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Topic B8. Simulations and real energy consumption

Model Development and Comparison for the Evaluation of the Energy Performance of Three Tertiary Institutional Buildings in Singapore

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SUMMARY

This study presents an investigation and discussion on the energy performance of three tertiary institutional buildings in Singapore. Building information, energy consumption data of the air-conditioning system, and energy consumption data of the plug loads were collected separately. MATLAB identification models are developed to simulate the real daily energy consumption data:. Three functions are introduced to represent the function of daily occupancy, function of additional occupancy due to visitors and the function of outdoor air temperature. The results show that the predicted value follows the trend of real energy consumption value very well and can predict the daily variations. The newly developed methodology is able to simulate the daily variations of energy consumption. R^2 of 0.54, 0.66 and 0.63 can be achieved for the three buildings respectively.

INTRODUCTION

It is reported that for tropical countries like Singapore, buildings account for about 31% of the total electricity (Energy Efficiency Program Office, 2005). Similar data was found in other tropical countries, where 24.2% of energy consumed by building sector in Thailand (Energy policy and planning office, 2010), and 34% in Malaysia (United Nation development program, 2006). The mechanical air-conditioning system in buildings typically comprises up to 30 - 60% of the total energy consumption (Mathews et al., 2001; Lam et al., 2003, Chua et al., 2013). In US, 40% primary energy use was accounted by buildings.30% of the energy used in building is consumed by HVAC system. Therefore, study of building energy performance and identification of factors that influencing building energy consumption is significant economically and environmentally. Among the researches and studies involving strategies used to improve building energy audit, control and operation, building energy model is a very critical component. There are three categorizes for existing building energy model: white box (physics-based) models, black box (data-driven) models and grey box (hybrid) models. This study uses the data-driven model method to investigate three institutional buildings in Singapore.
The rooms of the three buildings A, B and C are mainly offices, lecture rooms, labs, studios, etc. Buildings A and C have five stores while building B only have three floors. Most of the lecture rooms and seminar rooms are in building C.

METHODS

Data Collection

Energy data for these three institute building is obtained over one year (year 2013). The data is divided into Air-conditioning and Non Air-conditioning loads (Plug-load). The data is available daily for 365 days.

Outdoor climatic condition data is also obtained. Average daily outdoor temperature, relatively humidity ratio and radiation are available every one hour for each day. In order to be consistent with the building energy consumption data, average value are taken from 7am to 6pm.

Data preprocess

First, the whole year air-conditioning energy consumption data is plotted as shown in figure 1. The maximum, minimum and average value is marked and shown. The figures show that the variation of energy consumption of C is much larger than A and B.

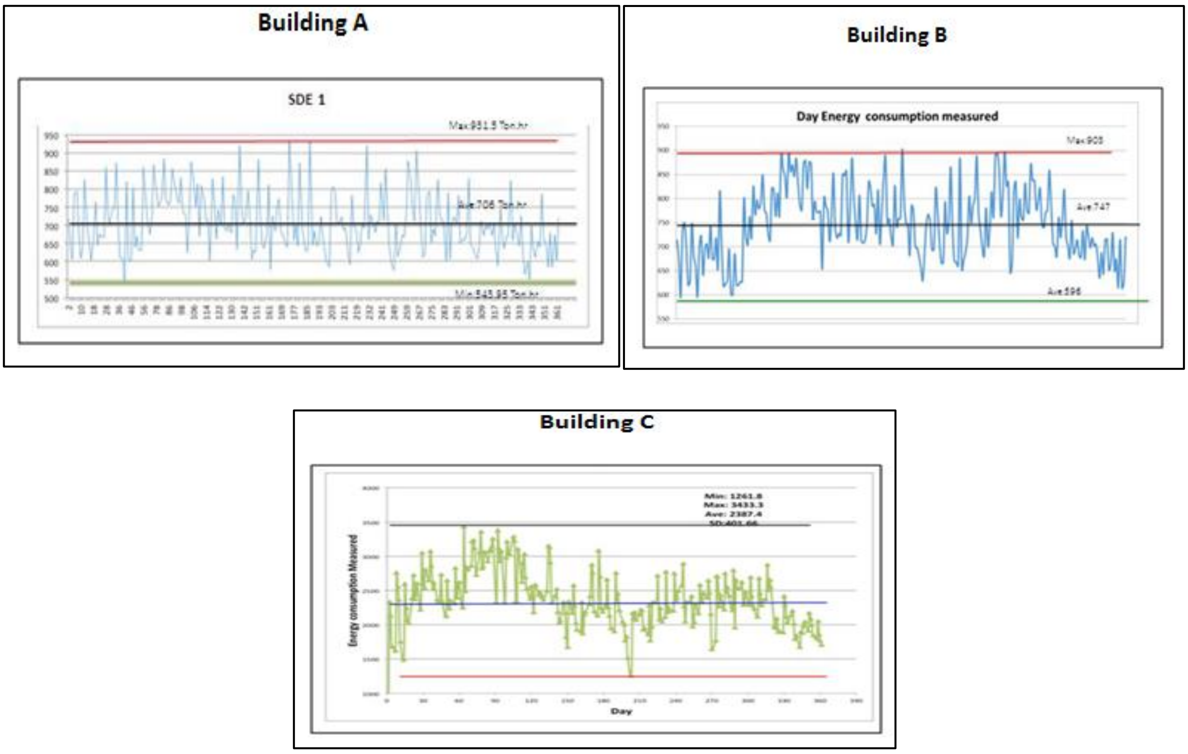


Figure 1. Whole year air-conditioning energy consumption data for the three buildings

Under Data preliminary analytics, the air-conditioning consumption energy data is initially correlated with the three climatic variables as listed in table 1. The results show the air-conditioning energy consumption has very low correlation with climatic data, especially the relative humidity and radiation.

Table 1. Correlation of the HVAC energy consumption data and three climatic variables

R2	Outdoor Temperature	Relative Humidity	Radiation
Building A	0.26	0.1	0.19
Building B	0.3	0.01	0.02
Building C	0.1	0.02	0

Methodologies

For each of the building, we have the energy consumption data from HVAC system and the energy consumption data from the plug load system. If we take N as the number of occupancy for a day, for the energy consumption data from HVAC system Qhvac, there is a parameter(b) related to the presence of number of occupancy and another parameter(a) independent of the occupancy, as expressed as equation 1. Similarly, for plug load, c is assumed to be the occupancy dependent parameter while d is assumed to be the independent parameter as shown in equation 2.

$$Qhvac=a+Nb \tag{1}$$

$$Qplug=cN+d \tag{2}$$

Hence, Qhvac and Qplug are interrelated by the occupancy number N and Qhvac can be expressed as equation 3.

$$Qhvac=a+(Qplug-d)b/c \tag{3}$$

Therefore, MATLAB system identification toolbox can be used to estimate the functions which can predict the energy consumption.

RESULTS

Model 1

Non-parametric model called time domain is used to build the inputs and outputs. As expressed in equation 13, plug load is used as input and hvac load is used as output. Because the identification model uses past input values to calculate the next output values, the less the past values the less the accuracy, the first 80 data predicted by the model would have a lower accuracy. In order to predict the whole year energy consumption value with a higher accuracy, a data set with a series of data starting from September using 16 months' data is created. It includes all values from September, October, November, and December and followed by the whole year from January to December. The data of the first four months, (September to December), are used to stabilize the identification model 1 and improve its convergence.

Transfer function is used to estimate the model. After having tried different numbers of poles and zeros, the 'best fit' model is chosen as function f1 of equation 4 to estimate the HVAC load.

$$Qhvac(i)=\Sigma f1(i)Qplug\ (i) \tag{4}$$

Although outputs for the 16 months are calculated, the results for the first four training months are erased (September to December). Figure 2 shows the predicted value by model 1 and the measured value with the data of a complete year between January to December for the three buildings. It is found the R^2 are 0.14, 0.25 and 0.44 for building A,B and C respectively.

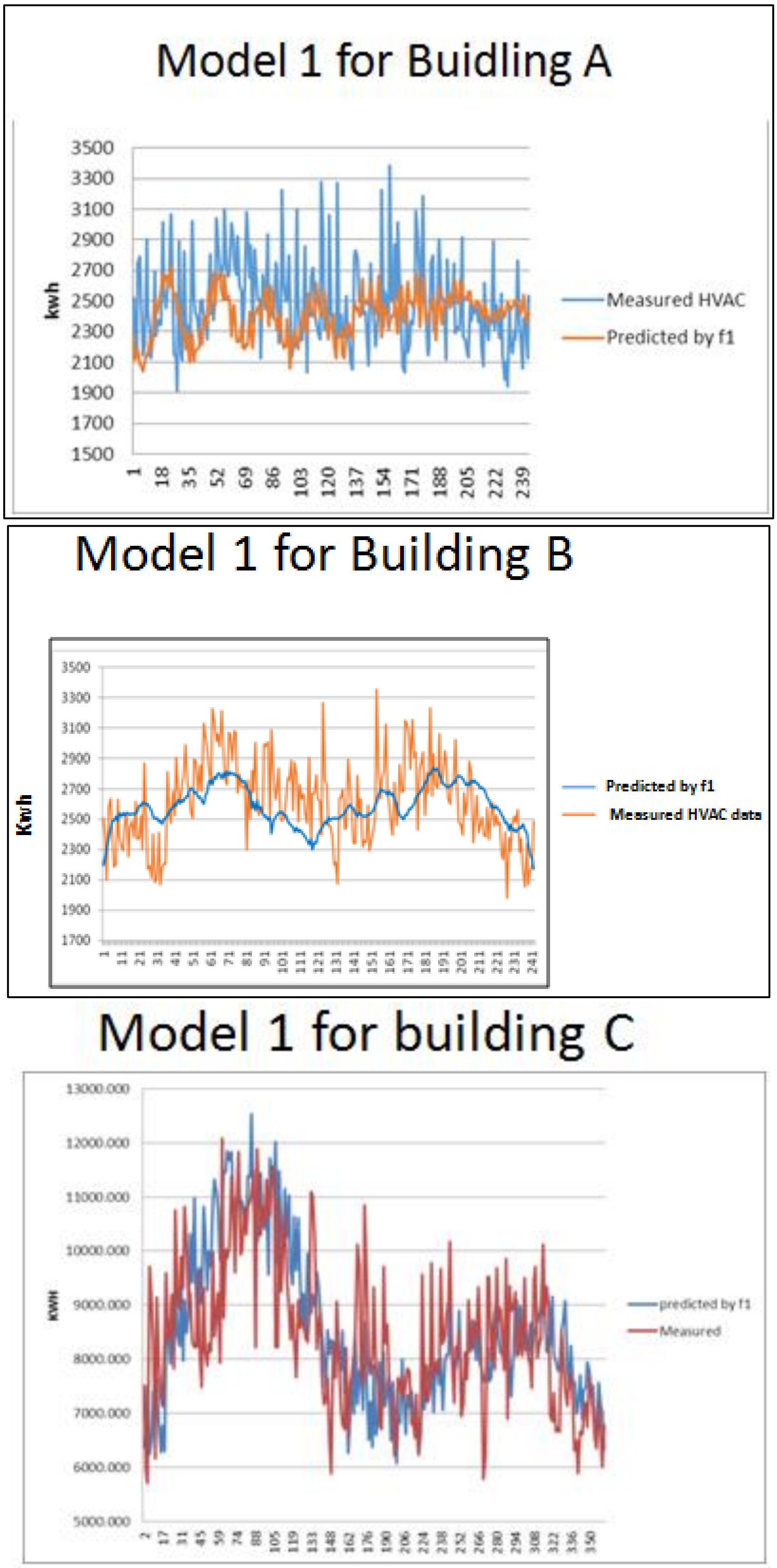


Figure 2. Comparison of predicted value by model 1 and the measured value

Model 2

Model 1 consider the daily permanent occupancy number as an interrelated factor between plug load and hvac load. However, in real situation, there are additional visitors which contributes to the hvac load but not to the plug load. In order to take account of the influence of additional occupancy such as visitors on hvac energy consumption, equation 5 and equation 6 are developed to interrelate the plug load and hvac load. Hence, the MATLAB single input single output can be applied by using ΔQL(i) as inputs and ΔQhvac (i) as outputs. Transfer function is used to estimate f2 in equation 7

$$\Delta Qhvac(i) = Qhvacmeasured(i) - Qhvac(i) \text{ (Qhvac (i) as predicted by Model 1)} \quad (5)$$

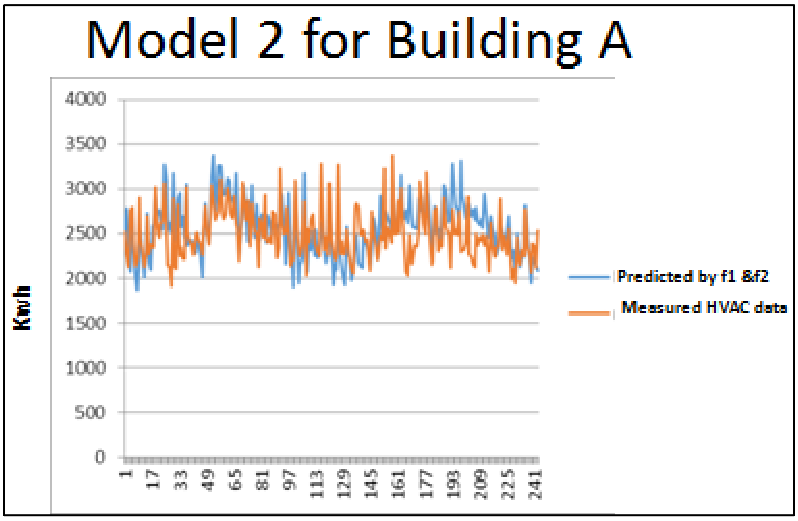
$$\Delta QL(i) = Qhvacmeasured(i) - Qplugmeasured(i) \quad (6)$$

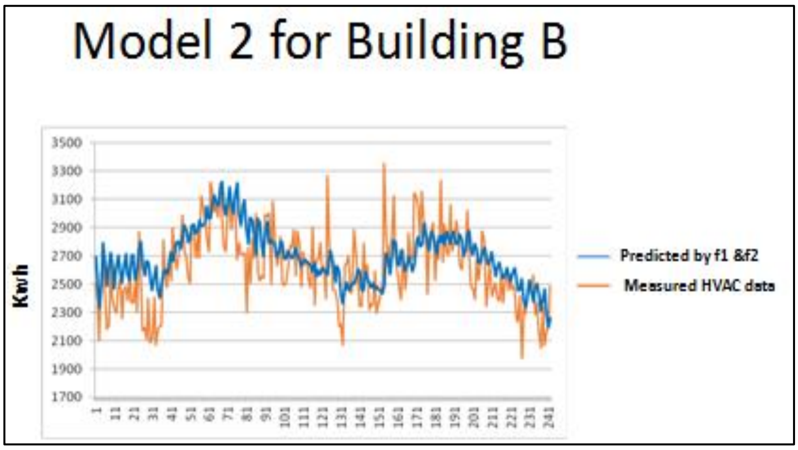
$$\Delta Qhvac(i) = \Sigma\, f2(i)\, \Delta QL(i) \quad (7)$$

Although 16 months data is available, the first 30 sets of data estimated by f1 and model 1 has a quite low accuracy. Therefore, 15 months data starting from October are used in model 2. Again, the first 3 month's data is just used for stabilizing and getting convergence. Then the predicted hvac energy consumption can be get through equation 8.

$$Qmodel2(i) = Qhvac(i) + \Delta Qhvac(i) \quad (8)$$

Comparison of the predicted results and the measured results is shown as figure 3.The R^2 are 0.35, 0.46 and 0.49 for building A,B and C respectively.





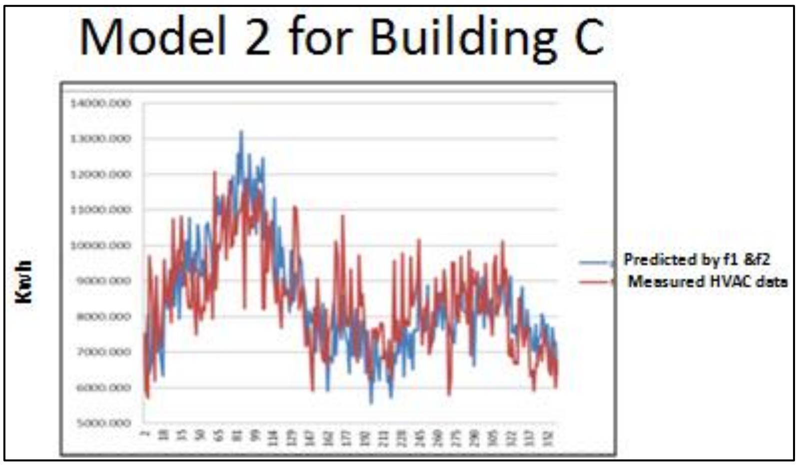


Figure 3. Comparison of predicted value by model 2 and the measured value

Model 3

The second model follows the trend of measured data much better but still cannot predict the peak value. This happens because the two identification models do not consider the impact of the variation of the outdoor temperature. In fact, there is a variability of the measured QHVAC as a function of the ambient temperature as shown in table 1. This function is represented by the following equation 9

$$\text{Qhvacmeasured (i)} = \beta \, T_{out} - \mu \qquad (9)$$

Different building will have a different β value. Considering that Indoor temperature remains the same during the whole year, then, we introduce a temperature correction term, Qtempcrct , which is expressed in equation 10.

$$\text{Qtempcrct (i)} = \beta \, (T_{ouy}(i) - T_{aveout}) \qquad (10)$$

Therefore, equation 11 can represent the final model which includes three models. Figure 4 shows that the identification model follows the trend of the energy consumption and also predicts most of the peaks. The R^2 of final identification models are 0.54, 0.66 and 0.63 for building A,B,C respectively.

$$\text{Qhvacfinal(i)} = \text{Qhvac(i)} + \text{DQhvac (i)} + \text{Qtempcrct(i)} \qquad (11)$$

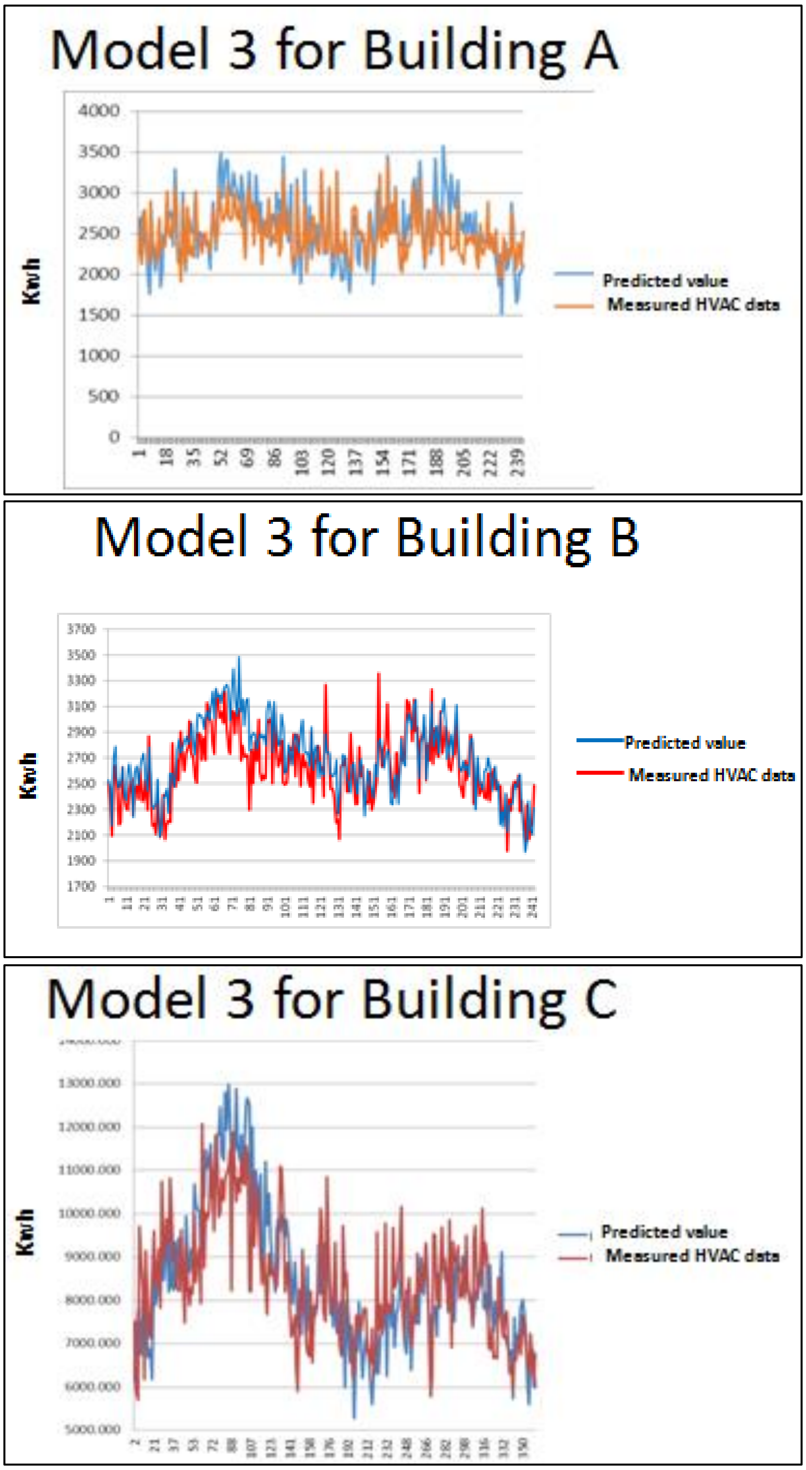


Figure 4. Comparison of predicted value by final identification model and the measured value

DISCUSSION

For Model 1, it is found the predicted value follows the trend of the measured value. R^2 of 0.14, 0.25 and 0.44 is achieved for this model. Since it considers the daily permanent occupancy, the results shows the daily occupancy dominant building C energy consumption more than buildings A and B, which agrees with the factor that building C consists of most of the lecture rooms and seminar rooms with much more occupancy.

With model 2, it is found that the predicted value is of much higher accuracy than that from model 1. It is able to predict quite satisfactory the trend of the energy consumption but cannot predict the peaks because the increase of the Qhvac caused by the additional occupancy is much higher that the corresponding increase of the Qplug. The R^2 of 0.35, 0.46 and 0.49 were achieved. The improvement of R^2 is 0.21 for building A and B but only 0.02 for C. This is because building A and C are mainly executive offices or staff offices. There will be much more additional occupancy as visitors coming to two buildings.

Although the model 2 follows very closely the trend of the experimental values of QHVAC however it still cannot predict the peaks. In model 3, by considering the daily outdoor temperature, the predicted value follows the trend of the energy consumption and also predicts most of the peaks. In model 3, instead of using smooth trend line in most of researches, the variation from day to day is achieved for energy consumption simulation.

CONCLUSIONS

This study presents an investigation and discussion on a newly developed methodology to simulate daily energy performance of three tertiary institutional buildings in Singapore. Building information, energy consumption data of the air-conditioning system, and energy consumption data of the plug loads were collected separately. Three models are developed to simulate the real energy consumption data. Critical factors for energy consumption were identified as daily permanent occupancy number, additional occupancy number and the outdoor temperature. Daily variation of energy consumption was achieved which can contributes to a more micro energy simulation field. R^2 of 0.54, 0.66 and 0.63 can be achieved for the three buildings respectively.

The significance of this developed model is to use simple and less parameters, which is only function of occupancy and outdoor temperature to get a daily variation of energy consumption instead of traditional smooth trend. The model may only work for institutional building with highly variation of daily occupancies.

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