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Application of Design Experiments to Evaluate the Effectiveness of Climate Factors on Energy Saving in Green Residential Buildings

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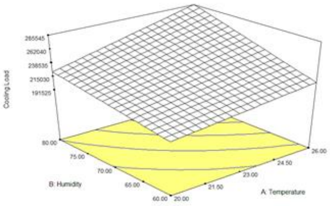
Graphical abstract



Abstract

Green building and energy consumption are two important issues in the construction industry. Residential buildings use the biggest share of energy throughout the world. Based on investigations, most of the existing green buildings are not really energy efficient. The estimation of energy consumptions for building has become a critical approach to achieve the goals on energy consumption and to decrease emissions. There are multiple factors for energy performance of buildings, such as building characteristics, main elements and equipment, climate factors, occupants and sociological influences. This paper shows a study of energy saving enhancement methods in residential buildings by considering the three climate factors that are temperature, humidity and airflow. To achieve this goal, building simulation and classical Design of Experiment (DOE) were combined to assess the effect of these climate factors on energy saving and cooling load. Based on the ANOVA test analysis, temperature and humidity have the most significant effect on energy saving. Moreover, the optimum saving energy within the range of the model with the value of 191525 is gained at the A (temperature) and B (humidity), which are equal to 20 °C and 60%, respectively.

Keywords: Green residential building; energy saving; building simulation; design of experiment; climate factors

Abstrak

Bangunan hijau dan penggunaan tenaga adalah dua isu yang penting dalam industri pembinaan. Bangunan perumahan menggunakan jumlah tenaga yang terbesar di seluruh dunia. Berdasarkan siasatan, kebanyakkan banguna hijau yang sediaada adalah tidak efisien-tenaga. Anggaran penggunaan tenaga untuk bangunan telah menjadi penujuan yang kritikal untuk mencapai matlamat dalam penggunaan tenaga dan pengurangan pelepasan. Terdapat pelbagai faktor untuk pencapaian tenaga oleh bangunan-bangunan seperti cirri-cirinya, unsur dan kelengkapan utama, faktor cuaca, penduduk dan pengaruh sosiologi. Kertas kerja ini menunjukkan satu kajian dalam kaedah-kaedah untuk menaikkan penjimatan tenaga di bangunan perumahan dengan mengambil kira tiga faktor cuaca, iaitu suhu, kelengasan dan aliran udara. Untuk mencapai matlamat ini, simulasi bangunan dan 'Design of Experiment' (DOE) klasik telah digabungkan untuk menilai kesan-kesan oleh faktor-faktor cuaca ini dalam penjimatan tenaga dan mutan penyejukkan. Berdasarkan ujian analisis ANOVA, suhu dan kelengasan mempunyai kesan yang paling penting dalam penjimatan tenaga. Tambahan lagi, penjimatan tenaga yang optimum dalam julat model yang bernila 191525 yang didapati dari A (suhu) dan B (kelengasan) adalah 20 °C dan 60%.

Kata kunci: Bangunan perumahan hijau; penjimatan tenaga; simulasi bangunan, faktor cuaca

■1.0 INTRODUCTION

Green building is one of the controversial issues in the construction industry. Construction managers usually will try to implement green building to decrease energy consumption in the buildings [1-2]. The design, operation and construction of the building have been tried to be carried out in a resource-effective way [3-5]. Based on investigations, most of the existing green buildings are not energy efficient [6-7]. Turner and Frankel (2008) claimed that 20 to 34% of these buildings used more energy than their traditional counterparts [8]. Therefore, construction management plays a leading role in achieving energy efficiency performance.

On the other hand, there is a global concern due to a probable lack of energy in the near future, as well as some environmental effects such as global warming. One of the most cost-effective measures to minimize carbon dioxide emission is to improve the energy efficiency of buildings [9]. Hence, energy efficiency is the key factor that should be considered as an effective solution [10]. Some investigations have been carried out to improve the energy efficiency in buildings in different countries. One investigation was done in Saudi Arabia to examine the energy consumption of a five storey office building by considering the hot and humid climate factors. Based on the results, it was shown that increasing the thickness of insulation did not have any important effect on the energy efficiency [11].

Another research was conducted in Singapore using thermal analysis software (TAS) to evaluate the effect of some microclimatic criteria on minimization of the heat as well as to assess the climate control in residential buildings that are ventilated naturally [12]. The effect of three factors was examined in Saudi Arabia to improve the thermal comfort and energy consumption [13]. In another study, the influence of main elements of buildings such as roof, wall and floor materials was investigated based on the cooling load. The results of this study showed that light-weight wall helped to save 16% in cooling load. Moreover, applying concrete roof tiles with white painted steel can improve the cooling load by 5.8%. In addition, climate factors should also be considered in the design of an energy efficient building in tropical areas [14]. Shakouri *et al.* [15] claimed that by applying different energy rating systems, a comprehensive analysis can be conducted to compare the details of roofs, walls, window, floors and ceiling based on energy usage. Perez and Capeluto [16] reported that climate factors such as temperature, humidity and airflow should be accounted appropriately to design energy efficient school building in tropical climates. In another investigation, the saving of electricity energy was evaluated by considering temperature's effect on the building and to increase the efficiency of air conditions [17]. They used linear matrix inequalities (LMI) based on a linear quadratic regulator (LQR) with a mixed H2 and H1 control algorithm. Zhang *et al.* [18] concentrated on the climate factors of temperature and humidity independent control (THIC) system in China. THIC air conditioning can improve the conservation of energy in buildings as compared to conventional systems. Computer simulation is also a useful method to analyse the different systems such as manufacturing system, construction process and energy analysis [19]. Energy Plus is an extensive and complete simulation environment for transient simulation of systems, including multi-zone buildings. Furthermore, some statistical software has been commonly used to analyse the variations in order to find the most appropriate combination of building elements [20].

Therefore, in this paper the effect of three climate factors; temperature, humidity and airflow, on the cooling load was evaluated by using building simulation and classical DOE to design green buildings as well as to reduce energy consumption.

■2.0 MATERIALS AND METHODS

2.1 Building Simulation

One residential building was simulated in a tropical climate as the case study. The total building area was 600 m^2. Software like Energy Plus, Transys and Ecotect for energy analysis and Revit Architecture for simulation has been designed in order to facilitate energy analysis and material simulation [21]. Energy Plus is an extensive and complete simulation environment that has been applied to simulate the building in this paper.

2.2 Design of Experiments (DOE)

DOE approach was developed for the model fitting of physical experiments as well as to apply for numerical experiments. The goal of DOE is the choice of points where the response should be assessed. Most of the criteria in finding the optimal design of experiments are collaborated with the mathematical model of the process. DOE is known as an experiment or series of experiments that are done through changing the input process variables, which may have an effect on the output responses. This technique can also help planners to specify the variables with the most considerable influence on response. Indeed, experimental design methods are considered practical tools that can improve the processes. In addition, DOE can provide a full insight into the interactions between certain factors that can influence responses or output [22]. In order to implement DOE, the following steps were followed [23]:

- ✓ Choosing the factors and their levels
- ✓ Choosing a response variable
- ✓ Choice of experimental design
- ✓ Performing experiment
- ✓ Data analysis
- ✓ Conclusions and recommendations

2.2.1 Choosing Factors, Levels and Response Variable

In this paper three climate factors were chosen to examine their effects on energy saving in the selected case. The variation range or level of factors is indicated in Table 1. Each factor has a high (+) and low (-) level.

Table 1 Climate factors and their levels

FACTOR	LEVEL		
	-1	0	1
Temperature	20	23	26
Humidity	60	70	80
Airflow	1	2	3

Moreover, cooling load was considered as a response variable. For the choice of experimental design, due to the small number of factors being investigated, full factorial design was used. In factorial design, all possible combinations of factors are considered in an experiment, which was replicated two times. In addition, three center pints were considered to assess the curvature of experiment, used to determine whether the proposed model is linear or quadratic.

■3.0 RESULTS AND DISCUSSION

3.1 Results of Simulation Experiment

Due to the small number of factors, the full factorial design has been applied in this paper to design the experiments. Based on the three factors and full factorial experiment, the number of experiments is equal to: 23 * 2(replicates) + (3 center points) = 19. Table 2 shows the results of 19 experiments that were run using the simulation software.

Table 2 Results of building simulation experiment

Run Order	Temperature	Humidity	Air flow	Response (Cooling load)	
				Replicate 1	Replicate 2
1	20	60	1	200150	199400
2	20	80	3	219450	225300
3	20	80	1	213050	235780
4	26	80	3	287150	278358
5	20	60	3	182200	184350
6	26	80	1	289450	287220
7	26	60	1	224140	188250
8	26	60	3	223470	235480
9	23	70	2	234500 245400	239850

3.2 Data Analysis

In order to analyze the data shown in Table 2, a statistical computer package is required. In this study Expert-Design 6 software was used. Table 3 shows the results of analysis of variance (ANOVA) for identifying significant factors. Decisions about the significance of a factor or effect are made based on the P-value. If the P-value of a factor or effect is less than 0.05, it is considered as significant [22].

The Model F-value of 45.67 implies that the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A (temperature), B (Humidity) and AB two way interactions are significant model terms (Figure 1). Values greater than 0.1000 indicate that the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

The "Curvature F-value" of 1.95 implies that the curvature (measured by the difference between the average of the center points and the average of the factorial points) in the design space is not significantly relative to the noise. Therefore it can be concluded that the proposed model is a linear model. There is an 18.48% chance that a "Curvature F-value" this large could occur due to noise.

The "Lack of Fit F-value" of 1.94 implies the Lack of Fit is not significantly relative to the pure error. There is an 18.02% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good as we want the model to fit. The "Pred R-Squared" of 0.8359 is in reasonable agreement with the "Adj R-Squared" of 0.8874. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 15.552 indicates an adequate signal. This model can be used to navigate the design space.

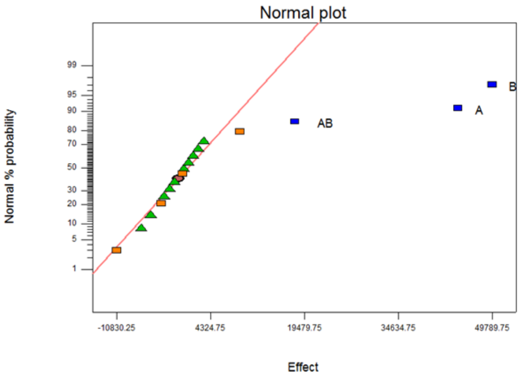


Figure 1 Normal plot

3.3 First Order Regression Model

Table 3 shows that the curvature is not significant, therefore the proposed model is linear. Based on the significant factors and coefficient of each factor (Table 4), first order regression model is proposed :

$$Y = B_0 + \sum_{i=1}^{n} B_i X_i + \sum_{i=1}^{n} B_{ij} X_i X_j \qquad (1)$$

Cooling Load = +2.296E+005 + 22114.87 * A+ 24894.87 * B + 8959.88 * A * B

Following that, the proposed model should be validated. The residuals from the least squares play a significant role in judging the model's validation [22]. Figure 2 indicates the structureless pattern of the residual versus predicted value shows that the suggested model is adequate and has a constant error. In addition, Figure 3 shows a satisfactory straight line so it can be concluded that he model is adequate and correct.

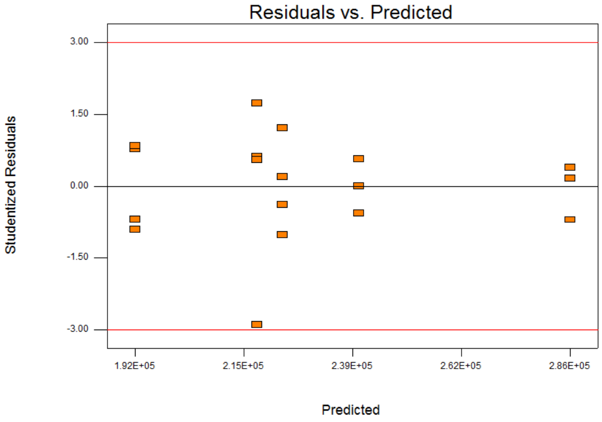


Figure 2 Residuals vs. predicted plot

In order to find the optimum value of each significant factor, the 3D response surface and the 2D contour plot are used. They are the graphical representation of the regression equation. At the lowest level of the surface inclination (191525) in Figure 4 and 5, the minimum cooling load is achieved at the lowest level of the temperature (200 °C) and the lowest level of humidity (60 %) based on the time contours trend. In this plot, the minimum cooling load occurs at the lowest point of the linear surface.

Ultimately, the optimum point within the range of the model with the value of 191525, after analyzing the experimental model, is gained at the A–, B– corner of the cube plot (Figure 6). This value is the minimum cooling load between the starting point after speed bump and the stop point. Based on the main objective of this experimental design and the local optimum point of the model, the optimum cooling load for saving more energy in this case is at 191252. Meanwhile, the interconnectivity of the critical variables

Table 3 ANOVA for the cooling load and significant factors

Source	Sum of Square	DF	Mean Square	F Value	Prob>F
Model	1.903E+010	3	6.342E+009	45.67	< 0.0001
A	7.825E+009	1	7.825E+009	56.35	< 0.0001
B	9.916E+009	1	9.916E+009	71.40	< 0.0001
AB	1.284E+009	1	1.284E+009	9.25	0.0088
Curvature	2.702E+008	1	2.702E+008	1.95	0.1848
Residual	1.944E+009	14	1.389E+008		
Lack of fit	8.495E+008	4	2.124E+008	1.94	0.1802
Pure error	1.095E+009	10	1.095E+008		
Cor total	2.124E+010	18			
Std. Dev.	11784.56	R-Squared	0.9073		
Mean	2.312E+005	Adj R-Squared	0.8874		
C.V.	5.10	Pred R-Squared	0.8359		
PRESS	3.485E+009	Adeq Precision	15.552		

Table 4 Estimated regression coefficient for the cooling load

Factors	Coefficient Estimate	DF	Standard Error	95% CL low	95% CL High
Intercept	2.296E+005	1	2946.14	2.233E+005	2.359E+005
A-Temperature	22114.87	1	2946.14	15796.03	28433.72
B-Humidity	24894.87	1	2946.14	18576.03	31213.72
AB	8959.88	1	2946.14	2641.03	15278.72

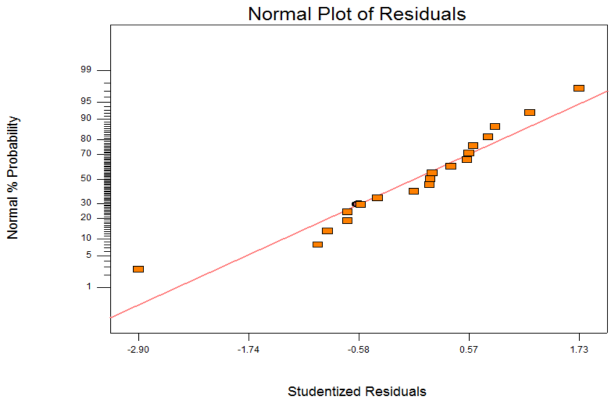


Figure 3 Normal plot of residuals

In order to find the optimum value of each significant factor, the 3D response surface and the 2D contour plot are used. They are the graphical representation of the regression equation. At the lowest level of the surface inclination (191525) in Figure 4 and 5, the minimum cooling load is achieved at the lowest level of the temperature (200 °C) and the lowest level of humidity (60 %) based on the time contours trend. In this plot, the minimum cooling load occurs at the lowest point of the linear surface.

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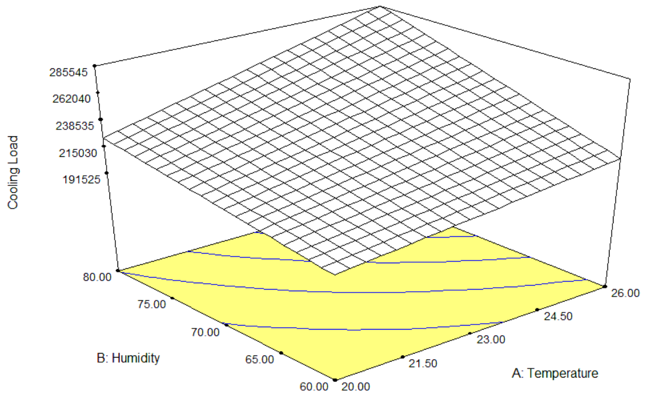

Figure 4 3D surface

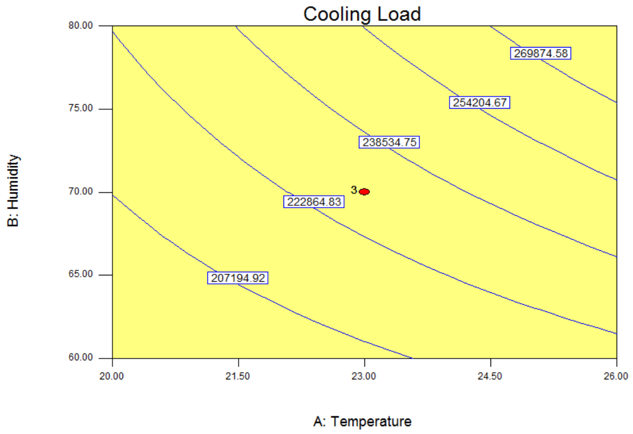

Figure 5 Contour plot

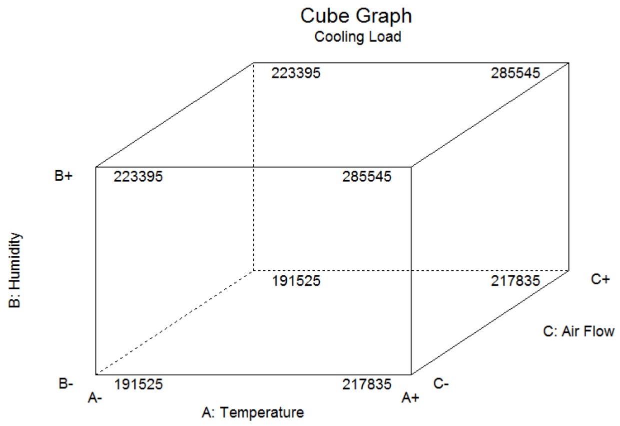

Figure 6 Cube plot

■4.0 CONCLUSION

The goal of this paper was to evaluate the effect of three important climate factors that are temperature, humidity and airflow, on the energy saving in green residential building as the case of study in tropical climate. Energy Plus is an extensive and complete simulation environment for transient simulation of systems that applied in this paper to simulate residential building. Furthermore, one statistical approach, classical DOE was conducted to find and analyze the significant factors that have the most important effect on the energy saving. The ANOVA test analysis indicates that the temperature and humidity, in comparison with other factors such as airflow, are regarded as the most significant factors that influence energy saving and cooling load. The final result showed that the optimum saving energy within the range of the model with the value of 191525, after analyzing the experimental model, is gained at the A– and B–, that are equal to 200°C and 60 %, respectively.

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