA and European countries. Singapore, and Australia are available for choice; hence, the same approach can be carried out to develop the simplified regression model accordingly.

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