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Single Objective Optimization of Net Zero Energy Residential Building in Tropical Climate

A M Leman[1], H Z Sharif [1, 2], A N Krizou[2], M T A Al-Tarawne[2], M Subbiah[2], M Al Farsi[2] and A R Irfan[3,4]

[1]Occupational Safety, Health and Working Environment (OSH-WE) Research Group, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Higher Education Hub, KM 1, 84600, Muar, Johor, Malaysia
[2]Higher College of Technology, Muscat, Oman
[3]School of Manufacturing Engineering, Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 02600 Arau, Perlis, Malaysia.
[4]Green Design and Manufacture Research Group, Center of Excellence Geopolymer and Green Technology (CEGeoGTech), Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia.

E-mail: mutalib@uthm.edu.my

Abstract. The Building sector is the largest consumer of energy worldwide. Net Zero Energy Residential Building (NZERB) is one of the prudent approaches to reduce pressure on primary sources of energy. The main objective of this study is to use Taguchi simulation based on orthogonal arrays approach to optimize thermal envelope of a building, SEER value of HVAC system, lighting power density, and ventilation level to reduce the Building Energy Intensity (BEI) 50% lower than the base case building according to International Energy Conservation Codes 2015. In this study whole building energy simulation was performed by Hourly Analysis Energy Program and PVWatts calculator was used to estimate the size of the PV system for balancing the energy demand of the house. The results of Taguchi simulation approach show that by decreasing the U value of wall, windows, roof, floor to 0.1, 0.8, 0.1, 0.2 W/m2. °K respectively and ventilation rate 0.15 l/s-m2, lights of 110 lm/W and SEER of the HVAC system 4 (W/W option) reduce BEI from 147.78 kWh/m2/year for base case building to 67.085 kWh/m^2/year for optimal design case. PV system size estimation was performed with PVWatts calculator. PV Watts recommended the size of 13kW DC rating system (open rack type) of 15% efficiency for the weather of Johor Bahru to meet the annual energy demand of the proposed optimal building design.

1. Introduction

The building sector is the largest consumer of energy worldwide and put substantial pressure on the primary sources of energy. Net Zero Energy Buildings (NZEB) is one of the best solution proposed by the energy expert to reduce pressure on the primary sources of energy. A site Zero Energy Building (ZEB) produces at least as much energy as it uses in a year when accounted for at the site[1].Agencies, policymakers, Societies, researchers, universities, HVAC companies, Economic leaders, recognize the vision of Net Zero Energy Buildings (NZEBs) for example: ENERPOS is a French National research project on Net Zero Energy Buildings Design in hot/tropical climates [2], The Energy Performance of Buildings Directive 2010/31/EU (EPBD recast) at the European level is the main governmental tool, for improving the energy efficiency of buildings[3], IEA-SHC Task 25[4], IEA-SHC task 53[5] , Zero Energy Ready Home program is run by The Department of Energy (DOE) U.S.A[6]

Much research in recent years has been focused on optimization of thermal performance, annual energy consumption, size of grid connected photovoltaic system, life cycle cost, and carbon dioxide equivalent emissions by the buildings[7]. Optimization techniques adopted by other researchers are summarized. For example, researcher utilized simulation based optimization approach for multi-objective optimal design with BEopt software developed on deterministic sequential search approach [8]. In another study building energy optimization was performed with BEopt software for different climates in Iran [7]. In another study multi-objective building performance optimization by MOBO and IDA-ICE (combined simulation and optimization) to reach optimal/near optimal solutions for buildings were performed[9]. Energy assessment of residential building in tropical climate was performed by combined use of design of experiment (DOE) , and dynamic building simulation tool(Energy Plus) [10]. In another study, orthogonal experiment design approach was used to optimize the building envelope which in turn minimize carbon emission of building operational energy consumption[11].

However, few studies explored the application of orthogonal experimental design method to optimize Building Energy Intensity. This research work objective was combined use of simulation tool of HAP software and Taguchi orthogonal array approach for optimal design of building. Taguchi introduces partial factorial approach to replace full factorial approaches which is less expensive, faster, and less time consuming[12]. Specially developed orthogonal array is used to perform simulation and only depends on the right choice of factor levels. Number of simulations for orthogonal arrays are very less as compare to the number of Monte Carlo simulations [13] Since the partial simulation is only a sample of the full simulations so standard statistical technique ANOVA (Analysis of Variance) is used to provide a measure of confidence from the variability (variance) of the data [12]. Optimal values of all the design variables determined from orthogonal arrays (Taguchi approach) optimized the target value of BEI equal to 67.085 kWh/m2/year from base cased building BEI of 147.73 kWh/m^2/year.

2. Building Characteristic

Experimentally verified model of NZEB at Higher College of Technology, Muscat, Oman (www.hctgreennest.edu.om) was used for the optimization of BEI (Building Energy Intensity) in tropical climate. Experimentally verified building is a two-story Net Zero Energy Building has covered floor area of 231m2. The house consists of one Majlis, dining Room, living room, and kitchen on the ground floor. The first floor consists of a master bedroom, one bedroom for kids, and one bedroom for guests. The house is designed to maintain temperature in the range of 25°C- 27°C and relative humidity in the range of 50 % - 70 % throughout the year powered by grid-tied solar energy system of 22.8 kW (DC rating) facing towards south at angle of 5° (fixed array) on the top of the house in the form of canopy as shown in the Figure .1

Figure 1. NZEB (Eco house) at Higher College of Technology, Muscat, Oman.

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The house was constructed by Insulated Concrete Forms (ICF) wall system with U value of 0.233W/m2. K, roof of hollow core slabs of U value of 0 .339W/m2. K additionally covered by solar panels, double glazed windows of shading coefficient of 0.48 with overall U value of 1.88 W/m2. K, and certified wooden doors of U value of 3.62 W/m2. K help to achieve the set target of energy balance during the competition period. The house was also equipped with energy recovery ventilators one for each floor, and variable refrigerant volume heat pumps one for each floor to achieve the comfort conditions in year around operation. Solar hot water system with electric backup, freezer, refrigerator, clothes washer, induction cooker, dishwashers, home electronics, internal and external lightings was installed in the house to perform different tasks recommended by competition organizer. The final constructed NZEB (Eco house) at Higher College of Technology, Muscat had a number of sustainable features as shown in table 1. These innovative features enabled the NZEB (Eco House) team to achieve the target of Net Zero Energy Building for competition period.

Table 1. Sustainable features of experimentally verified building

S/No	**Sustainable Feature Description**	**S/No**	**Sustainable Feature Description**
1	Appropriate sizing/ Number of floors	11	Food and low water plants
2	North-South oriented building	12	Environmental friendly refrigerant
3	Insulation of wall (NADURA ICF), roof &floor	13	Energy Recovery Ventilator
4	Double glazed windows	14	Grey water treatment system
5	External Shading	15	Rainwater collection
6	Cross flow ventilation	16	The solar hot water system
7	Certified wood (FSC certified)	17	Energy generation onsite by solar panels
8	Vertical green wall (West wall)	18	The solar mobile charging station
9	LED Lighting	19	Real-time energy and water usage display
10	5-Star energy efficient appliances	20	Paints with low toxicity

The house is equipped with Data Acquisition System (DAS) to monitor performance and administrative measured contests related to comfort zone contest, refrigerator sub contest, freezer sub contest, hot water, clothes washer, cooking, dishwasher, lighting and home electronics tasks, and energy balance contest as shown in Table 2.

Table 2. Operating schedule of NZEB

Equipment	Target	Operating schedule
MVAC	25-27°C / RH 50-70% all time	24 hours
Freezer/Fridge	1.1 to 4 .4°C / -29 to -15°C all time	24 hours
Dishwasher	Six plate washing task	9:00 AM to 11:00 AM
Clothes washer	six bath towel washing task	9:00 AM to 12:00 PM
Cooktop	Vaporizing of 3in of water	9:00 AM to 12:00 PM
Solar hot water heater	150L water at 43°C in 30 minutes	11:00 AM to 12:00 PM
Home electronics	3 hours in a day	9:00 AM to 12:00 PM
Cable phone	For video recording	24 hours
Data acquisition system	For temp, humidity, and weather	24 hours
Lightings indoor	As per ASHRAE standard	0-100%
Lightings outdoor	As per ASHRAE standard	0-100% dusk to dawn
People	Six number of people	24/7
Energy recovery ventilator	Not in use as per IECC recommendation for Base –case	24/7 option (not in use for base case analysis)

3. Methodology

Experimentally verified building geometry and operating schedule except for lighting hours were kept same for base case building design. In base case building design only weather conditions were changed from Muscat weather to Johor Baharu, Malaysia. Figure 6 shows BEI result obtained from HAP software for base case building design equal to 147.73 kWh/m2/year. The design optimization of BEI (Building Energy Intensity) is performed by using Taguchi simulation based on orthogonal approach of mixed level (2^1*3^7). In case of full factorial design method requires 4374 simulations whereas in this case only 18 experiments need to simulate for obtaining optimal results[14]. Table 3, illustrates the design factors or variable and their levels.

Table 3. Selected variable parameters and levels

Design Variable	Level 1	Level 2	Level 3
ERV (A)	0	1	-
Wall U value (B)	0.1	0.56	1.12
Window U value (C)	0.8	1.5	2.84
Roof U value (D)	0.1	0.15	0.2
Floor U value (E)	0.1	0.2	0.36
Ventilation (F)	0.15	0.25	0.5
Lights (lm/W) (G)	80	90	110
SEER W/W (H)	3.52	3.8	4

4. Result and Discussion

Energy analysis was completed with HAP (Hourly Analysis Program) for different combinations as shown in the table 4. Table 4 shows the result obtained from the simulation for BEI (Building Energy Intensity).

Table 4. Results of response BEI from HAP simulation tool

Experiment	ERV	U Wall	U window	U Roof	U floor	Ventilation L/s-m^2	lighting lm/W	SEER W/W	BEI kWh/m2.a
1	0	0.1	0.8	0.1	0.1	0.15	80	3.52	85.27
2	0	0.1	1.5	0.15	0.2	0.25	90	3.8	83.79
3	0	0.1	2.84	0.2	0.36	0.5	110	4	88.04
4	0	0.56	0.8	0.1	0.2	0.25	110	4	94.5
5	0	0.56	1.5	0.15	0.36	0.5	80	3.52	119.463
6	0	0.56	2.84	0.2	0.1	0.15	90	3.8	99.66
7	0	1.12	0.8	0.15	0.1	0.5	90	4	124.43
8	0	1.12	1.5	0.2	0.2	0.15	110	3.52	120.53
9	0	1.12	2.84	0.1	0.36	0.25	80	3.8	123.03
10	1	0.1	0.8	0.2	0.36	0.25	90	3.52	78.09
11	1	0.1	1.5	0.1	0.1	0.5	110	3.8	73.08
12	1	0.1	2.84	0.15	0.2	0.15	80	4	74.413
13	1	0.56	0.8	0.15	0.36	0.15	110	3.8	85.66
14	1	0.56	1.5	0.2	0.1	0.25	80	4	91.02
15	1	0.56	2.84	0.1	0.2	0.5	90	3.52	98.03
16	1	1.12	0.8	0.2	0.2	0.5	80	3.8	111.332
17	1	1.12	1.5	0.1	0.36	0.15	90	4	103.833
18	1	1.12	2.84	0.15	0.1	0.25	110	3.52	113.02

Data shown in table 4 was analyzed in a statistical computer software Minitab 16. Table 5 shows the results of the ANOVA (Analysis of Variance) to identify significant factors. Significance of factors based on p-value less than 0.05, it was considered to be significant [10]. As per ANOVA Table 5 ERV, U value of Wall, ventilation, lights and SEER factors are significant factors. Results for fits and diagnostics for unusual observation found satisfactory and no unsual observation was observed in the data.

Table 5. ANOVA results from Minitab 16

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	8	4882.11	4882.11	610.26	54.413	0.000001
ERV	1	675.10	675.10	675.10	60.193	0.000028
U-Wall	1	3798.24	3798.24	3798.24	338.660	0.000000
U-Window	1	23.83	23.83	23.83	2.125	0.178914
U-Roof	1	9.95	9.95	9.95	0.887	0.370758
U-Floor	1	11.28	11.28	11.28	1.006	0.342061
Ventilation	1	168.82	168.82	168.82	15.052	0.003733
Lightings	1	73.50	73.50	73.50	6.553	0.030691
SEER	1	121.39	121.39	121.39	10.524	0.009379
Error	9	100.94	100.94	10.94	11.22	
Total	17	4983.05				

Table 6, response table for means is generated by Minitab 16. This shows the average effect of a design variable at one setting. The response table for means also illustrate the ranking of the factors and their influence on achieving the target of low BEI. According to the response table for means effects of factor Wall-U, ERV, ventilation, SEER, lightings, roof U value, window U value, and Floor U value ranked 1 to 8 respectively.

Table 6. Response table for means

Level	ERV	U-Wall	U-Window	U-Roof	U-Floor	Ventilation	Lighting s	SEER
1	104.30	80.45	96.55	96.29	97.75	94.98	100.75	102.40
2	92.05	98.06	98.62	100.13	97.10	97.24	97.97	96.09
3		116.03	99.37	98.11	99.69	102.40	95.81	96.04
Delta	12.25	35.58	2.82	3.84	2.59	7.50	4.95	6.36
Rank	2	1	7	6	8	3	5	4

After estimating the impact of factors, general regression analysis was performed by Minitab 16. Table 7 shows the results of estimated model of coefficients for means. A two tailed t-test was performed at the level of confidence interval of 95% which means p-value should be less than 0.05. If p-value is less than 0.05 it means all sample means equal and effect of that factor on the result is statistically significant [16]. Minitab 16 produced prediction equation of BEI with respect to factors (Regression equation 1)

$$BEI = 78.1978 - 12.2483 A + 17.791 B + 1.40925 C + 0.91075 D + 0.969667 E + 3.75075 F - 2.47483 G - 3.18058 H \quad (1)$$

The coefficient of means for model as shown in the table 7.S = 3.34895 $(R)^2$ = 97.97% $(R)^2$(adjusted) = 96.17% PRESS = 389.423 $(R)^2$(predicted) = 92.19% S represents the standard deviation of errors in the model S= 3.34895 indicates that model can explain the variation in BEI of building to the extent of 96.65% which makes the model adequate to represents the process. R2 = 97.97 % indicated that model is capable to predict the response with high accuracy[17].

Main effects plot for the main effect terms versus factors, ERV, U-Wall, and U-window. U-Roof, U-Floor, Ventilation, lightings, and SEER is shown in the Figure 2. It has been observed from the Figure 2 that BEI (Building Energy Intensity) decreases with setting of ERV is ON, wall U value of 0.1 W/m^2.

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°K, window U value of 0.8 W/m^2. °K, roof U value of 0.1 W/m^2. °K, floor U value of 0.2 W/m^2. °K, Ventilation setting at 0.15 L/s-m^2, lights of 110 lm/w efficiency and SEER (W/W) at level of 4.

Table 7. Estimated model of Coefficients and SE coefficient for means

Term	Coef	SE Coef	T	P
Constant	78.1978	5.69213	13.7379	0.000
ERV	-12.2483	1.57871	-7.7584	0.000
U-Wall	17.7910	0.96676	18.4027	0.000
U-Window	1.4092	0.96676	1.4577	0.179
U-Roof	0.9108	0.96676	0.9421	0.371
U-Floor	0.9697	0.96676	1.0030	0.342
Ventilation	3.7508	0.96676	3.8797	0.004
Lightings	-2.4748	0.96676	-2.5599	0.031
SEER	-3.1806	0.96676	-3.2899	0.009

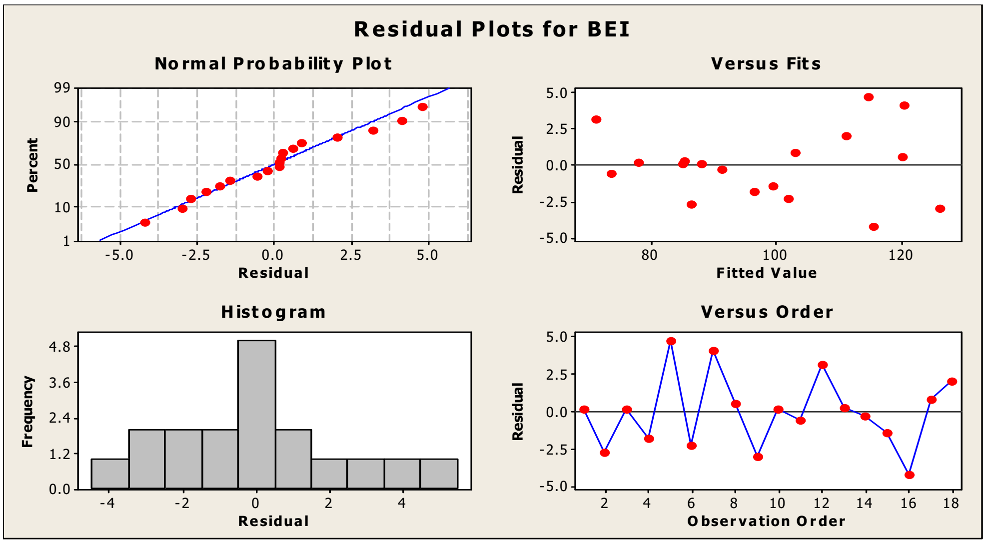

Figure 2. Residual plots for BEI

Regression model validation was done by applying the technique of residual analysis. The residual indicates the difference between observed values and the predicted values. In normal probability plot it should be located on a straight line as shown in the Figure 2, that the residual followed a straight line so it confirm the validation of the model[10] , Normality plot also indicates that outliers do not exist in the data [17]

According to Figure 2 proposed model was adequate because the graph of residual versus the predicted response is a less patterned structure. It is also indicated in residual versus fitted values graph in Figure 2 that the variance is constant and non-linear relationship exists. It can be seen in the Figure 2 for residual versus observation order of the data that there are systematic effects in the data due to data collection order or time. Part of Figure 2 for histogram (residual versus frequency) indicated that no outliers exist in the graph and also proves that data is not skewed [16, 17].

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4.1 Confirmatory Simulation for optimized building case

Table 8 shows the setting at which lowest Building Energy Intensity (BEI) can be achieved. These lowest factors setting used to perform the energy analysis for the verification with the help of HAP simulation tool.

Table 8. Optimal values for optimized building case derived from Taguchi L-18 OA

Factors	Level	Component	Setting
Factor A	A2	ERV	ERV ON
Factor B	B1	Wall U value	0.1 W/m2. °K
Factor C	C1	Window U value	0.8 W/m^2°K
Factor D	D1	Roof U value	0.1 W/m^2. °K
Factor E	E2	Floor U value	0.2 W/m^2. °K
Factor F	F1	Ventilation setting	0.15 L/s-m^2
Factor G	G3	Lights setting	110 lm/w efficiency
Factor H	H3	SEER (W/W)	4

Simulation result from HAP, annual energy cost of the house was 2170$ (tariff of 0.14 $/kWh assumed for Johor Bahru, Malaysia). It is also shown that total annual energy consumption of the house is 67.085 kWh/m^2/year with overall reduction of 13483 kg of CO_2 emission.

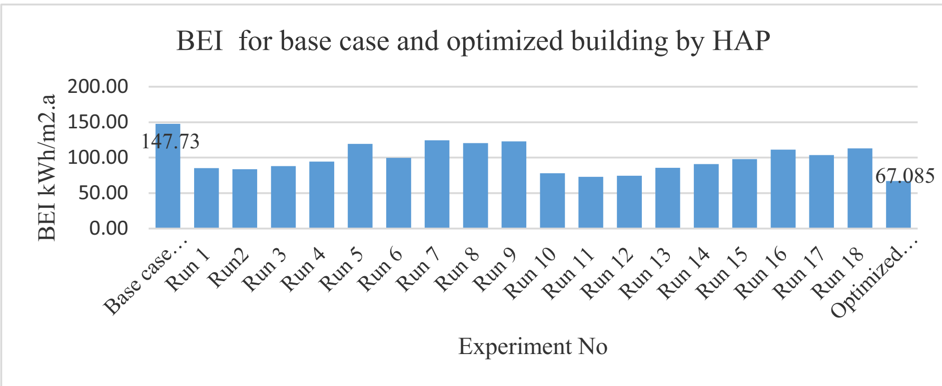

Figure 3. BEI for base case and optimized building by HAP

Figure 3 illustrates the results of base case building in tropical climate of Johor Bahru, Malaysia, 18 runs based on Taguchi, and optimized building case. It is clearly shown in the Figure 3 that BEI for optimized setting obtained from Taguchi approach is 67.085 kWh/m^2/year, 54.61%% smaller than BEI of base case building of 147.73 kWh/m^2/year. The lowest results obtained from optimal setting shows confidence on Taguchi approach. According to the simulation results obtained for optimally designed building from HAP software, Building Energy Intensity (BEI) was 67.085 kWh/m2/year, and total units were required 15496.635 kWh per year for floor area of 231m^2. Energy balancing was performed by PVWatts calculator and overall size of 13kW DC rating found suitable to produce 16375 kWh/year with safety margin of 10%.

5. Conclusion

In general, overall building energy consumption depends on the location, climatic conditions, thermal envelope, HVAC system, lighting, and ventilation rate and occupant behaviour. In this study wall, roof, floor, windows, lighting, ventilation rate, HVAC system and Energy recovery ventilator in terms of their ability to reduce overall energy demand of the building for tropical climate introduced and balancing of energy demand was encountered by PV system. Whole building energy analysis performed by HAP software for proposed building designed showed that highest impact in reduction of BEI was 1 to 8 for Wall-U, ERV, ventilation, SEER, lightings, roof U value, window U value, and Floor U respectively. This study has shown the application of Taguchi method on the BEI of NZERB in tropical climate. ANOVA technique was applied to determine the level of importance of eight factors, and regression equation was generated to describe the relationship between the factors and response. The result obtained from Taguchi approach leads designers and building providers to optimize BEI of the building by reducing U value of wall, introduction of ERV at residential scale, controlled ventilation rate and high SEER rated HVAC system.

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