Energy Conservation Measures in an Institutional Building by Dynamic Simulation Using DesignBuilder

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Abstract: - In this study, various energy conservation measures (ECMs) on heating, ventilating and air conditioning (HVAC) and lighting systems for a 4-storied building in subtropical (hot and humid climate) Central Queensland, Australia are evaluated using the simulation software called DesignBuilder (DB) which is based on EnergyPlus (EP) simulation engine. Energy consumption profiles of existing systems i.e. base case scenario are analysed and simulated first then, the simulated results are verified by on-site measured data using Hobo data logger and smart meters. ECMs, namely variable air volume (VAV) systems instead of constant air volume (CAV), photo electric dimming control system instead of general lighting, and double glazed low emittance window instead of single glazed window are evaluated. The effect of indoor environment on these ECMs is also discussed. It has been found that the building considered in this study can save up to 26.5% energy without compromising occupancies thermal comfort by implementing the above mentioned ECMs into the existing system.

Key-Words: - Energy conservation measures, hot-humid climate, DesignBuilder, energy simulation, variable air volume system, energy efficient lighting and day light control.

1 Introduction

Dynamic simulation of HVAC and lighting energy consumptions in the buildings are of considerable interest for engineers and architects due to its cost effective way of analysing and assessing ECMs before or after the building is built or retrofitted. Many institutional and office buildings in Australia use traditional cooling systems. Different ECM makes Australia both technologically and economically feasible in different climatic condition [1]. ECMs often provide better indoor air quality (IAQ) and enhance occupancies productivity [2]. However, a cost penalty is experienced if poor IAQ is traded for reduced energy consumption [3].

Building sectors are responsible for approximately 42% of the world's total annual energy consumption [4]. Most of this energy is used for the provision of lighting, HVAC systems and electricity based office appliances. Buildings in the developed countries account for 50%-60% of electricity use [5, 6]. In Australia 70% of the end-use energy consumption in non-residential buildings is devoted to HVAC and 15% to lighting [7]. Of the energy used for space conditioning 65% is in the form of electricity [8]. Studies have shown that energy savings of around 30% can be achieved through retrofit options in existing buildings without compromising the indoor comfort [9]. The operating costs of a building could be improved if the lighting and HVAC system of the building can be made more energy efficient. This study focuses on various ECMs that could potentially be implemented at any region in Australia. ECMs include a cost-effective way to improve the energy efficiency of a HVAC system by implementing VAV instead of CAV, double glazed window instead of single glazed and day light control instead of general lighting. To achieve these objectives, an appropriate simulation tool is first required which can efficiently and accurately simulate the performance of building HVAC systems. Although, many simulation programs are available, all of them do not meet these criteria [10-12].

A new and unique graphic user interface based simulation tool DesignBuilder [13] is used in this study to evaluate the above mentioned ECMs in a university building in subtropical Rockhampton, Central Queensland, Australia. DB's calculation method is based on EP simulation engine [14]. DB creates a virtual environment where HVAC and lighting systems of the building are evaluated in order to determine the feasibility of various ECMs without compromising thermal comfort. The capability and accuracy of this new simulation tool is demonstrated through a case study on a 4-storied building system. The results of the simulation are verified with measured data and then, compared with different energy conservation strategies. Thermal performance of these ECMs strategies are also evaluated and verified by thermal comfort index.

2 Building and System Description

The information technology division (ITD) building, a four-story university building was selected for this case study. The building is located in Rockhampton campus of Central Queensland University (CQU), Australia at Latitude 23.4 S and Longitude 150.5 E. Its orientation is 75 metres in the east-west direction and 45 metres in the north-south direction (345° N). Complete air-conditioned floor area of the building is 4260 m^2 and has floor-to-floor height of 4.2m. ITD Building has a fairly standard construction, with light weight 130mm concrete floor slabs, single glazed conventional external walls (40%) with blind, light weight 100 mm cavity brick partition wall covered with 2×15 mm^2 gypsum board, suspended type 15mm ceiling tiles. Occupancy rate is $10m^2$/person with 10L/s outside air rate. The lighting system serving the building is mainly of regular 40 Watt double fluorescent lamps. The HVAC systems used in the building is constant air volume (CAV) with 17 air-handling units (AHUs) serving the different zones of the building. The cooling of the building is provided by chilled water from the plant through two reciprocating air cooled chillers with their total capacity of 747.2 kW. Both chillers are controlled by the cooling demand of the AHUs. Each floor has separate thermostat control with zone set points between 23.5 to 24 °C for summer and 21.5 to 22 °C for winter.

2.1 Data Collection

Each zone of the building was physically investigated with the assistance of the building's operation and maintenance personnel in order to obtain information and data on the building lighting, equipment and occupancy for the purpose of knowing details of thermal characteristics of building envelope. The building architectural and engineering drawings were also studied. The equipment used in this building includes personal computers, small and large printers, Xerox machines, and few scanners. Total number of equipment and lighting fixtures of each zone of the building was counted. The power densities of equipment were calculated according to ASHRAE standards [15]. Information on HVAC systems, AHUs and chillers was collected as per the design data, equipment tags, as well as the information provided by the building maintenance personnel. The model was assessed using 2006 electricity data.

2.2 Simulation and Base Model Development

DB is one of the most comprehensive user interface for EP dynamic thermal simulation engine. The DB knowledge base can be organized into different categories. These are model importing CAD, template components, material database, natural ventilation model, etc. EP is a stand-alone simulation program without a 'user friendly' graphical interface. DB joins the software EP calculation model and maintained the EPBD (European Parliament Board of Directive) European standards [16]. The simulation principle used by DB is the most detailed simulation with dynamic parameters and they include all energy supply and energy dispersion. However, EP uses a modular program structure, which makes the calculation method easy to understand and modify. The EP solution is based on the heat balance technique referred to as the Predictor–Corrector Method [17] and assumes that the room air is well stirred, providing a uniform temperature. The basic strategy behind the Predictor-Corrector Method is to predict the mechanical system load needed to maintain the zone air set point, and then simulate the mechanical systems to determine their actual capacity, and then recalculate the zone air heat balance to determine the actual zone temperature.

DB models were structured in order of site, building, block, zone and surface data. This structure sets up data globally in a building model. Building blocks are basic geometric shapes that are used to assemble a 3D model as similar to the building physical model made of bricks. In the modelled building (Fig.1), building blocks, which represent the outer shell of the model or part of the model, are composed of building elements such as walls, floor slabs and roofs, and are partitioned internally to form thermal zones. The partition of the space boundaries of the thermal zones were modelled according to the HVAC drawing. The whole building energy simulation was performed using data from the nearest available hourly weather station (Rockhampton Airport).

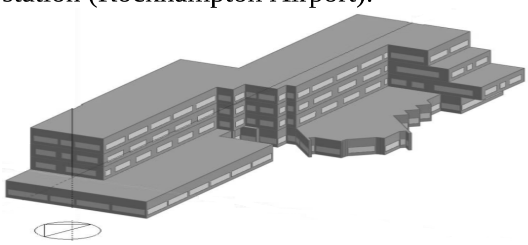

Fig.1 Model geometry of ITD building in DB

2.3 Validation of the Base Model

Model validation is an essential task to ensure that the architectural, mechanical and electrical systems are properly modelled and integrated together for the purpose of estimating the building energy performance. Either hourly or monthly data can be employed for validation [18]. Kaplan and Canner made recommendations for the maximum allowable difference between predicted and metered data [19]. For instance, the prediction of energy use is satisfactory when the difference is within 5% on a monthly basis and 15% on a daily basis for internal loads such as lighting, appliances or domestic hot water. However, the acceptable difference may increase up to 15%-25% (monthly) and 25%-35% (daily) for the simulation of HVAC systems. The annual simulated energy use should be within 10% of metered data, while a difference less than 25% is acceptable on a seasonal basis.

The capacity of DB is not only to predict zone loads, cooling coil loads, cooling equipment energy consumption but also to predict zone environmental parameters such as temperature, humidity, etc [20]. For calibrating the base model, data were collected from the building energy management system (BMS), HOBO data loggers and smart meters. In the simulation the temperature of existing system (base case) was maintained about 23.5^{o}C during the occupied period of a typical summer day. Simulation results of energy consumption of HVAC system, lighting system and office equipment are compared with the real consumption of ITD building's electricity in 2006. The inputs of internal loads, HVAC system, infiltration, non-HVAC systems are revised and refined as a continuous calibration process to achieve an acceptable degree of convergence between measured and estimated data. The simulated values of monthly total energy consumption in a typical year are compared with the measured data in Fig. 2. It was found that the simulated results are within 9 % of the measured value. This demonstrates that the DB predictions are in good agreement with the data collected by the BMS, HOBO data loggers and smart meters at the ITD building.

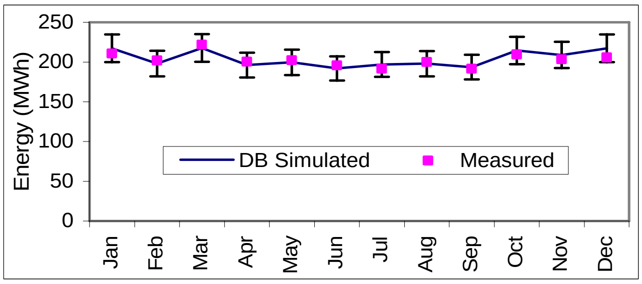

Fig.2 Measured vs. simulated energy consumption

The simulated results also showed that the average monthly total electricity consumption of the building is about 310.96kWh/m^2 in the year 2006 which is closed to the metered data (311.04 kWh/m^2). Fig. 3 compares the simulated temperature profile with measured temperature. The simulated temperatures were found within 3.4 % variation with the measured value during the working hour (08:00 to 18:00) of a typical summer day (Fig.3). Hence, it can be concluded the baseline model is capable of producing approximately the actual operating condition of the existing ITD building.

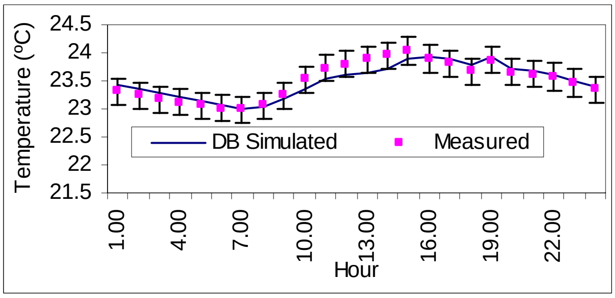

Fig.3 Measured vs. simulated temperature in a day

3 Evaluation of ECMs

An evaluation was performed from the baseline model to establish the potential of energy savings in the building. The energy consumption breakdown for modelled building is shown in Fig. 4. It can be seen from Fig.4 that the largest amount of energy (48.1%) is consumed by the office appliances while HVAC system consumes 32.3% and lighting system consumes 19.6%. In this study, the retrofit options were investigated only for the HVAC system and lighting system of the building. ECMs analysed were VAV instead of CAV, daylight control instead of general lighting and energy efficient low emittance double glazed window instead of high emittance single glazed window. These are discussed below.

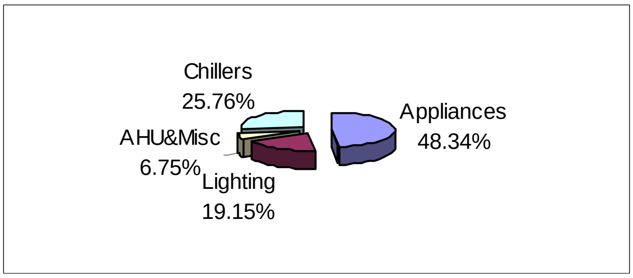

Fig.4 Total building energy consumption breakdown

3.1 ECM by VAV against CAV

In the CAV system, all AHUs fans operate with constant speed. They supply conditioned air through a constant volume air supply system to the conditioned zones. The system is designed to supply enough air to cool the building under design conditions. As an ECM, changing the system to a VAV system reduces the amount of air supply by all AHUs as a function of zone load and normally results in less energy to condition the various zones. Three different VAV options namely VAV1 with outside air reset, VAV2 with terminal reheat and VAV3 with fan assisted-terminal reheat were simulated for evaluating ECM. The simulation results are shown graphically in Fig.5. About 26.5% chiller energy savings can be achieved using VAV1 option. It is equivalent to 12.4% of total energy consumption.

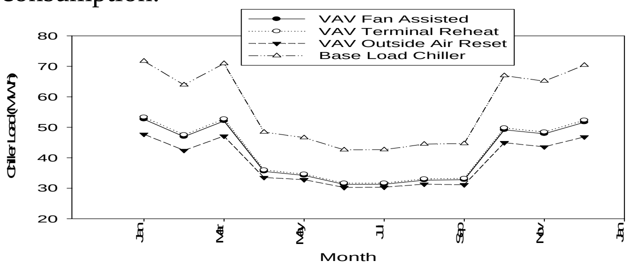

Fig.5 Chiller energy savings under various VAV

3.2 ECM by Daylighting with Energy Efficient Lamp

Lighting for a typical office building represents about 40% of the total electrical energy use [21]. There are a variety of simple and inexpensive measures to improve the efficiency of lighting systems. As an alternative to standard lighting, daylighting offers a lighting source that most closely matches human visual response and provides more pleasant and attractive indoor environment. It is also reported in the literature that daylighting improves student performance and health in classes [2]. These ECMs include the use of energy-efficient lighting lamps and dimming control ballasts. Currently, for the case study building, 40 W fluorescent lamps are being used. As an ECM, energy efficient fluorescent lamps with the power of 34 W and three different dimming control strategies namely T8 Fluorescent-triphosphor with (1) Linear, (2) Stepped and (3) On/Off dimming day lighting control were considered for simulation. The monthly electric energy savings are shown graphically in Fig.6.

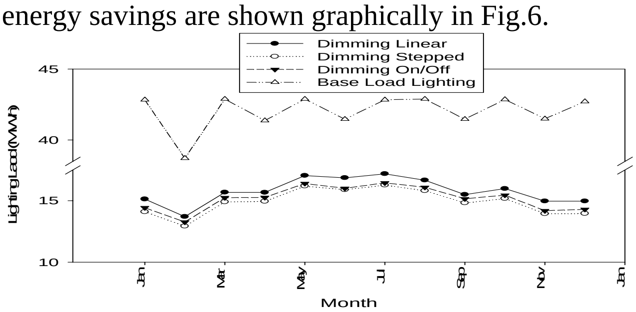

Fig.6 Lighting energy by various Dimming control

In this case, the highest energy consumption is reduced up to 34.5% monthly in comparison with base light consumption by considering T8 Fluorescent-triphosphor with Stepped option. On the other hand, a huge amount of heat gain is reduced by using daylighting strategy in the building. As a result, an additional 12.8% chillers energy savings also contributed from this daylighting strategy which is shown in Fig.7. It is equivalent to 15.6% of total energy saving by this daylighting strategy.

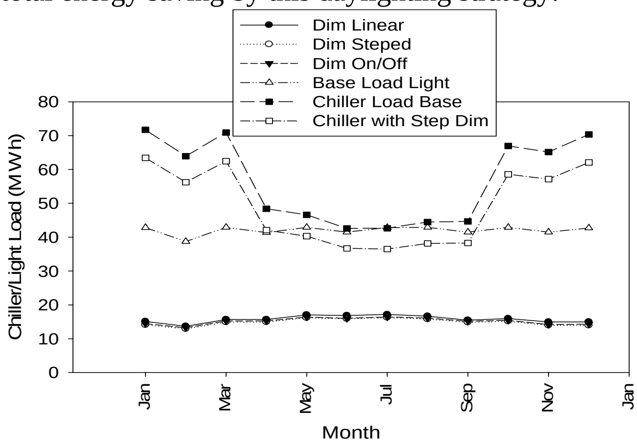

Fig.7 Chiller energy saving under various Dimming

3.3 ECM by Energy Efficient Window Glazing

Energy-efficient window glazing (high *R*-value and low emissivity) could be favourable in both reducing the energy use and improving the indoor comfort levels. As an ECM, the existing glazing systems were replaced with three different low-emissivity double-glazed window. Details of existing and one alternate glazing system characteristics are shown in Table 1 and the other two types of glazing are similar but only differences in emissivity, 0.2e and 0.3e instead of 0.1e. The simulation results of the new systems arrangement are shown graphically in Fig.8. In this case, the highest energy consumption of chillers is reduced by 4.9% monthly and it is equivalent to 2.1% of total energy consumption by considering double glazed window of low emittance (e=0.1).

Table 1: Characteristics of glazing systems for ITD

Base case (double-glazed 6/12air/6 mm)	Low-emittance glazing (double-glazed 6/12air/6 mm), e=0.1
U=2.71 W/m^{2}K	U=1.77 W/m ^{2}K
Direct solar transmittance =0.604	Direct solar transmittance=0.474
Total SHGC=0.697	Total SHGC=0.563
Light transmission =0.781	Light transmission=0.745
Color=clear	Color=clear

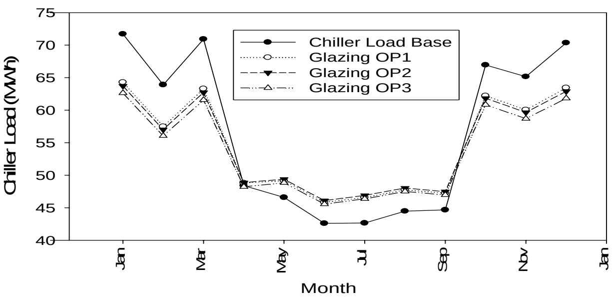

Fig.8 Chiller energy savings under various Glazing

3.4 Thermal Comfort Index

To determine appropriate thermal conditions, practitioners refer to standards such as ASHRAE Standard 55 [22] and ISO Standard 7730 [23]. These standards define temperature ranges that should result in thermal satisfaction for at least 80% of occupants in a space. The standards were developed by Fanger and colleagues on the basis of laboratory studies of whole body thermal comfort, known as the Predicted Mean Vote (PMV) model [24]. The seven-point ASHRAE thermal sensation scale is shown in Table 2. The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and activity level) into an index that can be used to predict thermal comfort.

Table 2: ASHRAE seven point thermal scales

ASHRAE Thermal Sensation Scale						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3

Fanger's mathematical model of PMV is expressed in equation 1.

$$PMV = \left(0.303e^{-0.036M} + 0.028\right) \times L \qquad (1)$$

Where, M = metabolic rate

L = thermal load defined as the difference between the internal heat production and the heat loss to the actual environment.

Thermal comfort index of the modelled building was determined and checked against Fanger's seven point thermal sensational scales. The results of the thermal comfort simulation are plotted in Fig.9 for each of the ECM and they were found within the $-0.5<PMV<+0.5$ limits as per ISO 7730 during office hours on a typical summer day [23].

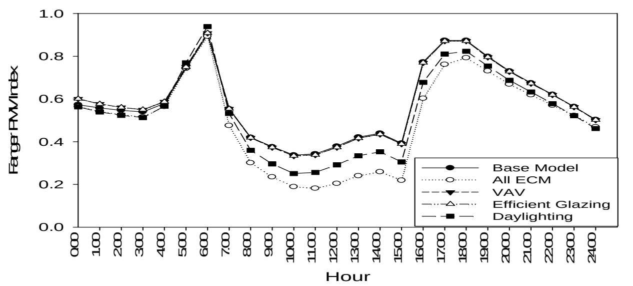

Fig.9 Thermal comfort evaluation in a typical day

3.5 Energy Savings from Combined ECMs

The annual energy consumption of different scenario is shown in Fig.10. From the presented simulation results, energy savings of up to 11.7% can be achieved by using the VAV system only. Energy savings of up to 15.6% can be achieved by using more energy efficient lighting and stepped dimming daylighting control strategies. Double glazed low emissive glazing can also contribute savings of up to 2.1%. By implementing all three ECMs, about 26.5% of total electricity can be saved annually.

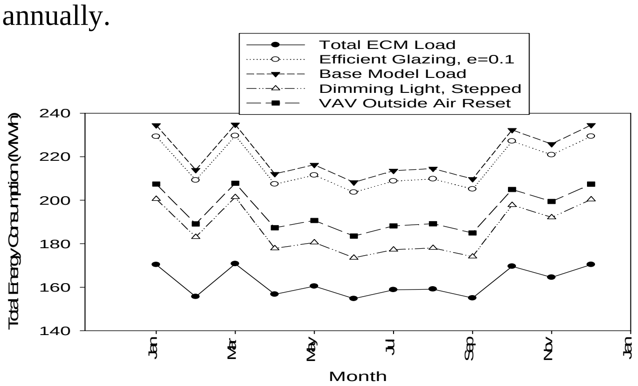

Fig.10 Energy savings under various ECMs

4 Conclusions and Recommendations

Based on the evaluation of various ECMs using the DB energy simulation program, the following conclusions and recommendations can be made.

An annual energy saving of up to 11.7% can be achieved by implementing a VAV system instead of the current CAV system. It is a major investment option. The VAV system can be applied by performing thermal rezoning to the existing building.

By implementing a low-e double-glazed window with a U-value of 1.77 W/m^2-K instead of the U-value of 2.71 W/m^2-K, an annual electric energy savings of only 2.1% can be achieved. This is not a significant savings for investment, however, this can be considered for construction of new buildings. Therefore, current glazing system is considered to be adequate.

By implementing 34 W energy-efficient lamps with stepped dimming control technology, an annual energy savings of up to 15.6% can be achieved. It is the highest savings opportunity and should be given priority for retrofitting. However, it is not practical for replacing all existing lamps with energy-efficient dimming lamps at once. They can be replaced gradually as they burn out. Priority should be given to perimeter area's lights first for replacement.

The combined effect of all ECMs can achieve annual energy savings of up to 26.5%. The study revealed that ECMs can be successfully applied to buildings located in hot and humid climates where high energy use of an air conditioning system is required.

As the weather becomes extreme in summer and mild in winter, it is strongly recommended that a VAV system is used as system renovation takes place in such existing buildings and should be considered for similar climate and office buildings. The applications of VAV and daylighting for ECMs to subtropical regions like Rockhampton are highly recommended.

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