A MORPHOLOGY-BASED MODEL FOR FORECASTING COOLING ENERGY DEMAND OF CONDOMINIUM BUILDINGS IN SRI LANKA

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Building morphology has significant influence on operational energy demand of buildings. Energy consumption for space cooling accounts for more than 75% of electricity use in typical condominium buildings. With increase in the number of condominiums in Sri Lanka, the requirement for space cooling has increased resulting in significant energy demands. Accordingly, this study developed a morphology-based model for forecasting cooling energy demand of condominiums. The study employed a quantitative approach involving questionnaire survey and document review to collect data from thirty (30) condominiums in Sri Lanka. The correlation analysis performed on the data collected indicates that the number of floors (0.940), building height (0.930), building shape (-0.686), grouping of buildings (-0.647) window-to-wall-ratio (0.597), gross internal floor area (0.489), and wall-to-floor-ratio (-0.457) have significant correlations with the cooling energy demand of condominiums in Sri Lanka. A multiple linear regression model developed shows that the number of floors and window-to-wall-ratio account for 91.2% accuracy of the cooling energy estimation for condominiums in Sri Lanka. Thus, using the developed model, the annual cooling energy demand of a condominium can be forecast, considering significant design factors that could inform decisions at the building design and construction stage to ensure energy efficient designs.

Keywords: building morphology, condominiums, cooling energy, Sri Lanka

INTRODUCTION

The building sector consumes more energy than both industrial and transportation sectors. For example, end-use sector shares of total energy consumption in the US in 2011 shows that the building sector contributed 41% of total energy consumption, with the residential sector dominating by consuming 22% (United States Department of Energy [USDOE] 2012). According to USDOE (2012), the two largest energy using residential sub-sectors are single-family homes and multi-family condominiums. A significant share of electricity consumption is by Heating, Ventilation and Air Conditioning (HVAC) systems and these generally reaches 50-60% in developed countries, and could be up to 70% in Australia (Australian Green Organization [AGO] 1999).

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In Sri Lanka, the building sector has become the dominant end-user of primary energy consumption (Ministry of Power & Energy 2011). The building sector consumes 170.6 quads of energy, which is 46% of the total energy consumption while the industrial sector and transportation sector consume 94.7 quads (25%) and 107.4 quads (29%) respectively. Anecdotal evidences from construction professionals suggest that both government and private sector investments on condominium buildings have significantly increased in recent past. Consequently, the requirements for space cooling energy demand have increased significantly. In Sri Lanka, comparison of the electricity bills and aggregated sub-metering data of buildings for an annual average of electricity end-use breakdown for HVAC system accounts for about 51% (Rajapaksha, Hyde and Rajapaksha 2010).

Given the dramatic increase in energy demand for HVAC of condominiums in Sri Lanka, this research develops a regression model based on principal building morphology data for forecasting cooling energy demand of condominium buildings in Sri Lanka. Since, morphology data of buildings are known at early stages such as construction or acquisition, the developed model could be used to predict the required energy for space cooling in condominiums. With this focus, the study believes such information could help both building owners and contractors to make informed decisions over properties. Further, being the prime factor in running costs of a building, the energy demand for space cooling will indicate the future implications on running costs of condominiums.

LITERATURE REVIEW

Building Morphology Factors and Cooling Energy Demand of Buildings

The drivers of HVAC energy consumption in buildings are many and different in nature. Susorova, Tabibzadeh, Rahman, Clack, and Elnimeiri (2013) indicated that the space cooling energy demand of a building is influenced by internal and external heat gains, although heat gain through building facades contributes more highly to space cooling energy demand. Subsequently, Zangheri *et al*., (2014) explained that three major determinants of cooling energy demand include building geometry, internal gains, and building technologies. Brown, Cox, Staver, and Baer (2014) established the linkages between weather and energy use in buildings, indicating that warmer climate will increase the demand for electricity due to air conditioning but will decrease the end-use demand for natural gas and fuel oil. In another light, Bousquet, Cremel, and Loper (2014) contend that socio-demographic, economic and building characteristics play an important role. In addition, a study by a team at the London School of Economics and Political Science (Rode 2014) indicated eight factors that determine the space cooling energy demand of buildings. These factors are building typology, building density, surface-to-volume-ratio, average building height, surface coverage, insulation, glazing ratio and the climate.

The foregoing review show that building morphology factors play important roles in cooling energy demand determination. In this context, building morphology refers to building characteristics, building structure and design, building geometry, and use intensity drivers. Useful studies in this regard, include those of Catalina, Virgone, and Iordache (2011) that investigated 12 buildings with varying building forms and glazing percentages. Catalina *et al*., (2011) concluded that the impact of building shape is most important in hot climates with higher solar radiation and outdoor temperature values. Further, Alanzi, Seo, and Krarti (2009) analysed several building shapes including rectangular, L-shape, U-shape, and H-shape with different building aspect ratios, Window-to-Wall-Ratios (WWR), and glazing types. The results of a detailed parametric analysis indicate that the effect of building shape on total building energy use depends on primarily three factors: the relative compactness, the WWR and glazing type. For buildings with low WWRs, it is found that the total energy use is inversely proportional to relative compactness independent of its form in severe cold and scarcely sunny winters. Moreover, Ayeb (2016) elaborates that south and north oriented buildings are the most energy efficient building structures in hot and dry climates.

Besides, window area or WWR and Wall-to-Floor-Ratio (WFR) are another two vital factors affecting energy performance of buildings. Yang *et al*., (2015) analysed the variation of annual heating energy demand, annual cooling energy demand, and the annual total energy consumption in different conditions. Yang *et al* (2015) included different orientations, patterns of utilization of air conditioning system, WWR, and types of windows in hot summer and cold winter zones in China and concluded that total energy consumption increased with the increase of WWR. It appears more obvious when the window orientation is east and west. Also, Ayyad (2011) investigated the impact of WFR on the thermal performance of office buildings in Dubai, hot and humid climate and concluded that the higher WFR were responsible for reduced energy consumption.

In another light, Omari (2015) found that heating cost is influenced considerably by the relationship between the area of roof and walls, as roofs are a major element in heat loss. However, the impact of other building morphology factors such as building height, number of floors, Gross Internal Floor Area (GIFA) and grouping of buildings on the cooling energy consumption of buildings are not evident in both international and local context. Therefore, those factors were considered within this study.

Models for Estimation of the Cooling Energy Demand

Literature shows that most of the models, which attempt to predict the cooling energy demand, have employed a statistical data analysis technique called Regression Analysis. For example, Kirkham, Boussabaine, and Grew (1999) applied a regression technique to model the energy cost of sports centres where the floor area and the number of users were used as two independent inputs. Mack and McWilliam (2013) proposed a model that contains eight predictors to calculate the percent change in cooling energy consumption to an accuracy about of 20%. Mack and McWilliam's model is applicable during the running stage of buildings, where there are adequate historical building operational data available. Other models seem less accurate and restricted to a specific life cycle. However, building morphology data are known at the pre-construction stage of a building and therefore, could serve as predictors of cooling energy demand of the building.

Further, the lack of reliable and consistent data make it impossible to establish energy models to predict energy demand for space cooling of condominiums in Sri Lanka at the early stage of buildings. This research, therefore, analyses energy consumption behaviour for space cooling of luxury and high-rise condominiums in Sri Lanka and develops a simplified regression model based on principal building morphology factors for forecasting annual cooling energy demand. With this model, one can forecast the annual cooling energy demand of a condominium and give due considerations to significant design factors to make informed decisions at the building design and construction stage to ensure energy efficient designs.

RESEARCH METHODS

A quantitative approach was employed to develop a morphology-based model for forecasting annual cooling energy demand of condominium buildings in Sri Lanka. A questionnaire survey was administered to collect data related to building morphology factors and annual energy consumption for space cooling. Given the time constraints and limited access to data, a sample of thirty (30) (out of 70) registered luxury residential condominiums with 12 or more floors, constructed after 2010 were selected considering the minimum sample required for a survey design. A sample size between 30 and 500 at 5% confidence level is generally sufficient for many researches (Altunışık, Coşkun, Bayraktaroğlu, and Yıldırım 2004; Borg and Gall 1979). The data was collected from architectural drawings, sub-metering logs, records on annual energy consumption and utility bills. Questionnaire survey participants included professionals who have more than 10 years of experience in condominium operations and maintenance and having extensive knowledge on building morphology and energy consumption patterns in condominiums. A summary profile of survey participants is presented in Table 1.

Table 1: Profile of the survey respondents

Designation	Number of participants		Work experience	Number of participants	
	No.	%		No.	%
Engineers	19	63.3	More than 20 years	8	26.7
Managers	11	36.7	20 - 15 years	7	23.3
			15 - 10 years	15	50
Total	30	100	Total	30	100

As observed from Table 1, majority of the participants (63.3%) are engineers whose designations are: Maintenance Engineer (7), O&M Engineer (5), Chief Engineer (4), Facilities Engineer (1), Mechanical Engineer (1) and Electrical Engineer (1). Rest of the participants are managers including Maintenance Managers (5), Facilities Managers (4) and Operations Managers (2).

For data analysis, basic descriptive, correlation and multiple linear regression analyses were employed in the study. Firstly, the set of significant morphology factors, which cause changes in cooling energy demand of condominiums were identified using Pearson correlation coefficient statistics. Seven out of nine morphology factors, which significantly correlated with the average annual cooling energy demand were forwarded for further analysis, based on the significance of correlation. Correlation strength determination followed suggestions by Ricciardy and Buratti (2015). Accordingly, correlation coefficient 'R' is $0 < |R| < 0.3$ - weak correlation;
$0.3 < |R| < 0.7$ - moderate correlation; and $|R| > 0.7$ - strong correlation respectively.

Later, a model for forecasting cooling energy demand of condominiums in Sri Lanka is developed using a stepwise multiple linear regression analysis. In regression analysis, there are several criteria to be tested to select the best-fit model. Initially, the effect of multicollinearity should be checked. Although there is no formal criterion for determining the bottom line of the tolerance value or Variation Impact Factor (VIF), Chatterjee and Hadi (2012) suggest that a tolerance value of less than 0.1 or VIF greater than 10 generally indicates a significant multicollinearity. Besides, the commonly used measure of the goodness of fit of a linear model is R2 (the coefficient of determination) which ranges between 0 and -1. However, in multiple linear regression modelling, the best model is defined by its highest adjusted R2, as it is more accurate than R2.

DATA ANALYSIS AND FINDINGS

The Relationship between Building Morphology Factors and the Cooling Energy Demand of Condominium Buildings

In order to identify significant set of building morphology factors, building morphology details of the 30 condominiums were correlated with the average annual cooling energy demand using the SPSS Statistics 19.0. The result of the correlation analysis is shown in Table 2. The table depicts the Pearson correlation (R), the coefficient of determination (R2) and the significance of building morphology factors with respect to the annual cooling energy demand of condominiums in Sri Lanka.

Table 2: Correlations of average annual cooling energy consumption and building morphology factors

Building morphology factor	Average annual cooling energy consumption		
	R	R2	Sig. (2-tailed)
Area of roof	-0.180	3%	0.341
Orientation	0.319	10%	0.085
WFR	-0.457*	20%	0.011
WWR	0.489**	24%	0.006
GIFA	0.597**	36%	0.000
Grouping of buildings	-0.647**	42%	0.000
Building shape	-0.686**	47%	0.000
Building height	0.930**	86%	0.000
No. of floors	0.940**	88%	0.000

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

As observed from Table 2, based on Pearson correlation coefficients and the significance of correlations at 5% and 1% significant levels, seven out of nine factors resulted in significant correlation values. The factors include the number of floors, building height, building shape, the grouping of buildings, WWR, GIFA, and WFR. Amongst, all correlations except WFR are significant at the 0.01 level. Although building orientation did not result in a significant correlation, it has moderate and positive correlation with the cooling energy demand (0.319) while having 10% impact. Weak and a negative correlation is shown by the area of roof (-0.180). Factors having significant correlations are discussed in more detail below.

Correlations with cooling energy demand: Number of floors and building height

As observed from Table 2, the number of floors (0.940; 88%) and building height (0.930; 86%) have strong positive relationship with cooling energy demand. This indicates that cooling energy demand will increase with increase in number of floors and building height. Building height would most definitely increase in proportion with number of floors. Thus, once the number of floors increases, energy demand for space cooling of condominiums increases due to the increase of occupancy, appliance used and building volume. Further, it is obvious that the space required to condition will be increased with the increase of building height, therefore, resulting in growing cooling energy demand. Moreover, the increased wall area caused by increased height generates extra heat gain from environment. For number of floors, the coefficient of determination is 0.88, which means that 88% of the variation in mean cooling energy demand can be predicted from the relationship between number of floors and cooling energy consumption. Similarly, 86% of cooling energy, demanded by a condominium building depend on the building height while 14% depending on the other factors.

Correlations with cooling energy demand: WWR and GIFA

Both WWR (0.597; 36%) and GIFA (0.489; 24%) have positive and moderate relationship with the cooling energy demand of condominiums. It indicates that the energy consumption for space cooling increases with the increase of WWR and GIFA. High WWR can be resulted when the net glazing/window area becomes larger than the gross exterior wall area. Thus, wide glazing areas increase the external heat gain and lead to excessive cooling energy demand. Furthermore, the correlation analysis shows that the WWR is positively correlated with the height of the building (0.455) and number of floors (0.458). The coefficient of determination calculated indicates that the WWR determines 36% of the mean cooling energy demand of condominiums. Similarly, the increased GIFA will lead to more occupancy, excessive usage of heat emitting appliances and additional building volume to be conditioned. With the increase of aforementioned factors, the space cooling energy demand is definite to increase. Nevertheless, 24% of coefficient of determination resulted by GIFA indicates that building size is not the only factor which influences the energy demand of space cooling.

Correlations with cooling energy demand: Building shape, grouping of buildings and WFR

Contrary to number of floors, building height, WWR, and GIFA, correlations of building shape (-0.686; 47%), grouping of buildings (-0.647; 42%) and WFR (-0.457; 20%) with the cooling energy demand are negative. In addition, all negative correlations have moderate impact on the cooling energy demand. Here, building shape is considered as irregular and regular shapes with values 0 and 1 respectively. The resulting negative correlation indicates that where the shape is regular, the consumption of cooling energy is reduced as it generates less external heat compared to irregular configuration, which has same building volume. However, building shape is not the only parameter, which determines the cooling energy demand of a condominium in tropical climates as it has only 47% of coefficient of determination. Besides, when grouping of building exits, the energy demand for space cooling may decrease due to covering effects. However, when a building is located separately, there will be an increase in energy consumption for space cooling. Only 42% of the mean value of cooling energy demand could be explained by this parameter. Finally, when there is a high WFR, the cooling energy demand of that particular condominium would decrease. In order to result in high WFR, the external wall area of a building should be greater than its GIFA. Correlation value obtained for GIFA also indicates that little GIFA consume low energy for space cooling, as it offers space for limited number of occupants and limits the number of appliances used within the area. However, the coefficient of determination of WFR is 20%, which means 80% of the mean value of cooling energy demand of condominiums in tropics will be determined by other factors.

These seven significantly correlated building morphology factors were forwarded for regression analysis, and the results are described in the following section.

A Morphology-Based Model for Forecasting Annual Cooling Energy Demand

Initially, the regression model was fixed with the seven independent variables: number of floors, building height, building shape, the grouping of buildings, WWR, GIFA, and WFR using a stepwise method. Stepwise regression process systematically adds the most significant variable or removes the least significant variable during each step by eliminating correlations between independent variables, which can reduce the model accuracy. Accordingly, the regression analysis offered two models and Table 3 represents the coefficients and collinearity statistics of the two regression models.

Table 3: Coefficients of the Regression Model

Model		Unstandardized Coefficients		Standardized Coefficients	Collinearity Statistics	
		B	Std. Error	Beta	Tolerance	VIF
1	(Constant)	-34732.863	45087.186			
	No. of floors	21356.009	1470.347	0.940	1.000	1.000
2	(Constant)	-194913.837	60759.881			
	No. of floors	19160.987	1409.023	0.843	0.790	1.265
	WWR	4339.533	1275.393	0.211	0.790	1.265

a. Dependent Variable: Average annual cooling energy consumption

The collinearity statistics in Table 3 show that the tolerances are large and the VIF is considerably low. As mentioned in research methods, both the models 1 and 2 are considered for non-existence of multicollinearity. Table 4 provides the summary of the two models for forecasting the cooling energy demand of condominiums in tropics. Accordingly, the second model, which yields the highest adjusted R2, was selected as the best model and goodness of fit of the model is 91.2%.

Table 4: Summary of Model

Model	R	R2	Adjusted R2	Std. Error of the Estimate	Change Statistics		
					R2 Change	F Change	Sig. F Change
1	0.940a	0.883	0.879	69268.28675	0.883	210.960	0.000
2	0.958b	0.918	0.912	59013.17120	0.035	11.577	0.002

b. Predictors: (Constant), No. of floors

c. Predictors: (Constant), No. of floors, Window-to-Wall-Ratio

d. Dependent Variable: Average annual cooling energy consumption

Based on these statistics, the annual cooling energy demand of condominium buildings in tropical climates could be expressed by:

Cooling energy demand (Kwh/y) = -194913.837 + 19160.987 (Number of floors)
+ 4339.533 (WWR)

This developed model consists of two independent variables: number of floors and WWR. Thus, the cooling energy demand can be forecasted if the proposed number of floors and the WWR can be determined at the early stages of condominiums located in tropics.

DISCUSSION

Unlike previous studies, which revealed altogether five morphology factors influencing the cooling energy demand of buildings in both hot and cold climates, the current study provides an extensive set of seven variables. The cooling energy demand is significantly influenced by number of floors (0.940, 88%), building height (0.930, 86%), building shape (-0.686, 47%), grouping of buildings (-0.647, 42%), WWR (0.597, 36%), GIFA (0.489, 24%), and WFR (-0.457, 20%).

Similar to Catalina *et al*., (2011), the current study found that building shape has a significant impact on cooling energy demand, reasoning that regular building configurations are more energy efficient compared to irregular building forms. Further, this study confirms the findings of Ayeb (2016) and Yang *et al*., (2015) who studied hot and dry climate, and hot summer and cold winter zones in China, respectively by concluding that buildings, which have long south and north axis, result in a reduction in energy consumption compared to east and west oriented buildings. Moreover, similar to Yang *et al*., (2015), the current study found that buildings with high WWR are more likely to experience high-energy demand and that would further increase with having east and west oriented window area. In addition, buildings with high WFR would result in low energy consumption for space cooling of condominium buildings. This result confirms previously held conclusions of Ayyad (2011) for office buildings in Dubai, which is a hot and humid climate.

The current study further determined the following vital relationships between building morphology and cooling energy demand. That a positive and strong correlation found between number of floors, building height and GIFA with the cooling energy demand of condominiums in tropics, indicates that cooling energy demand increases with increase in aforementioned variables. This could be due to the growing internal heat gain (i.e. by increased occupancy and usage of heat emitting appliances) and external heat gain (i.e. additional heat gain from the building façade). Further, where grouping of building exists; cooling energy demand for condominiums reduces due to their covering effects.

In terms of significance, only seven out of the analysed nine factors, resulted in significant correlation. Building orientation (0.319) and area of roof were the two exceptions. The impact of orientation on cooling energy demand could be mitigated by the covering effects caused by the grouping of buildings; therefore, this did not determined as a factor, which has a significant impact on cooling energy demand. Then, the area of roof resulted in a minimum correlation value (-0.180). Since roofs are a major heat gain element, most buildings in hot and tropical climate ensure buildings' thermal comfort through insulation. With that note, most of the buildings included to the research sample are roof insulated; therefore, the impact of roof area on cooling energy demand has been mitigated.

Unlike previous studies: Bousquet *et al*., (2014) and Mack and McWilliam (2013), the developed model in the current study is based on only two simple predictors: number of floors and WWR, which are frequently known at the pre-construction stages of buildings. The goodness of fit of the model is over 91%, indicating that this model could predict over 91% of the mean value of cooling energy demand of condominiums in tropics. Further, the mean value of accuracy of the developed model for forecasting cooling energy demand of condominiums in Sri Lanka is much improved compared to the mean value of accuracy (20%) reported by Mack and McWilliam (2013) in their cooling energy consumption by the climate model.

CONCLUSIONS

In this study, a correlation analysis was initially performed to identify significantly correlated morphology factors with cooling energy demand and thereby developed a regression model for forecasting cooling energy demand of condominiums in Sri Lanka. It is concluded that number of floors, building height, building shape, grouping of buildings, GIFA, WWR, and WFR have significant effects upon the cooling energy demand of condominiums. Except for building shape and grouping of buildings, increase of other variables result in increase of cooling energy demand. Results further highlight that regular building configurations (i.e. square, rectangular circle) and having grouping of buildings consume less energy for space cooling of condominiums in a tropical climate.

The main finding of the study is the morphology-based model for the estimation of cooling energy demand of condominiums in Sri Lanka. The developed model shows over 91% accuracy on the estimation of cooling energy demand. This model is based on two principal morphology factors: number of floors and WWR. The selected independent variables are positively contributing to the cooling energy demand. Therefore, energy demand for space cooling of condominium buildings can be predicted to make informed decisions at the early stages of buildings' life cycle. This would have implications on the operational costs and the running costs of residential condominiums.

It is hoped that these findings would provide useful knowledge towards energy efficient building designs. Building morphology factors could then be appropriately varied for condominium buildings in line with passive energy conservation strategies, consequently reducing cooling energy consumption in Sri Lanka. Finally, the study recommends that the model developed in this study, to be validated in other tropical climates.

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