The Design and Analysis of Energy Efficient Building Envelopes for the Commercial Buildings by Mixed-level Factorial Design and Statistical Methods

Xuejun Qian*, Seong W. Lee

Abstract - One of the goals in the engineering education is how to apply the understanding of engineering and statistical methods to real world problems. Many students conducted experiments and simulations using the knowledge gained from the experimental design, design & analysis of energy systems courses. This paper shows the student apply the design the experiments methods and analyze the data using statistical methods. Energy performance of building envelopes is critical to determine how much energy is required for space heating and cooling. The energy efficient building envelope's design is not only enable permanent ongoing reduction in energy consumption, but also improve the occupant comfort and air quality for the millions of populations. Students used the mixed factorial design method during the design phase to figure out the significant factors and their effects. Building envelopes including wall, window, roof and door were selected as the interesting factors regarding to the different layers, materials and insulations. Response factors were: (1) annual building energy consumption, (2) cooling energy consumption, and (3) heating energy consumption in the small-sized commercial building respectively. Hence, this study focuses on the design and analysis of the buildings envelopes by energy modelling tool (e.g. TRACE™ 700) and statistical tool (e.g. Minitab ® **17**). The design of building envelopes continued on the previous integrated ventilation systems (e.g. desiccant wheel and energy recovery wheel systems with variable air volume). Data analysis and simulation results (e.g. contour plot, response surface plot) indicated energy reduction more than 16.6% along with the humidity reduction by the aforementioned energy efficient design. This design will offer valuable options for retrofitting and new construction for the next generation and societies.

Keywords: Commercial Buildings, Building Envelope, Design, Energy Consumption

I. Introduction

According to the 2011 Building Energy Data book, U.S. consumes 19% of world energy consumption, this amount of energy mainly consumes by the industrial, transportation, residential and commercial sectors as shown in Figure 1. Building consumes nearly 41%, and the commercial building sectors consume nearly 19% of total U.S. energy consumption [1].

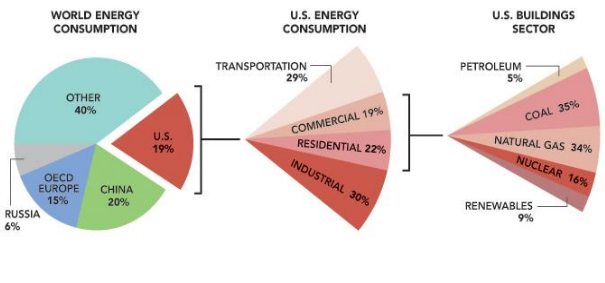

Fig. 1 Energy Consumption in the United State

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Commercial buildings include offices, retail stores, educational facilities, restaurants, warehouses, and other buildings which are used for commercial purposes. The trend of U.S. commercial energy consumption is slightly increasing from 2005 to 2011. In 2005, buildings accounted for 38.9 percent of total U.S. energy consumption, while commercial buildings accounted for 46.3 percent of that total energy consumption [2]. In 2009, commercial buildings consumed 17.9 quads of primary energy, representing 18.9% of total U.S. energy consumption [3]. In 2011, commercial buildings consume nearly 19% of total U.S. energy consumption [1]. Furthermore, according to the *AEO2012* Reference case, the growth of energy end-use predict in the commercial sector is about the 3.3 quadrillion Btu from 2010 to 2035. Even as standards for building shells and energy efficiency are being tightened in the commercial sector, the growth rate for commercial energy use is the highest among the end-use sectors [3]. According to the "Sustainability: Energy Efficiency" report by National Renewable Energy Laboratory (NREL), 11 parameters influence energy efficiency of the building design are building envelopes, site analysis, orientation, configuration, space planning, ventilation, heating, cooling, lighting and appliances, water heating and waste management [4]. In the previous literature reviews, building energy consumption depends on the various factors, such as building envelopes, orientation, room configuration, efficient of equipment (boiler, chiller, cooling tower), comfort level (various by the set point), occupant's behavior, accessory equipment (video displays, medical devices, office equipment, mainframe computer, refrigerator, and coffee machine) and systems (heating, ventilation, cooling, lighting etc.).

Among them, space heating and cooling account for over one-third of all energy consumed in buildings, rising to as much as 50% in cold climates and over 60% in the residential sub-sector in cold climate countries [5], and the building envelope is critical to determine how much energy is required for space heating and cooling. Therefore, the building envelope's impact on commercial building energy consumption should not be underestimated, and can be significantly improved to reduce the space heating and cooling.

Research group of the Center for Advanced Energy Systems Environmental Control Technologies (CAESECT) at the Morgan State University were used design of experiment (DOE) approach, software and analysis tools to reduce the cost, time to achieve the deliverables. In addition, this study will more focus on energy efficient envelope's design to reduce HVAC energy consumption for the commercial buildings using scientific design methodology. The objectives of this study are: To

- Determine the process of energy consumption in the small-sized commercial buildings
- Design and analysis the different building envelopes design by means of mixed-level factorial design and statistical methods
- Find out the significant factors and its individual levels among the building envelopes to provide the energy efficient design on the small-sized commercial buildings, to support around 15% reduction in annual total energy consumption

II. Background

A. Current Methods and Technologies

Under-floor air distribution (UFAD) system as shown in Figure 2 is one of the heating, ventilation and air conditioning (HVAC) system that used to the open space (i.e. the pressurized underfloor plenum) between the structural slab and the underside of a raised floor to deliver conditioned air to the occupied zones through diffusers [6]. Compared to conventional overhead (OH) mixing systems, where the air in the zone is well-mixed, UFAD has several potential advantages are: 1) Reduced energy use by cooling and fan energy 2) Flexibility and reduced life-cycle building costs 3) Improved occupant control and comfort 4) Improved air change effectiveness [7]. The barriers in the adoption of UFAD systems are: 1) still new and unfamiliar technology, 2) lack of information and design guidelines, 3) no whole-building simulation program for the system, 4) high initial costs, 5) condensation and dehumidification issues, and 6) spillage and dirt entering the UFAD systems [6].

Fig. 2 Sample of the UFAD Systems

According to the published statistics, the HVAC systems consume significant as 50% of building consumption [8, 9]. The heuristic techniques such as neural networks, support vector machine, and boosting tree have largely expanded to the modeling process of HVAC. This new approach is to apply the evolutionary computation approach in optimizing the performance of HVAC system to improve its efficiency and different preference-based operation methods to optimally utilize the resources [10].

Other way to save energy for the building is to interact with surrounding environment as much as possible. Natural ventilation (NV) strategy is one of the approaches widely implemented in buildings [11, 12]. The main hybrid ventilation principles are: Natural and mechanical ventilation as shown in Figure 3, Fan assisted natural ventilation, stack and wind supported mechanical ventilation [13]. The hybrid ventilation systems have been developed later because the natural ventilation has been proven to provide thermal comfort under limited conditions. According to the cases studies by Heiselberg (2002), a reduction of 20%~30% in overall energy consumption and 50% in electricity have been achieved by hybrid ventilation systems comparing to full air conditioned office buildings [14].

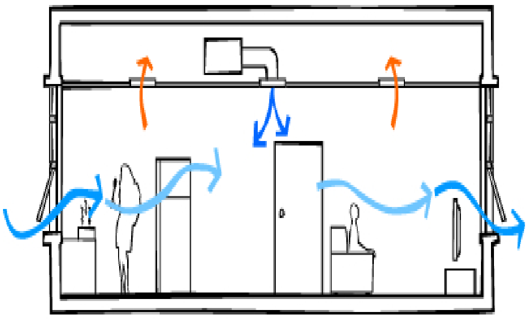

Fig. 3 Hybrid Ventilation Systems

B. Previous Research

Desiccant wheel as shown in Figure 4 is a wheel with desiccant coating (silica gel or molecular sieve) to serve as a heat recovery system [15]. It is a honeycomb circular matrix, and rotated slowly within a system by a small electric motor and spins the desiccant coating on the wheel which absorbs the humidity in the airstream. This technology uses a considerably smaller amount of electricity than refrigerators based on the vapor-compression cycle, which is an electricity driven cycle [16]. Electricity is often more expensive than other types of energy and has CO_2 emissions associated with its generation, so desiccant cooling has the potential of achieving both economic and envrionmental benifits [17]. Thus, the desiccant wheel has a high potential to saving energy and improve the indoor air quality.

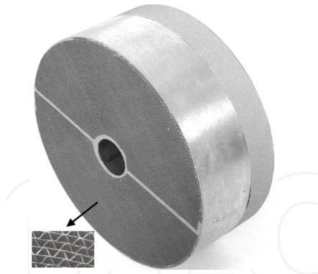

Fig. 4 The Pictorial View of Desiccant Wheel

Energy recovery wheel (ERW) as shown in Figure 5 is a wheel absorbs heat through the exhaust air stream to support the regeneration process at the DW [18].

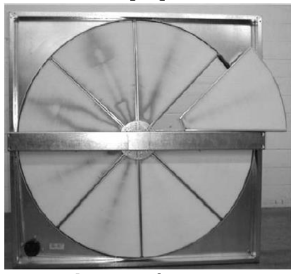

Fig. 5 The Pictorial View of Energy Recovery Wheel

The proposed integrated ventilation system is the combination of the two energy wheels: ERW and DW to the conventional overhead variable air volume (OHVAV) as shown in the Figure 6 [19]. Here, “EA” means exhaust air, “RA” means return air, “MA” means mixed air, “SA” means supply air, “OA” means outside air and “C” means cooling coils.

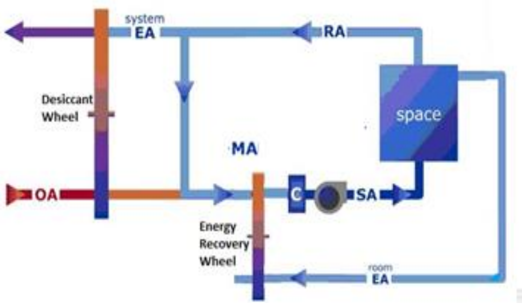

Fig. 6 Integrated Ventilation Systems

Two wheels were optimally designed inside air handling unit (AHU) as shown in Figure 7 by Morgan State University on the demonstration site for energy efficiency and improvement of indoor air quality (IAQ). Simulation results indicate the DW could remove over 50% of humidity and integrated ventilation system in the optimum position of the AHU could save over 20% of annual energy consumption [19].

Fig. 7 The Pictorial View of Air Handling Unit (AHU)

C. Building Envelopes

Building envelopes comprise wall, window, roof, door and foundation. Normally, building envelope has multi-layers by the various building envelope materials and insulations. In a well-designed buildings, building envelope is the interface between the inside building and outside environment. The building envelope serves as the thermal, air and moisture barriers completely enclose the entire building, especially as the thermal barrier plays an important role in regulating interior temperatures and helps determine the amount of energy required to maintain thermal comfort for the occupancy, and crucial for reducing the need for space heating and cooling [20]. Overall, building envelopes mainly impact on the space heating and cooling, which account for one-third of all energy consumed in buildings, but can impact up to 57% of commercial use [21]. Because of considerations above, the building envelope is a key aspect of energy-efficient and high performance buildings. In addition, the design and construction of the building envelope has a significant effect on occupant comfort.

D. U-factor

Building envelope components have three important characteristics that affect their thermal performance: U-factor or thermal resistance; their thermal mass or ability to store heat, measured as heat capacity (HC); and their exterior surface condition/finish (for example, are they light in the color to reflect the sun or dark to absorb solar heat) [20]. U-factor is mainly affected by the thermal resistance of the insulation material. It is the amount of heat in British thermal units (Btu) that flows each hour through 1 ft^2 of surface area when there is a 1°F temperature difference between the inside and outside air. The U-factor is also the rate of steady-state heat flow, and the concept of steady-state heat flow is a simplification because the temperatures change constantly in the real world. The steady-state heat flow (U-factor or R-value) is a part of the basic vocabulary of building energy performance because of it is easy to understand and use. However, U-factor can predict average heat flow rates over time and is commonly used to explain the thermal performance of construction assemblies. For the U-factors, they are the lower the better.

III. Scientific Methodology

A significant goal of this project is how to reduce a commercial building's energy consumption by using design of experiment (DOE) approach, specially mixed-level factorial design and statistical methods were used to the energy efficient envelope's design. Building energy modeling software (TRACE^{TM} 700) and statistical software (Minitab ® 17) were used. Preliminary design and simulation were used to choose the more significant building envelopes. First, this study was used mixed-level factorial design at the design phase. Then, gathered the accurate information from the physical plant for the building energy modeling. Residual plot, main effect plot, contour plot, and response surface method were used to analysis the factor's effect.

A. Design of Experiment

Design of Experimental design as a tool for engineer and scientists to use for product design and development in the product cycle as well as process development and improvement in a variety of disciplines, which will substantially reduce development lead time and cost, leading to processes and products that perform better, and have high reliability than other approaches. General model of a process or system as shown in the Figure 8, the process transforms some input into an output that has one or more observable response variables. Some of the process variables X_1, X_2,…, X_p are controllable, whereas other variables Z_1, Z_2,…, Z_p are uncontrollable. The mean objective of the experiment is to determine which variables are most influential on the response, even you can set the influential factors that response is near the desired nominal value with small variability, and reduced the effects of uncontrollable factors [22].

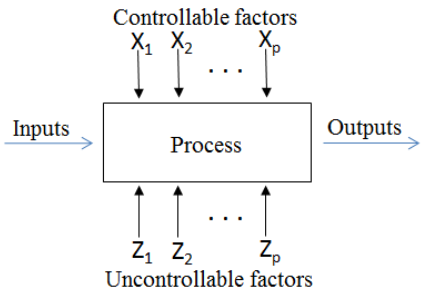

Fig. 8 General Model of a Process or Systems

There are three strategies to conduct the experiments including:

- Best guess approach: First, suppose the initial guess does not produce the desired results. Second, suppose the initial best guess produces an acceptable result.
- One factor-at-one-time: the major disadvantage is fails to consider any possible interaction between factors.
- Factorial experiment: correct approach to dealing with several factors. In this approach factors are varied together

This study were used the factorial experiment to study the both individual and interaction effects of building envelopes. Analysis of variance (ANOVA) is a computational technique that enables the engineer to quantitatively estimate the relative contribution each control factor makes to the overall measured response. Response surface methodology (RSM) is a mathematical and statistical technique useful for the modeling and analysis of problems in which a response(y) of interest is influenced by several variables (X_1, X_2), and to optimize this response. So the ANOVA and RSM were applied in the data analysis [23].

B. Building Energy Modeling and Statistical Analysis Tools

In this study, building energy modeling software (TRACE^{TM} 700) and statistical software (Minitab ® 17) was adopt as the modeling and analysis tools.

To analysis and manage effectively a building's energy consumption, many effective analysis tools and simulation software were utilized, such as DOE2, eQUEST (Quick Energy Simulation Tool), Energy Plus, and TRACE^{TM} 700 etc. TRACE^{TM} 700 (Trane Air Conditioning Economics) software is a load design-and- energy analysis software program that helps building designers to optimize the building's envelope, heating, ventilating and air-conditioning system and equipment designs on the basis of energy utilization and life-cycle cost [24]. Minitab ® 17 is leading statistical software which assists you to analysis your data and improves your products and services for quality improvement worldwide. Regression and ANOVA table will represent relationships between variables and identify important factors affecting the quality of your products and services [25].

C. Energy Consumption in the Small-sized Commercial Buildings

This study was selected one of the small-sized commercial buildings: Schaefer engineering building at Morgan State University as a demonstration site (especially classroom 201). The building contains four walls, one roof, two double clear glass windows, and three small glass windows near by the door as the buildings envelopes. It also has four ceiling diffusers and one ceiling returns. There are 36 recessed fluorescent light fixtures. Other appliances and equipment which is not installed inside the class also need to consider in the design process, to provide the energy efficient design of the building envelopes for this small-sized classroom.

Table 1 shows the baseline information of classroom from the field trip and measurement. It includes the direction, thickness, dimension of each wall, window, door and roof for the classroom.

Table 1. Dimension of the Building Envelopes

Type	Direction	Length * Height (ft.)
Wall 1	South	19.25 *9.33
Wall 2	East	28.75*9.33
Wall 3	North	19.25*9.33
Wall 4	West	28.75*9.33
Window on wall 1	South	5.45*6.5
Window on wall 3	North	2.33*1.42
Door	North	3*7.42(width*height)
Roof	Top	28.7519.25

Energy consumption process for the demonstration site as shown in Figure 9 also contains controllable and uncontrollable factors. The controllable factors comprise building envelopes (wall, roof, window and door), plant (boiler, chiller), HVAC (air handling unit, diffuser, variable air volume box) and lighting. The uncontrollable factors comprise temperature, humidity, and wind condition of the outside environment around the buildings which is not controlled by the occupancy. Here, the input means the set point for the different zones inside the buildings, such as temperature, humidity and air flow rates by the occupants. Output means the annual energy consumption, or heating, cooling energy consumption for the demonstration site.

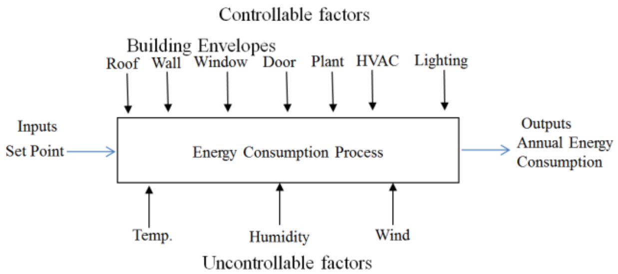

Fig. 9 Energy Consumption Process

D. Choosing the Response Variables, Interesting Factors and Its Individual Levels

From the aforementioned factors, the interesting factors are building envelopes as well as the wall, roof, window and door for this study. Some of them have the three individual levels: low, intermediate and high. Other factors may have two or more individual levels. Normally, the level varies by the material types, insulation and thickness which have the different U-factor and shading or glazing coefficients. Response factor will be annual energy consumption/ heating and cooling respectively for this small-sized classroom.

Due to the thermal mass of the concrete wall, a study shown that houses with concrete wall had lower heating and cooling costs than houses with frame [26], so the building the interesting factors for the exterior wall systems with concrete and block including 8” LW (low weight) block with 4” insulation walls, 8” LW block with 5” insulation walls, and 8” HW (high weight) block with 4” insulation walls.

Glass type represents the thermal properties of the windows, skylights, and doors in the building. The associated properties of the glass (U-factor and Shading Coefficient) will have a direct effect on solar and conduction loads into the room, and also directly effect by Low-E. Low-E means low emissivity with a very thin, almost invisible layer, coating to glass to deflect ultra violet and infrared radiation (but allowing the light pass through) for increasing its thermal efficiency. Interesting factors for the windows including 6mm single clear, 6mm double clear, and 6mm double low E with 6mm air insulation.

Roofing materials including clay tile, slate tile, concrete tile, metal, wood shingles & shakes, laminated, and asphalt shingles etc. Although metal and steel materials are increasingly used, they are mostly used only to build tall buildings due to the high cost. Therefore, the interesting structural materials for roof are mainly concrete and wood. One of them is 4” high weight concrete with 6” insulation and the other one is the 4” wood with 6” insulation. For the door, interesting factors are standard door which has U-factor as 1.5, the other one is U-factor equal to 0.2., and glass besides to the door were considered as same material for the windows on the wall.

E. Simulation

Based on the several interesting factors and its individual level are varied together for the building Envelopes, this study applied the mixed-level factorial design and statistical methods. Minitab ® 17 was used to generate the design sheet to model the different building model to conduct the random experiments.

According to the mixed-level factorial design worksheets, the different building models will be designed and simulated by the TRACE™ 700 software. Such as the building envelope, window, lighting, ventilation system, plants for buildings. The TRACE™ 700 software interface was shown in the Figure 10. This software has a capability to model the individual room by the different systems and plants. Building environment (weather information) will be varying by the building location. Even though, the software allows the cost analysis by putting the price of the fuel, electricity, building materials etc. to the software, but not discuss cost analysis at this point because of the lack of information on the cost of each system.

Baseline Information was collected from the demonstration site, including:

- Building envelopes materials and thickness: wall, window, roof and doors
- System capacity and type: HVAC, Lighting, DW and ERW
- Plant capacity and type: boiler, chiller, cooling tower
- Input values: Set point for the air flow rate, temperature and humidity for the rooms

By using a detailed computer simulation method, this study will compare the energy efficient model with the baseline model. Baseline model is the small-sized class room with the existing building energy systems in the in the Schaefer Engineering Building of Morgan State University.

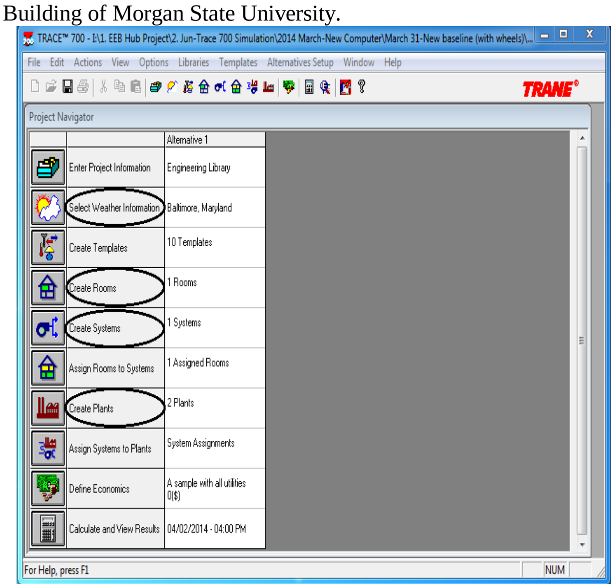

Fig. 10 Software Interface (TRACE™ 700)

IV. Results and Data Analysis

Based on the mixed-level factorial design worksheets, the different building models has been modeled and simulated by the TRACE™ 700 software. Simulation results of annual heating, cooling, and total energy consumption in different scenario as shown in Figure 11, including bar-chart represents the relation between building envelopes (wall, window, roof, and door) and the annual energy consumption. The x-axis is annual energy consumption (KBtu/yr) and the y-axis is the level of building envelopes. The results indicated the individual levels of the wall and window have the strong relation with the energy consumptions. And the influence for the door and roof were pretty small.

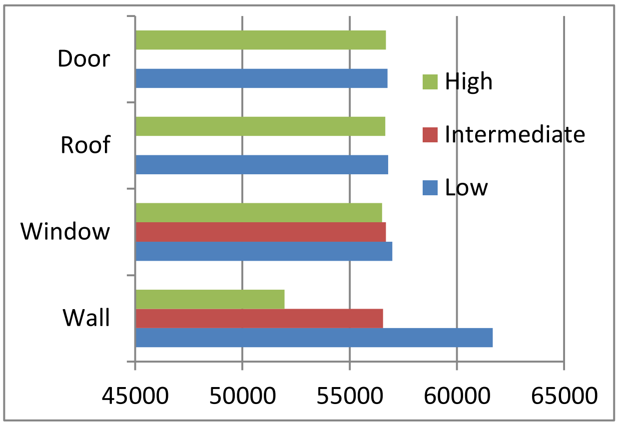

Fig. 11 Relation between Building Envelopes and Energy Consumptions (KBtu/yr)

Figure 12 shows the residual plots and normal probability plot of residuals for total energy consumption in the commercial building were nothing unusual about the plot of residuals. From the normal probability plot, there is no severe indication of non-normality, nor is there any evidence pointing to possible outliers, the plot resembles a straight line and the error distribution is approximately normal distribution. In the residuals versus the fitted value plot, the residuals are structure-less and not reveal any obvious pattern. So the model is correct and the assumptions are satisfied.

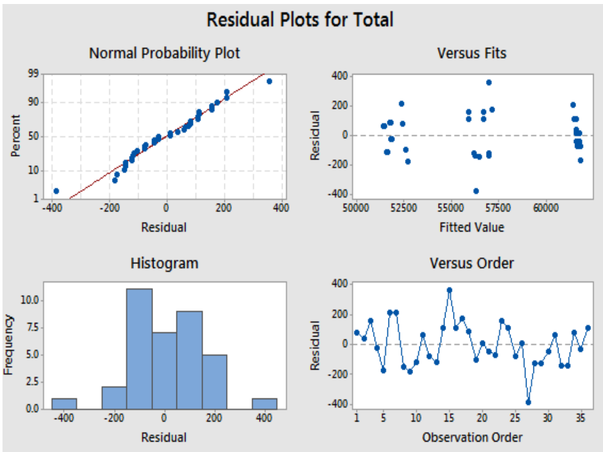

Fig. 12 Residual Plots for the Total Energy Consumption

Figure 13 shows the main effects plot for total energy consumption in the small-sized commercial buildings. Results also indicated the wall and window have a significant effect; but roof and door have slightly effect on the total energy consumption. In addition, the wall has more significant effects on the total energy consumption than the window.

Fig. 13 Main Effects Plot for Total Energy Consumption

We could find that P-value for the wall and window in the Table 2 is smaller than zero, where again indicated wall and window have a significantly effect on the total energy consumption.

Table 2. Analysis of Variance Table

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	19	569212696	29958563	645.91	0.000
Linear	6	566322739	94387123	2034.99	0.000
Wall	2	564713188	282356594	6087.61	0.000
Window	2	1385835	692918	14.94	0.000
Roof	1	187489	187489	4.04	0.062
Door	1	36227	36227	0.78	0.390
2-Way Interactions	13	2889957	222304	4.79	0.002
Wall*Window	4	2088915	522229	11.26	0.000
Wall*Roof	2	328275	164138	3.54	0.053
Wall*Door	2	108851	54426	1.17	0.335
Window*Roof	2	270480	135240	2.92	0.083
Window*Door	2	82757	41379	0.89	0.429
Roof*Door	1	10678	10678	0.23	0.638
Error	16	742115	46382		
Total	35	569954811			

In order to provide the energy efficient design, the contour plots for interaction between the significant factors wall and window were shown in the Figures 14 (for total energy consumptions) and 15 (for heating energy consumptions). The light green means the lowest energy consumption and the dark blue means the region of the highest energy consumption. So the optimal level for the window is either low or intermediate, and the level for the wall is better to keep as high level.

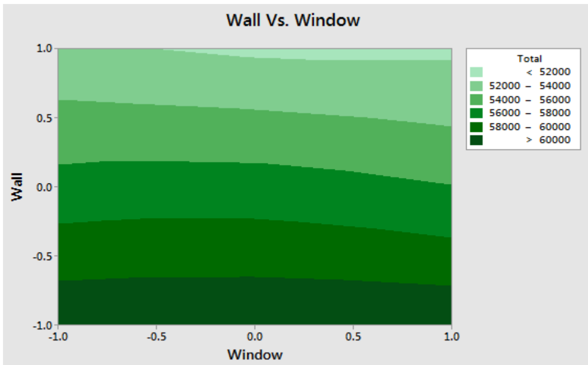

Fig. 14 Contour Plot for Total Energy Consumptions

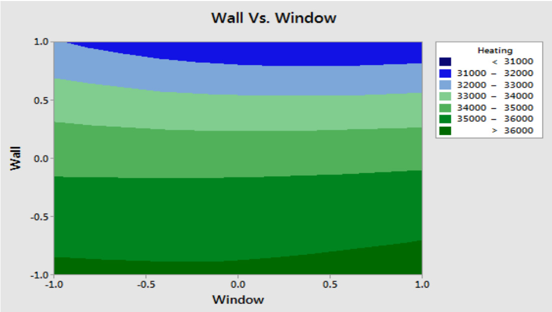

Fig. 15 Contour Plot for Heating Energy Consumptions

The surface plot for the total annual energy consumption as shown in Figure 16, it assists with contour plots to give the designer and building owner before the construction or for the retrofitting options which is saving both heating and total energy consumption for the small-sized commercial buildings.

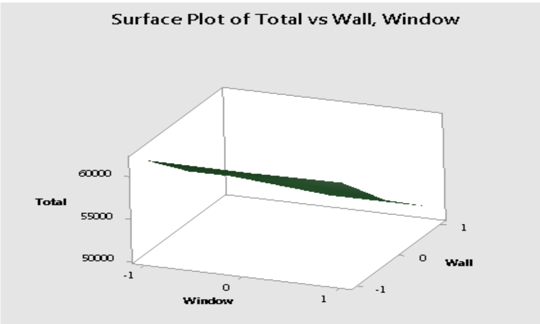

Fig. 16 Surface Plot for the Total Energy Consumption: Wall vs. Window

V. Conclusion

Based on the mixed-level factorial design and statistical data analysis of building envelopes, the major accomplishments of the research can be summarized as follows:

1. The process of energy consumption in the small-sized commercial building was determined. In addition, different level of the wall, window, roof and door were modeled and corresponding total, heating, and cooling energy consumption were obtained.
2. Simulation results were statistically analyzed by the ANOVA method. Both P-value and ANOVA table indicated wall and window are significant factors.
3. Contour plots and surface plot indicated that optimal setting for the lowest energy consumption in the building envelopes. For the window is either intermediate or high level, and for the wall is better to keep as high level.
4. Energy efficient building envelope could save around 16.6 % on the total energy consumptions.
5. Student successfully apply the design the experiments methods and analyze the data using statistical methods in the energy efficient building envelopes design project.

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