Sustainable Design for Hospitals in Taiwan

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***Abstract*—This Hospitals consume large amounts of energy due to its operation characteristic. The HVAC system designed in hospital buildings runs 24 hours and has special air supply requirements. This study aims to evaluate the energy-saving efficiency of HVAC system by studying two Taiwan's green hospital buildings. Results show 39.3% energy saving efficiency based on integrating VFD (Variable Frequency Drive) chiller, VAV (Variable Air Volume) system and VWV (Variable Water Volume) system for an existed hospital buildings. Verification shows eQUEST simulation results are within 7% margin of error. The new-built hospital is evaluated based on appropriate parameter assumptions and life-cycle analysis (LCA). Four cases are generated based on different chiller capacity designs. Four cases are estimated to reduce an average 40% energy consumption compared to the baseline model. It is concluded that the optimum chiller capacity design are two 300RT chillers with investment cost of 8,848,400 NTD and life-cycle cost of 69,150,134 NTD. Total payback period is four years. To sum up, this study demonstrates the integration of computer simulat1ion and LCA in evaluating green hospital buildings, and the HVAC energy-saving performance is approximately 40%.**

Keywords—Hospital Building; HVAC; Energy Simulation; eQUEST; Life Cycle Analysis

I. INTRODUCTION

The number of hospital building in Taiwan has increased due to domestic care demand rises. Many systems in hospital are operated 24 hours, including electricity system, HVAC (Heat, Ventilation and Air-Conditioning) system, and emergency systems which should all be maintained stably to provide reliable service. Hospitals consume large amounts of energy. Among all the electricity consumption in hospitals, HVAC system accounts for nearly 50%, equipment use accounts for 30%, lighting use accounts for 20% [1].

HVAC system design and operation play an important role in managing energy consumption of hospital buildings. For existed hospitals under renovation or new-built hospitals, it could be helpful and energy efficient if HVAC system can be early evaluated by implementing energy simulation tool to propose the best HVAC design. Taiwan's green building certification system EEWH has been established more than ten years. HVAC system design is one of the highest score which can be achieved by adopting energy-saving design.

Study of hospital energy use can be divided into two types: building envelope and energy concerning to internal use. Chou [2] studied regional hospitals based on building envelope and concluded that the EUI (Energy use Intensity) value of regional hospital buildings are 225 kWh/m2・year. In Taiwan's green building certification published in 2012, the EUI value is 254 kWh/m2・year. With more sophisticated technology and equipment used in hospitals, the energy consumption also climbs up compared to years ago. Chen [3] studied energy consumption of hospitals by measuring the actual electricity use, and concluded the most energy-consuming area in hospital is operating room, see Table 1.

TABLE I. ELECTRICITY CONSUMPTION IN HOSPITALS CHEN [2]

Area	EUI (kWh/m^2・year)
Out Patient Clinic	234.9
Rehabilitation	367.3
Pharmacy	511.4
Radiology	514
Hemodialysis Unit	597.1
General Laboratory	695.7
Patient Room	276.5
Emergency Room	448.7
ICU	562.5
Operating Room	740.1

Energy-saving design in HVAC system have been developed and are widely adopted by designers in recent years, including using VSD (variable speed drive) chillers, variable air volume system, and variable speed pump to increase energy use efficiency. The above systems are the most widely adopted HVAC energy saving designs. This study will discuss the energy saving performance based on the above three designs to evaluate the potential energy saving performance of hospital buildings by using energy simulation tool.

TABLE II. HVAC ENERGY SAVING DESIGNS

System	Description
VSD Chillers	Use variable speed drive to adjust motor speed when chillers are in part load capacity operation

VAV	Control temperature by varying the supply air volume
VWV	Use variable speed pump to allow pump to operate over a wide speed range

The concept of energy simulation began when need for environmental protection in construction industry increased. Energy simulation provides a tool to evaluate different design alternatives in early designing stage. Famous simulation tools include DOE-2, EnergyPlus, eQUEST etc. Different software has its own designed input interface and load calculation process. Energy simulation tool chosen in this study is eQUEST3-64 version, developers are constantly updating and adding new features to make sure programs are efficient in use. Singh [4] compared the difference in model built-up process and calculation results between eQUEST and DesignBuilder. All input data were the same in both software. However, there was constant difference of 7% in calculation result. The reason was finally tracked down to the area of the experimental models. Design Builder used user-defined dimensions as external boundary, and deducted the external wall thicknesses from the plan reducing the floor area. However, eQuest treated it as internal zone space and kept the full area as conditioned floor area.

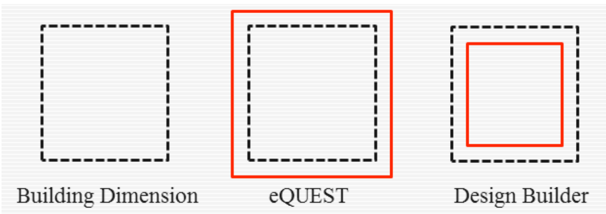

Fig. 1. Building Dimension Definition

Rallapalli [5] compared the simulation process and result between EnergyPlus and eQUEST. Results show that EnergyPlus provides more accurate calculation results than eQUEST, while eQUEST performs better in terms of calculation time. Ke [6] uses eQUEST in examining the energy-saving performance of an office building by applying IPMVP Option D verification process. It is concluded that eQUEST calculation results can be verified within 6% margin of error compared to actual data. Lee [7] concluded that compared to VAV and VWV system, energy-saving design in chillers performs the best energy-saving efficiency. The life cycle year of HVAC systems are usually 5 to 10 years. It is important to consider the time value of money when it comes to evaluating the investment benefit and payback period of HVAC systems. Chan [8] uses saving to investment ratio (SIR) evaluating the best design option for chillers in a building renewal project, energy cost is also considered to provide a comprehensive financial analysis for HVAC system.

II. METHODOLOGY

This study aims to use energy simulation tool eQUEST 3.64 to simulate a hospital building and verify with actual electricity data. Based on the experience1 familiarizing using eQUEST and model built-up process, a new-built hospital is evaluated to propose the ideal HVAC design based on the energy consumption and life cycle cost study. Research flowchart is shown in Figure 2.

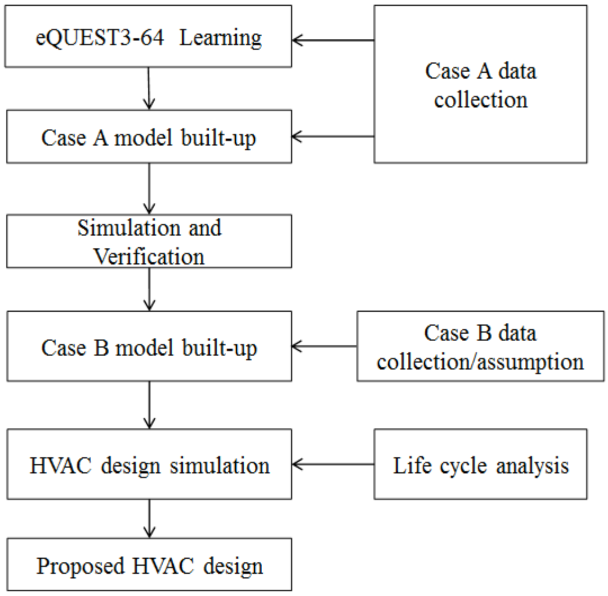

Fig. 2. Research flowchart

A. *Study Scope*

Two hospitals chosen in this study are located in the center of Taiwan. Level of hospital is regional hospital (medium scale with the amount of inpatient bed over 250). This study focuses on studying the electricity consumption and energy-saving efficiency of HVAC systems, heat and natural gas energy are not discussed in this study.

B. *eQUEST*

Input data in eQUEST includes climate data, building footprint, space allocation (zoning), material property/placement of windows and doors, heat load and occupancy (lighting, equipment and people), HVAC system design, indoor temperature and schedule. Building footprint is collected from hospital management manager who provides the original CAD drawings of architectural and HVAC designs. Lighting and equipment density are collected from hospital's central monitoring center, site visit and data from previous study [3]. Occupancy schedule is investigated through paper survey. The whole input process takes time to finish and check. Figure 3 shows the process of how eQUEST calculates thermal load.

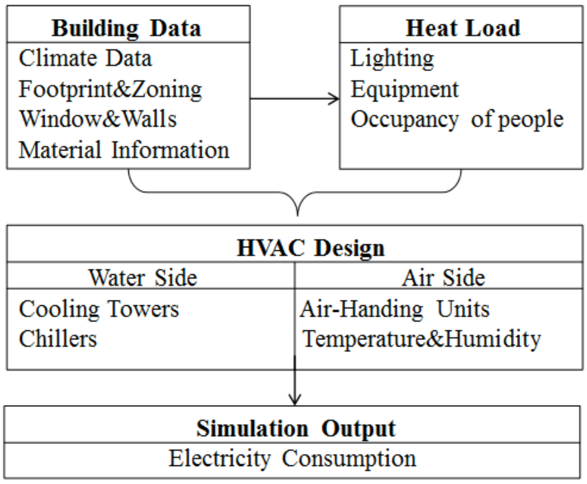

Fig. 3. Thermal Load Calculation of eQUEST

C. Life Cycle Analysis

Life cycle analysis in this study considers the investment cost, maintenance and repair (M&R) cost, replacement cost, and energy cost of HVAC system. Life cycle year uses 15 year based on the average life cycle year of chillers. Cost data are collected from HVAC system suppliers. Calculation model is shown in Figure 4.

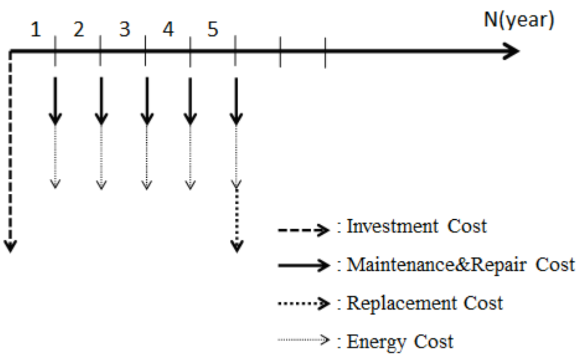

Fig. 4. Life cycle analysis

Payback period is calculated by considering the energy cost which can be saved. Taiwan's hospital buildings usually sign individual contract with electricity supply company to determine the unit electricity price. Unit price in summer will be charged higher than non-summer period. The unit electricity price used in this study us listed in Table 3.

TABLE III. ENERGY COST [9]

Season	Price (NTD)
Summer (Jun.-Sep.)	2.55
Non-Summer	2.37

During the life cycle year, it is estimated to have 2% increase annually in energy cost, see Figure 5. In compounding interest calculation, i=2% is used in calculating the time value of money based on current statistical data provided by Taiwan's financial authority [10].

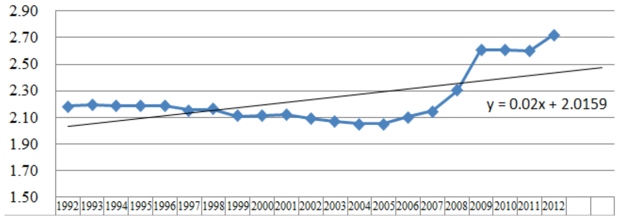

Fig. 5. Average Electricity Price in Taiwan since 1992.

III. CASE STUDY-HOSPITAL A

Hospital A was launched since 2007 and was certified as green building with achieving four energy-saving indexes. Electricity cost accounts for 90% of total energy cost. Hospital A is 24-hours monitored in electricity and emergency use, and provide optimum computer control in HVAC system. Building information of hospital A is shown in Table 4.

TABLE IV. HOSPITAL A - BUILDING INFORMATION

Content	Detail
Climate Zone	Taichung, Taiwan
Orientation	N-S
Floor	B2-6F
Floor Area	32526 sqm
Conditioned Area	25328.7 sqm

A. Data Input

Data input is eQUEST takes time and effort to finish. Try and error method is used during model built-up process to investigate the setting that most fits with actual design. Heat transfer property of building envelope should be input in imperial unit in eQUEST. Table 5 shows input data in SI unit.

TABLE V. DATA INPUT OF HOSPITAL A

Category	Content	Detail
Building Envelope	Exterior Wall	U=3.5 $W/m^2.k$
	Curtain Wall	U=2.4 $W/m^2.k$
	Interior Wall	U=0.68 $W/m^2.k$
	Roof	U=0.75 $W/m^2.k$
	Window	U=5.68 $W/m^2.k$
Lighting Power Density	Medical Area	15W/m^2
	Public Area	12W/m^2
	Corridor	10W/m^2
	Patient Room	11W/m^2
	Office	15W/m^2
HVAC chillers	Centrifugal	420RT*2
	Screw	250RT*2

Building footprint defined in the model is drawn according to the conditioned area line of each zone. There're no tall buildings around hospital A, sunlight affected by surrounded tall buildings can be ignored. Interior occupancy is mainly divided into 12-hour for office use, and 24-hour for medical use. Model of hospital A is shown in Figure 6.

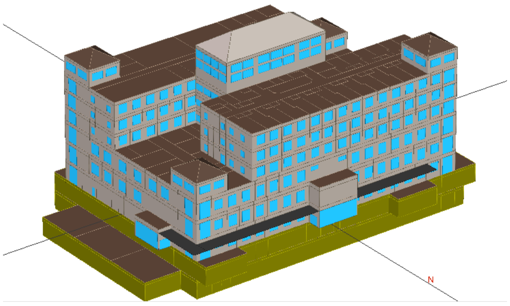

Fig. 6. Hospital A model in eQUEST

B. *Verification*

Verification result of hospital A is shown in Table 6. Actual data is the average electricity consumption of each month between year 2009 to 2012. Electricity consumption in 2007 and 2008 are excluded due to the uncertainty of space use in the first two years of building operation. Simulation results are within 7% margin of error, which proves that eQUEST can perform reliable simulation result with fully understanding model's operation characteristic and adequate data assumption.

TABLE VI. VERIFICATION RESULT

Actual (1000kWh)	Simulated (1000kWh)	Error (%)
404.2	419.9	3.9
415.4	398.8	-4.0
502.8	470.9	-6.3
498.8	512.2	2.7
603.7	603.2	-0.1
631.0	607.0	-3.8
639.5	647.1	1.2
657.8	630.4	-4.2
627.2	591.7	-5.7
578.1	592.2	2.4
502.3	470.6	-6.3
465.6	454.4	-2.4

C. *HVAC Energy-Saving Analysis*

Three energy-saving designs: VSD chillers, VAV system, and VWV system are discussed in this study to investigate the energy-saving performance of HVAC system. In eQUEST, variable speed drive in chillers is set up by inputting coefficients of performance curve to simulate VSD chillers. VAV ventilation system and VWV system is set up by selecting eQUEST program setting from constant to variable. Energy saving efficiency is calculated by formula (1).

$$ESP = \frac{(WESD - BL)}{BL} \times 100\% \quad (1)$$

ESP: Energy-saving percentage
BL: Electricity consumption of baseline model
WESD: Electricity consumption without HVAC energy-saving design

Baseline model is set up exactly the same as hospital A with energy-saving design in HVAC system being implemented. In order to calculate how much energy is saved, energy-saving design is excluded in another model to calculate the energy-saving efficiency of hospital A. Simulation result shows the electricity consumption of HVAC system in hospital A increases 39.3% annually, almost 20% of total electricity consumption of hospital A. Compared to summer period, HVAC system saves more energy during non-summer time because energy-saving design performs better when systems are in part-load supply.

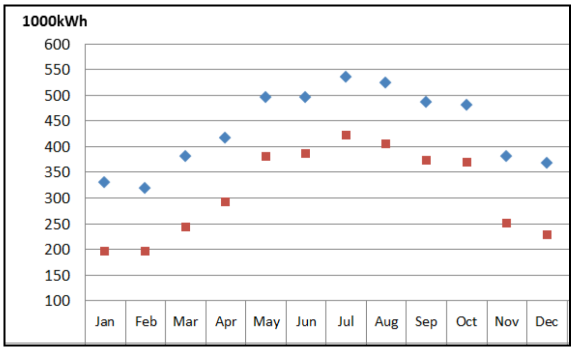

Fig. 7. HVAC energy-saving efficiency of Hospital A

IV. CASE STUDY-HOSPITAL B

Hospital B is under designing stage. Compared to hospital A, it is designed to be a mix-use hospital with 8^{th} to 10^{th} floor used as dormitory. In this part, floor 8 to 10 will not be discussed because the air-condition system is not served by central HVAC chillers. Hospital B contains less conditioning area than hospital A. Building information of hospital B is shown in Table 7.

TABLE VII. HOSPITAL B - BUILDING INFORMATION

Content	Detail
Climate Zone	Taichung, Taiwan
Orientation	North-South
Floor	B2-10F
Floor Area	31130 sqm

N-S

Conditioned Area	11522 sqm

A. Baseline Model Data Input

. Baseline model defined in hospital B will be without energy-saving design, which is different from what is defined in model A. Due to the limitation in collecting building information data from hospital B, building envelope is set up according to ASHRAE standard 90.1-2010 [11]. Lighting and equipment density are input according to Chen's study [3], who has measured the actual electricity consumption of different areas in hospital. The total capacity of chillers is designed to be 600RT. Model of hospital B is shown in Figure 8. Hospital B processes large amount of curtain wall to allow more daylight in the room, which can be expected to reduce lighting power during daytime.

TABLE VIII. DATA INPUT OF HOSPITAL B

Category	Content	Detail
Building Envelope	Exterior Wall	U=3.3 $W/m^2.k$
	Curtain Wall	U=1.46 $W/m^2.k$
	Interior Wall	U=0.68 $W/m^2.k$
	Roof	U=0.78 $W/m^2.k$
Lighting Power Density	Medical Area	13.9W/m^2
	Radiology	16.1W/m^2
	Patient Room	11.3W/m^2
	Office	12W/m^2
Equipment Power Density	Outpatient Clinic	42.3W/m^2
	Operating Room	65.2W/m^2
	Radiology	346.5W/m^2
	Patient Room	15.9W/m^2
	Office	52.1W/m^2
HVAC chillers	Centrifugal	300RT*2

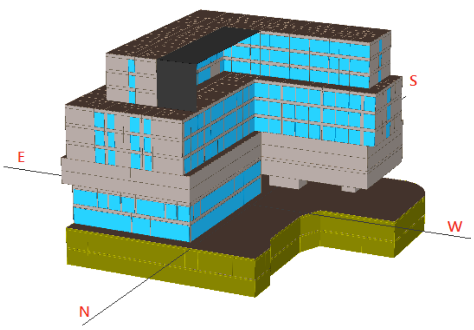

Fig. 8. Hospital B model in eQUEST

Baseline model simulation result is shown in Table 9. Total electricity consumption is estimated to be 2,439,100 kWh each year. This will be used as comparison basis for simulating different HVAC design alternatives.

TABLE IX. HOSPITAL B –BASELINE MODEL SIMULATION RESULTS

Month	Electricity consumption of HVAC system (1000kWh)
1	165.4
2	155.7
3	185.6
4	199.7
5	225.0
6	225.4
7	244.0
8	235.3
9	225.7
10	224.0
11	176.5
12	177.9
Total	2439.1

B. Design Alternatives

Chiller design have huge impact on HVAC energy consumption. This study uses the total capacity of baseline chillers (600RT) to generate different capacity combinations. Taiwan's green building regulations also indicates that at least two chillers should be used in hospital buildings. Four design alternatives are simulated, see Table 10. All designed chillers are centrifugal chillers with VSD.

TABLE X. DESIGN ALTERNATIVES

Case	Chillers (RT)
1	200+200+200
2	300+300
3	400+200
4	500+100

N-S

Energy efficiency calculation in hospital B is different from hospital A. Baseline model defined in hospital B is input without any energy-saving design in HVAC system. Energy efficiency is calculated using formula (2).

$$ESP = \frac{(BL - ESD)}{BL} * 100\% \quad (2)$$

ESP: Energy-saving percentage
BL: Electricity consumption of baseline model
ESD: Electricity consumption with HVAC energy-saving design

Simulation results shown in Table 11 indicates that case4 has the lowest HVAC energy consumption. Average energy-saving efficiency is expected to be 40%.

TABLE XI. SIMULATION RESULT

Case	Design alternatives(RT)	Simulated Result (1000kWh)	ESP (%)
1	200+200+200	1500.9	38.5%

2	300+300	1432.9	41.2%
3	400+200	1480.7	39.3%
4	500+100	1355	44.4%

C. *Life Cycle Analysis*

In this part of the study, life cycle analysis is used to compare different design alternatives and provides recommendation from financial point of view. Maintenance&repair cost is calculated every 5 years. Table 12 shows the life cycle cost of each design alternative. Case 4 has the lowest life cycle cost compared to other three cases.

TABLE XII. LIFE CYCLE COST

Content	Case1	Case2	Case3	Case4
Investment Cost	8848.4	8848.4	9168.4	8728.4
Total life cycle cost	74382.3	69150.1	71139.3	66216.6

a. Unit: 1,000NTD

Table 13 shows the payback period of each design case. Four cases have average 4.3 years based on the energy cost which can be saved.

TABLE XIII. PAYBACK PERIOD

Year	Case1	Case2	Case3	Case4
1	2226.8	2387.1	2275.8	2574.6
2	4453.8	4774.2	4551.7	5149.3
3	6680.5	7161.2	6827.4	7723.9
4	**8907.3**	**9548.2**	9103.1	**10298.4**
5	11134.0	11935.1	**11378.8**	12872.9
Initial Cost	8848.4	8848.4	9168.4	8728.4
Payback period	4	4	5	4

a. Unit: 1,000NTD

To conclude the life cycle analysis, case 4 performs the best in terms of life cycle cost analysis. The reason for this is because case 4 contains 500RT chiller which has higher COP. However, it is risky to implement and reply only on one primary chiller in the air supply of hospital. Once the primary chiller is under maintenance or malfunctioned, the whole air supply in hospital will be jeopardized. Case1 and case3 both have the same capacity of chillers, once any one of them is under maintenance or malfunctioned, there are the other chillers which can provide sufficient air to hospital. Therefore, the better option will be using case1.

V. CONCLUSION

This study integrates energy simulation in evaluating hospital buildings. Using eQUEST in simulating complex hospital buildings is reliable with 7% margin of error. Study results also conclude that HVAC energy-saving design proposed by Taiwan's green building regulation can largely lower the electricity consumption of HVAC system, saving nearly 40% of energy consumption. The life cycle year of proposed design is four years. For future study, automatic data input in eQUEST can be developed to increase project evaluation efficiency.

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