A modelling appraisal of design standards in retrofitting a high-rise office building in Brisbane

Indrika Rajapaksha[1,2], **Richard Hyde**[1], **Upendra Rajapaksha**[1,2]

[1] The University of Sydney, Australia
[2] University of Moratuwa, Sri Lanka

ABSTRACT: This paper reports the testing of appropriate design standards to optimize energy performance in the pursuit of building retrofits. The impact of whole-building "best" and "normal" practice standards are predicted and evaluated using as a case study a forty-year-old heavy core-dependent deep-plan twenty-three storey office building in Brisbane. Predictive modelling used *DesignBuilder* simulation software. A Forward Simulation Model (FSM) and Data-Driven Simulation Models (DDSM) contributed to the evaluation of "normal" and "best" practice standards. With higher thermal resistance in the built fabric the PassivHaus Model (PHM) – a “best” practice standard – demonstrated a maximum energy saving of 9.5%. Findings suggest that retrofitting for energy saving in internal-load dominated office buildings requires strategies to control internal loads. The whole-building energy standards with efficient operational profiles promoted 46% of energy savings, showing systematic appraisal and prediction to derive case-specific design solutions in satisfying the regulatory measures for future commercial buildings in Australia.

Keywords: energy modelling, retrofitting, office buildings, design standards

INTRODUCTION

Modelling performance of retrofit solutions to buildings in respect to energy use becomes an important stage in the decision making process. For this, computer based simulation packages are used to assess the energy behaviour of retrofit solutions. A simulation model representing a respective problem domain is required to ascertain the prediction based on what is desired and what is possible. The modelling involves the input of data in respect to performance comparison among the actual building and retrofit solutions.

Performance predictions using simulation is dependent on two main modelling approaches such as forward modelling and data-driven modelling (ASHRAE, 2005). The forward modelling of an energy simulation is originated by developing a forward building model to represent the actual physical and operational conditions of the reference building utilising physical and mechanical characteristics, occupancy, operating schedules, lighting, plug load densities and weather data . The calibrated forward simulation model will generate energy performance data which will be utilized in data driven modelling to evaluate the retrofit solutions in energy performance optimization.
Performance of retrofit options for energy efficiency is usually evaluated against various design standards set by environmental performance targets. Design standards represent optimum energy performance requirement which are set for either elements of a building or for the whole building system. Elements for retrofitting include envelope component, occupancy, operational profiles and internal loads.

This paper uses a critical case building to present a scenario that shows the energy performance benefits of retrofit options for a whole-building in respect to recognised “normal practice” and “best practice” energy performance benchmarks of ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) standard 90.1-2004 (ASHRAE,2004), Building Code of Australia (BCA,2010), and PassivHaus standard (Wolfgang,2005) .

1. SIGNIFICANCE OF RETROFITTING

More than half of the CBD (Central Business District) building stock of Australian cities constitute of ageing office blocks over 35 years of life span. The commercial sector emissions are expected to grow at faster pace in the Australian cities with a projected annual growth rate of 2.1% (ASBEC, 2009). The existing office stock with business-as- usual practice is accountable for present increase in greenhouse gas emissions. Retaining these aging office buildings with operational inefficiencies will double the CO2 level of 2000 by 2030. Thus the ageing office stock in cities will drive unsustainable levels of GHG (Green House Gas) emissions and present a substantial responsibility to combat the threat of climate change.

Buildings account for a significant share of energy use and around a quarter of Australia’s GHG emissions. Considerable portion of this energy is used in the operational phase of a building for lighting, HVAC systems and office appliances. In developed countries energy used in HVAC is 50-60%. However in Australia 70% of the energy is consumed for HVAC and 15% for lighting (AGO, 1999). Remarkably the energy end use in buildings is dominated by electricity consumption which is dominated by coal fired generation at the end of long transmission networks.

Garnaut climate change review identified that energy efficiency in the building sector offer significant opportunities in reductions of emissions (Garnaut,2008).There is considerable unexploited potential for energy efficiency in the building sector and International Energy Agency foreshadows that 30% of emissions could be saved through retrofit options in existing office and commercial buildings (IEA,2003). Thus retrofitting for operational energy efficiencies becomes significant importance for the sustainability of Australian cities.

2. METHODOLOGY

Methodology of the research used a modelling appraisal of a critical case study building to understand its thermal behaviours. Current obsolete behaviour of the selected case study due to energy consumption and environmental performances demonstrates it as a critical case which provides evidence of more general characteristics of issues of concern and then to develop findings into general propositions and theories (Hyde et al, 2009). The modelling appraisal of selected design standards in respective to energy saving is validated in comparison to actual energy consumption, which is represented by the calibrated forward simulation model.

This paper is not focussed on improvements to the existing HVAC system of the building and will not discuss the material compositions of the envelope components of design standards. Practical interventions and economic considerations of the retrofit strategies will be presented elsewhere.

2.1. Critical case building and mechanical system

The critical case of this study is a 23-story office building located in the city of Brisbane, Australia (Fig.1). Open plan typical floors consist of a service core at the rear centre and office spaces in front and sides. Total building area is approximately 19600m^2 of which net lettable air-conditioned office and commercial areas are approximately 15877m^2. All the floors are above ground, 19 floors (1st, 4th - 21st) consist of air-conditioned typical office spaces of 820m^2. Floor-to-floor height is 3.43m. The front area of the ground floor is consisted of a coffee shop, reception and the rear half is occupied by the mechanical equipment room and service passage. Two naturally ventilated parking floors are in the 2nd and 3rd floors with a floor-to-floor height of 2.6m and the 22nd floor occupies mechanical equipments and a control room. Miscellaneous services such as male and female toilets, fire stairs, lifts and the main lobby are contained in a core located at the rear centre in all levels of the building.

NE- Solid, side facade SE - Front facade NW - Rear facade

Figure 1: Critical case study, 23 story office building located in the city of Brisbane, Australia

Fig. 1 shows the main architectural characteristics of the facades. The street facade is 39m in length, facing Southeast (135°N) direction and composed of wall-to-window ratio of 40%. Double glazed pane windows are fitted with mid pane blinds. Concrete vertical fins with horizontal spandrel panels of varying overhangs, 900mm (level 4) - 500mm (level 22) acts as a local shading device for the glazed window bays of the front facade. The rear facade is composed of same windows, central solid wall and horizontal spandrel panel shading device with 280mm overhang. The side facades of solid textured concrete walls are facing towards NE and SW directions. High volume-to-envelope surface area ratio of 7 confirms the deep plan configuration of the typical office. Table 1 describes the physical characteristics of the building.

The HVAC system of this building is based on a variable air volume (VAV) with terminal reheat. Each floor consists of 7-10 VAV boxes with 4.2 to 6 KW capacity of electric reheat. Cooling of the building is provided by a central plant consists of two water cooled chillers of approximate capacity of1.2MW each, which operates in a common condenser and two cooling towers with variable speed fans. The VAV terminals are programmed for set point between 22-23C for summer (December-February) and 21.5-22C for winter (June-August). Building is located in the centre of Brisbane's CBD. Neighbouring buildings in front and two sides are with 7-9 stories and the rear facade is overshadowed by a taller building with 25 stories.

2.1.1. Occupancy and operational schedules

Occupancy schedule of typical offices in Levels 1, 4 to 18, 20 and 21 were assumed for a range of 80-100% occupancy during the weekday working hours between 08:00-18:00h but Call Centre in the Level 19 operates 24 hrs, seven days per week. The coffee shop in the ground level was assumed of having 40% of occupancy from 8.00 to 12.00h and 14:00 to 18:00h with 80% of occupancy from 13:00-14:00h. Lighting, appliances and HVAC profiles of the typical offices are the same as office occupancy profiles. Open plan offices are provided with lighting power density of 12W/m^2 with a desired illuminance level of 320 Lux. Lighting power densities for parking floors are 6W/m^2.

Components	Description
Envelope	
Walls	200mm RCC dense with 10mm gypsum plastering inside and outside layers, U = 2.6 W/m^{2}K
Internal floors	200mm RCC dense with 20mm cement and sand render
Roof	250mm RCC dense with 20 mm Bitumen pure outside layer, U = 2.3 W/m^{2}K, 15mm suspended gypsum tile ceiling
Glazing	Bronze tinted outer pane, 50mm cavity with venetian blinds and 6mm clear glass inner pane. Total U=2.6 W/m^{2}K; SHGC= 0.6; Solar transmittance (SC) = 0.5
Shading	Front facade (SE direction) - 0.9m overhang of Aluminium clad spandrel panels Rear facade (NW direction) - 0.3m overhang of Aluminium clad spandrel panels
Infiltration rate	1.0 ACH
Internal loads	
Lighting	12W/m^2 - Typical office and entrance lobby, 6W/m^2 - Parking floors T8 Fluorescent, Triphosphor
Equipment	
Computers	15 W/m^2
Office equipment	5 W/m^2
People	
Occupancy	10m^2/person
Ventilation rate	10/l/s-person
HVAC system	VAV system with terminal reheat
Chillers	2 No.s; each with COP 2.5; Capacity 1.2MW, 4 AHU each running for 700Pa pressure, each floor contains 7-10 no.s of VAV boxes
Set point temperature	23°C (summer) 22°C (winter)

Table 1: Physical characteristics of the critical case study

2.1.2. Energy Use and the NABERS (National Australian Built Environment Rating System) rating

Comparison of the electricity bills and aggregated sub metering data of the building for three years revealed an annual average electricity end-use breakdown for HVAC system, tenants (lighting and equipment), lifts and miscellaneous are as 51%, 48% and 9% respectively. Operational energy consumption of the building such as plug load, lighting and HVAC system accounts for 90% of the total annual electricity consumption.

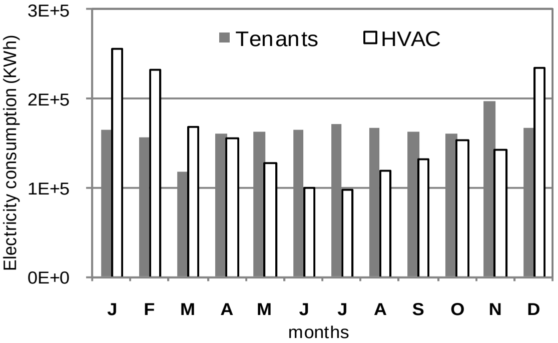


Figure 2: Monthly electricity consumption for the year 2008/09

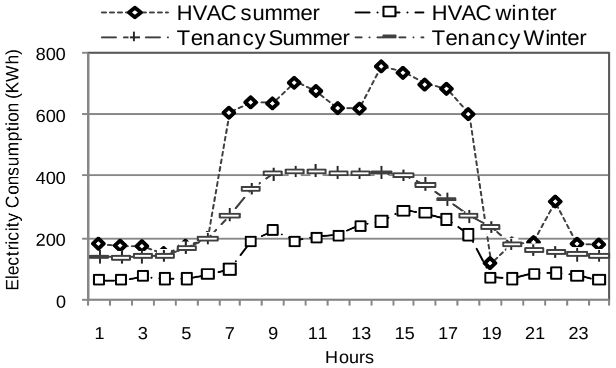


Figure 3: Hourly electricity consumption of summer (13th Feb.) and winter (15th July) typical day

Fig. 2 shows monthly electricity consumption for the year 2008/09. Detailed investigation of the energy usage pattern reveals a clear seasonal variation in the total energy consumption for summer (from October to March) and winter (from April to September) periods. HVAC electricity consumption is higher in the summer months and accounts for 56% of the total annual electricity consumption. Cooling energy load is 62% of the total annual HVAC electricity consumption. L lighting and plug loads in summer and winter periods are 49% and 50% of the total annual tenant's electricity consumption respectively. Fig. 3 shows the hourly tenant and HVAC electricity consumption in a typical weekday of the summer and winter. Cooling and lighting energy usage increases during the daytime from 7:00 to 18:00 hrs which represents the working hours of the day. Large air-conditioned volume and insufficient penetration of daylight have increased the electricity consumption due to artificial lighting and cooling load of high internal heat gains built up inside the building.

NABERS (National Australian Built Environment Rating System), a performance-based energy rating system defines a star rate for energy consumption and greenhouse gas emission for existing office buildings (NABERS, 2010). The ratings are available for three types of energy consumption patterns in office buildings, named as Tenancy, Base Building and Whole Building. The tenancy rating is limited to tenant lighting and equipment energy consumption. The Base building rating considers centrally serviced energy consumption such as common area, exterior lighting and power (including parking areas), lifts and HVAC system. Total energy consumption by tenants and the central services contribute to whole building rating.

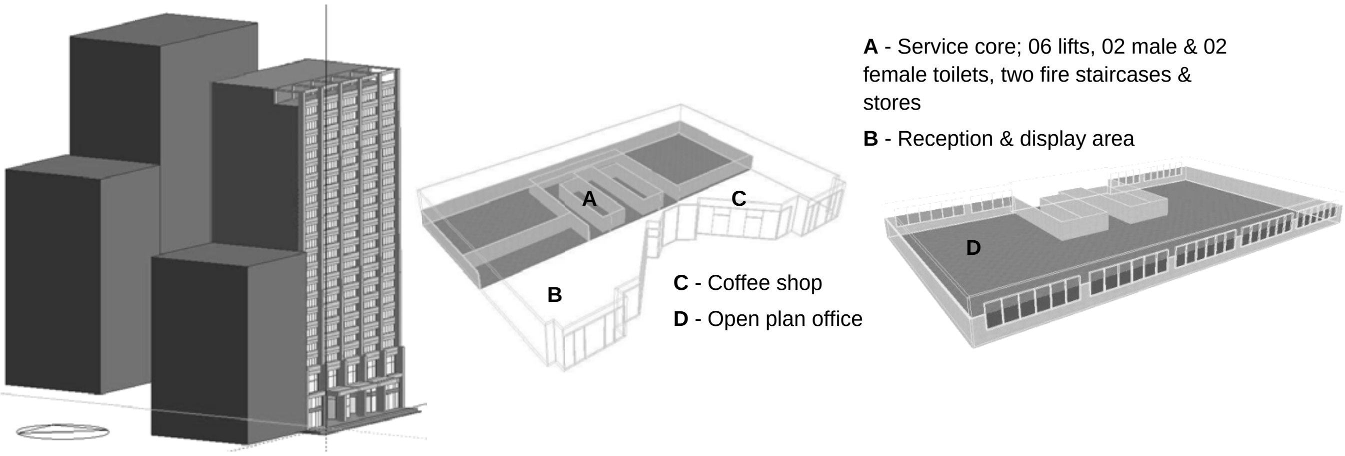
In 2005/06 period, the base and whole building NABERS star rating of the case study was 0 and 1.5 respectively (Bannister, 2006). This has been improved in recent years by the introduction of various energy management measures thus current base and whole NABERS rating is 2.0 stars. Present energy usage confirms its status of criticality in satisfying the four-star energy efficiency rating requirement of Queensland's emission target initiative of 2010. The research aimed to improve its rating to current acceptable levels using non-technological aspects such as operational and occupancy profiles, and technological aspects such as envelope upgrading and equipment efficiencies as defined in design standards. In order to do this, several simulation models were carried out, first in understanding the thermal behaviour and then justifying the performance of retrofit options suggested.

2.2. Model Development

There are many building simulation software programs based on simplified and detailed energy analysis tools. Detailed energy simulation software with dynamic thermal simulation engine provides hour-by-hour detailed energy analysis of buildings accounting for real factors of building's operation such as occupancy and operational profiles. EnergyPlus (EP) is one of the comprehensive energy simulation program used by many researchers as a building energy analysis and simulation tool. DesignBuilder (DB) is a comprehensive graphical utility interface for EP simulation engine. DB interface with EP calculation model maintains the European Parliament Board of Directive standards (EPBD, 2002) and recent standard testing method (ANSI/ASHRAE Standard 140-2007) has confirmed, DB version 2.1 results are identical to EP version 4 (GARD,2009). The dynamic energy simulation tool used in this study is DB version 2.2.5.

A forward simulation model was created, using architectural, operational and mechanical system input data of the selected critical case building. Building typology of heavy-core dependent open plan is a typical urban office built form of early 1970's, which could be classified as an aging office built forms in Brisbane, Australia. This 40 year old critical case of this study is a clear representation of an aging office building stock in the CBD of Brisbane.

Forward simulation modelling was performed with varying weather files and input data of building characteristics. The model acceptance was done primarily through calibration approach based on comparison of daily typical summer and winter week energy usage of HVAC, lighting and plug loads to daily utility bill data. Several simulation runs were performed revising the model inputs and refined the model within acceptable tolerance guidelines of calibrations representing the Forward Simulation Model (FSM). This model was modified with the benchmark envelope and internal load characteristics. Data-Driven Simulation Models (DDSM) were developed in compliance with the parameters defined in three standards.



A - Service core; 06 lifts, 02 male & 02 female toilets, two fire staircases & stores

B - Reception & display area

C - Coffee shop

D - Open plan office

a. Critical case and its surrounding **b.** Ground floor **c.** Typical office floor (Level 4 - 21

Figure 4: Forward simulation model of DesignBuilder graphical utility interface

2.2.1. Forward Simulation Model - FSM

The Forward Simulation Model (FSM) of the critical case building was developed using the accurate physical characteristics which was collected during the onsite building investigation. The building envelope characteristics were gathered from the available architectural drawings and the audit report on building structure and facade (ARUP, 2008). The mechanical system, lighting, equipment, occupancy and operational profiles were collected with the assistance of building's operation and maintenance personnel and referring the energy audit report (Exergy, 2006). The FSM is consists of 98 zones, 23 blocks and each block is composed of 48 opaque and 50 transparent surfaces.

Details of the input data are given in the Table 1. The 3D view of the FSM in relation to the immediate surroundings, ground and a typical office floor level is shown in Fig.4, a, b and c respectively.

2.3. Simulation and calibration

The hourly whole building energy simulation of FSM was performed using Brisbane IWEC (International Weather for Energy Calculations) weather data (EnergyPlus,2010). The FSM was validated by comparing hourly, weekly and monthly electricity consumption predictions to utility bill data. The sub metering utility data was separated from main operational electricity usage categories of an office building such as tenants (lighting and plug load) and HVAC system. Several model calibrations was performed by revising the weather data files, operational profiles, zone set point temperatures, infiltration rates for summer and winter periods.

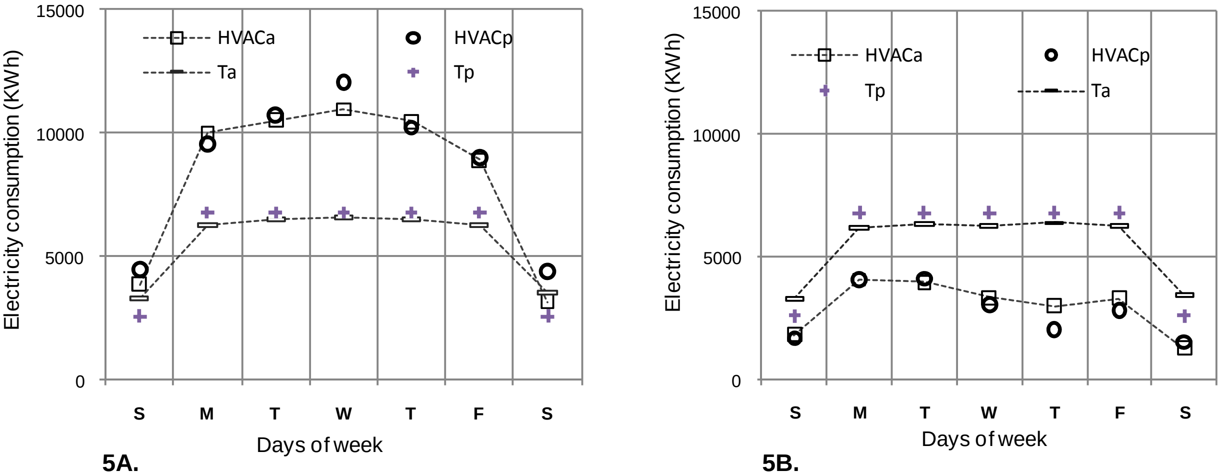
The acceptable tolerance for monthly and annual data calibrations are defined in the ASHRAE Guideline 14 (ASHRAE, 2002), Measurement and Verification of Federal Energy Management Program (FEMP,2000) and International Performance Measurement and Verification Protocol (IPMVP, 2002). Recommended allowable differences for daily, monthly and seasonal data calibrations for internal loads (Kaplan,1992) and the whole building are shown in the Table 2. Lower ERR and CV (RSME) signifies a better calibration (Pan et.al,2007).

Index	**Whole Building (%)**			Index	**Internal loads (%)**	
	ASHRAE 14	IPMVP	FEMP		Tenants	HVAC
ERR_{month}	± 5	± 20	± 15	ERR_{daily}	± 15	± 25-35
ERR_{year}	-	-	± 10	ERR_{month}	± 5	±15-25
$\text{CV(RMSE}_{month})$	± 15	± 5	± 10	$\text{ERR}_{seasonal}$	± 25	

ERR: mean bias error; CV (RMSE): coefficient of variation of root-mean-squared error

Table 2: Acceptable tolerance for daily, monthly and seasonal data calibration

The whole building mean ERR_{month} and CV(RMSE)_{month} for summer months (Oct. - Dec.) are 5% and 10% respectively. The comparison of predicted and actual electricity consumption for HVAC and tenants in summer (10th - 16th Feb.) and winter (13-19th July) typical weeks of the year 2008/09 is shown in Fig.5 A and B respectively.



5A. **5B.**

Figure 5: Comparison of actual and predicted energy consumption data for a typical week (A) Summer (10th-16th Feb.) and (B) Winter (13th -19th July)

Summer typical ERR_{week} for HVAC and tenants are -4.3%,-0.5% and winter ERR_{week} are 7.2% and -2.8% respectively. ERR_{daily} for HVAC and tenants of a typical week day in summer are -1.2%, -6% and winter are 10.6%, 8.3% respectively. Results demonstrate that the whole building and internal load indices are completely within the acceptable tolerances and allowable recommendations for calibrations. Thus the FSM is in a good agreement with the critical case study building and is capable of generating approximate real operating conditions for data-driven modelling for evaluation of the energy performance optimization of benchmark standards.

2.4. Thermal behaviour of the FSM

The predicted energy end- use and thermal performance of the FSM was performed to establish the retrofit measures for energy savings in the critical case building. As shown in Fig.5A the summer typical week consumes more energy than the winter typical week that accounts for 63% of the total energy use. Cooling energy and lighting plus plug load account for 61% and 39% respectively. Largest energy usage of 47% is for chillers and 15% for fans and pumps while office appliances and lighting consume 24% and 15% respectively. Fig 6 shows the heat gain of the building through fabric, infiltration and internal loads during the summer typical week. Internal heat gain accounts for 70% while 30% of heat gain is through environmental loads from the fabric and infiltration of the building envelope. These results show that the case study as an internal load dominated building. Thus verifies the importance of whole building retrofit measures to optimise the building's thermal performance for subsequent retrofit energy savings. The energy performance benchmarks based on multiple energy conservation strategies for building envelope and internal loads encompass improvements to the whole building. This study focuses on the investigation of three types of standards which represents the “normal practice” and “best practice” retrofit strategies.

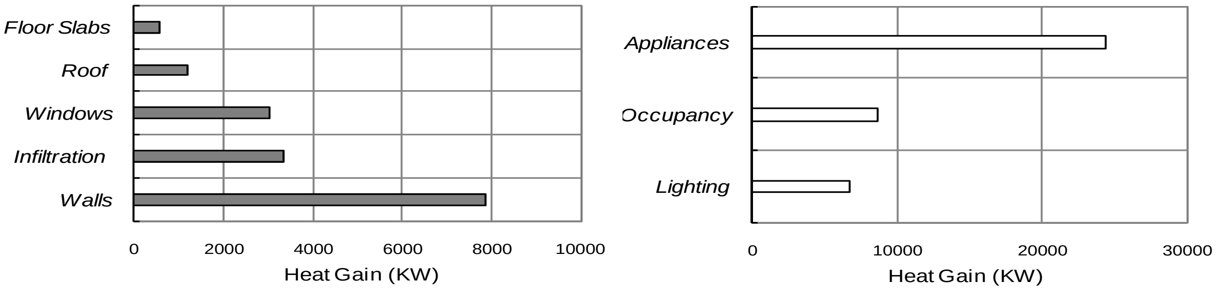


Figure 6: Comparison of heat gains from Fabric, infiltration and internal loads for summer typical week

2.5. Data-Driven Simulation Models - DDSM

Data-driven simulation models were developed for "normal practice standards" - the ASHRAE Budget and Australia Building Code - and the "Best practice standard' - the PassivHaus. The input data of the building envelope and internal loads of ASHRAE Budget, Australia Building Code and PassivHaus standards data-driven simulation models are given in Table 3.

ASHRAE Budget Model (ABM) is an ASHRAE 90.1-2004 compliant data-driven model developed on the minimum performance requirements for a building located in Brisbane, Australia. Building envelope requirements are based on the climate zone derived by the cooling (CDD) and heating degree days (HDD) of the location. The CCD and HDD of Brisbane is 7009 and 545 respectively, represent climate zone 2A.

Australia Code Model (ACM) is a reference building conforming to the envelope and internal gains of the current Building code of Australia, for climate zone 2 class 5 building (BCA, 2010). PassivHaus Model (PHM) is based on PassivHaus standards defined as a holistic approach to improve the thermal performance of the envelope to a level that mechanical system can be kept very simple (Wolfgang et.al,2005). The envelope is characterized by extremely low *U*-values for walls and windows with reduced levels of thermal bridges, very low air leakages, triple glazed panes and insulated window frames. Three DDSMs represents the occupancy, lighting, equipment and HVAC operational profiles of the Section J of the BCA. Internal loads were achieved by reducing lamp wattage with the use of energy efficient light fittings and diffusers.

Components	PHM	ACM	ABM
***Envelope** - U (W/m2K)*			
External wall	0.14	0.3	0.58
Internal wall	0.38	1.0	1.1
Floor slab	0.13	0.5	0.137
Roof	0.09	0.23	0.063
Window frame	0.59	-	1.22
Glazing	0.7	1.3	0.7
SHGC	0.49	0.26	0.26
% Glazed	30-40	30-40	30-40
Shading co-efficient	-	-	0.3
Infiltration (ACH)	0.11	0.5	0.5
Internal loads			
Lighting (W/m^2)	10	9	12
Equipment (W/m^2)	15	15	15
Occupancy (m^2/person)	10	10	10
Ventilation rate (l/s-person)	10	10	10

Table 3: Envelope and Internal loads of models

3. RESULTS AND DISCUSSION

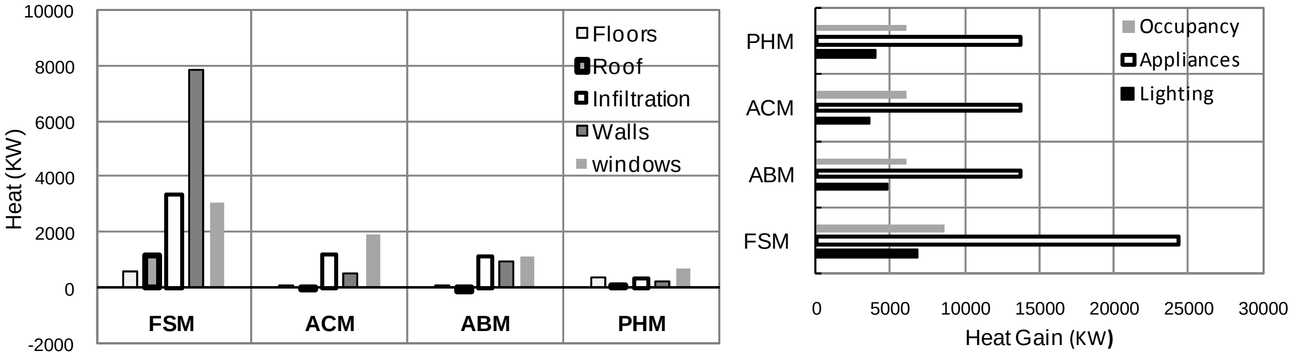
In this paper energy performance optimization benchmarks of "normal practice" (ABM and ACM) and "best practice" (PHM) standards are evaluated. Thermal behaviour of this heavy core dependent open plan air-conditioned office building is influenced by both the envelope characteristics and internal loads generated through occupants, appliances and lighting. Results of the simulations show that the internal heat load due to equipment and lighting as the main contributor of energy use. A holistic approach amalgamated with the strategies to improve thermal efficiency of the envelope and also the internal load reduction strategies with appropriate operational profiles will result in a significant energy saving.

3.1. Thermal behaviour appraisal of DDSMs

The insulated building envelope with varying component *U*-values specified in the standards defines different insulation thicknesses for different levels of thermal resistance. A cross comparison diagram of thermal behaviour of the insulated total envelope of DDSMs with the un-insulated total envelope of FSM is presented in Fig. 7. As shown in Fig. 7A, the percentage reduction of total heat gains of ACM, ABM and PHM are 70, 75 and 87 respectively. Thus the results are evident for significant reduction in the total envelope heat gain in DDSMs.

Heat gain impact varies among the envelope component. As shown in Fig.7A, the heat gain by external walls, windows, roof and floor slabs of FSM are 49%, 19%, 7% and 4% respectively. The unintentional infiltration through the leaky structure accounts for 21% of the envelope heat gain. Thus proves the importance of an airtight insulated external wall construction. DDSMs with upgraded envelope characteristics have resulted in a substantial change to the thermal behaviour of all envelope components. Maximum heat gain reduction is through external walls but varies among DDSMs. The percentage heat gain reduction of external walls of ABM, ACM and PHM are 88%, 93% and 97% respectively. Results show a linear relationship of *U*-value and heat gain. The lowest U value of PHM is a resultant of 200mm thick medium weight high performance glass wool panel, which is approximately 2.5 times the insulation thickness of ACM external walls. Total cooling energy saving from external walls of PHM and ACM are 2.8% and 2.5% respectively. This insignificant cooling energy saving of PHM with high thermal resistance proves that the use of PassivHaus standards in component upgrading is less appropriate.

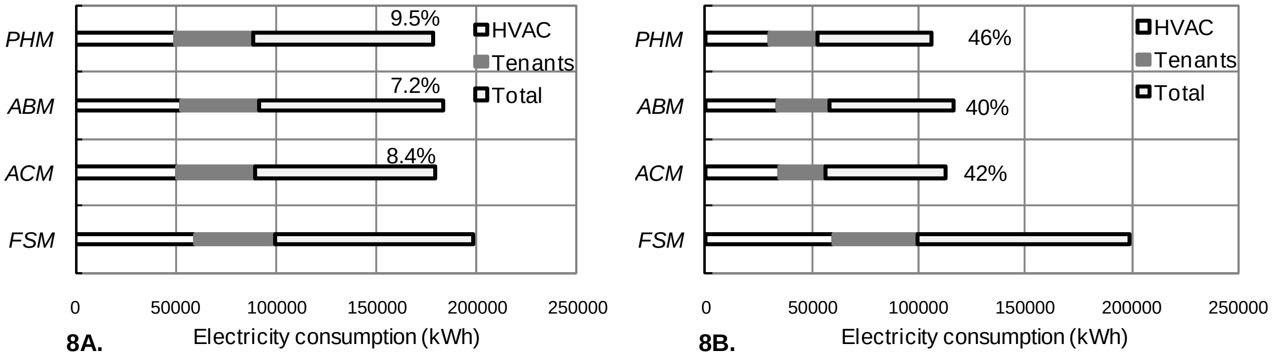
The infiltration which is the second largest heat gain through the building envelope is controlled through the airtight envelopes of DDSMs. ABM and ACM were simulated with 50% air tightness whilst PHM considered with 90% airtight envelopes as compared to the FSM. Percentage reduction of infiltration heat gain of ABM, ACM and PHM are 62% and 90% respectively. Percentage heat gain through glazing for ACM, ABM and PHM are 42%, 62% and 77% respectively. The highest heat gain reduction through windows is observed in PHM with efficient LoE triple glazing with argon gas and insulated window frames.



7A. **7B.**

Figure 7: Comparison of total envelope thermal behaviour and internal gains of FSM and DDSMs

BCA defines operational profiles for occupancy, lighting and appliances (BCA,2010). DDSMs were simulated with the BCA operational profiles with varying internal loads as shown in the Table 3. A comparative diagram of the internal heat gains of DDSMs is shown in Fig.7B. Differences in lighting densities changes the internal heat gain reductions of DDSMs with constant appliance and occupancy heat gain reduction, which is a result of same operational profiles. The percentage reduction of appliances and occupancy of DDSMs are 44% and 30% respectively. Lighting gains are reduced by 29%, 47% and 40% in ABM, ACM and PHM respectively. Comparison with FSM, the internal heat gain reductions of the DDSMs are within the range of 38% - 42% and ACM is observed for the highest reduction in internal loads.



8A. **8B.**

Figure 8: Comparison of total envelope energy saving of DDSMs

3.2. Retrofit energy savings of DDSMs

A comparative diagram of summer typical energy usage for HVAC, tenants and whole building of FSM and energy saving of DDSMs are presented in Fig.8. As shown in Fig.8A percentage energy saving of total envelope improvements of ACM, ABM and PHM are 8.4%, 7.2% and 9.5% respectively. Significant energy saving is observed with the reduction of internal loads from occupants, lighting and appliances (Fig.8B). Percentage energy savings from all component improvements of ACM, ABM and PHM are 42%, 40% and 46% respectively. Thus the results prove reduction of internal gains and optimized operational profiles plays a major role in energy savings of the internal-load dominated critical case office building.

CONCLUSION

In this paper a modelling appraisal was performed in order to evaluate performance of “best” and “normal” practice design standards using a Forward Simulation Model (FSM) of a critical case. Further, Data Driven Simulation Models (DDSM) were developed to assess energy savings due to retrofitting in respect to “normal practice" and "best practice" Standards. Predictive thermal analysis of FSM proved that the internal loads from office equipment dominate the heat gain in this heavy core-dependent deep plan office building. The FSM modelling defined this urban high rise office building as an internal-load dominant critical case for energy retrofitting appraisal. PHM with the best thermal resistant building envelope predicted 9.5% of energy saving for a typical summer week. Results proved that the elemental upgrading of envelope components contributes to only marginal energy savings in internal load dominated office buildings such as this. However, reducing internal loads, optimizing operational profiles and upgrading envelope in the context of whole building can increase energy saving up to 46% for a typical summer week. The research demonstrates the need to have a combined effect of strategies to control the development of both internal loads and environmental loads. An appropriate retrofitting methodology which appraises thermal behaviour of envelope components and occupancy patterns of buildings can contribute to the development of case specific retrofitting design strategies.

NOMENCLATURE

$$\mathrm{ERRmonth}(\%) = \left[\frac{(\mathrm{M-Smonth})}{\mathrm{Mmonth}}\right] \times 100 \qquad (1) \qquad \mathrm{ERRyear}(\%) = \sum\nolimits_{\mathrm{year}} \left[\frac{\mathrm{ERRmonth}}{\mathrm{Nmonth}}\right] \qquad (2)$$

M: Utility bill electricity (kWh); S: predicted electricity (kWh); N_{month}: number of utility bills in the year. RSME: root-mean-squared monthly error; A_{month}: mean of the monthly utility bills

$$\mathrm{CV(RSMEmonth)}(\%) = \left[\frac{\mathrm{RSMEmonth}}{\mathrm{Amonth}}\right] \times 100 \qquad (3) \qquad \mathrm{RSMEmonth} = \left\{\frac{[\sum_{\mathrm{month}}(\mathrm{M-S})2\ \mathrm{month}]}{\mathrm{Nmonth}}\right\} 1/2 \qquad (4)$$

$$\mathrm{Amonth} = \left[\frac{\sum(\mathrm{Mmonth})}{\mathrm{Nmonth}}\right] \qquad (5)$$

ACKNOWLEDGEMENT

Australian Research Council, Dr. Nathan Groenhout of AECOM, Dr .Ken Yeang and Mr. Francis Barram of EnSight, Australia for financial and knowledge support

REFERENCES

AGO (2010). “Australian commercial building sector greenhouse gas emissions 1990-2010”, Australian Greenhouse Office, Canberra

ANSI/ASHRAE Standard 140 (2007). *Standard method for test for the evaluation of Building energy analysis computer programs*

ARUP (2008). “160 Ann Street – Building structure and facade audit report”. Arup Pty. Ltd., Brisbane, Australia (unpublished report)

ASBEC (Australian Sustainable Built Environment Council), (2009). “The second Plank – Building a low carbon economy with energy efficient buildings”, retrieved from http://www.asbec.asn.au

ASHRAE/ANSI/IESNA Standard 90. (1-2004). *Energy Standard for Buildings except Low-rise Residential Buildings* (I-P Edition), ASHRAE Standing Standard Project Committee 90.1

ASHRAE Handbook (2005). “Fundamentals, Chapter 32: Energy estimating and modelling methods”. USA: ASHRAE

ASHRAE Guideline 14 (2002). “Measurement of Energy and Demand Savings”, ASHRAE Standards Committee

Bannister, P., Duponchel, H. (2006). “160 Ann Street Energy Audit”, Energy Australia Pvt. Ltd., (unpublished report)

BCA (2010). “Energy efficiency provisions for multi-residential and commercial buildings”. Building Code of Australia, The Australian Building Codes Board (ABCB), retrieved from http://www.abcb.gov.au

DesignBuilder user manual version 2.2.5, (2010), retrieved from http://www.designbuilder.co.uk

EnergyPlus (2009). “EnergyPlus manual version 4”. US Department of Energy

EnergyPlus (2009). “Testing with Building thermal envelope and fabric load tests from ANSI/ASHRAE standard 140-2007”, in *GARD analytics*, October 2009

European directive 2002/91/EC (2002). “Energy performance of buildings”. EPBD

Federal Energy Management Program (FEMP) (2000). “Ch.25: Measurement and Verification Guideline”

Garnaut (2008). “Climate change review”, retrieved from http:// garnautreview.org.au

Hyde, R. et.al.(2009). *Towards a methodology for retrofitting commercial buildings using bio-climatic principles*. 43rd ANZAScA Conference, University of Tasmania,

IPMVP (2002). *International Performance Measurement and Verification Protocol*, 2002, Vol.1

International Energy Agency (2003). *Cool appliances – policy strategies for energy efficient homes*, OECD, Paris

Kaplan, M., Canner,P.(1992). *Guidelines for energy simulation of commercial buildings*. Portland, Bonneville Power Administration

NABERS (2010). “National Australian Built Environment Rating System”, retrieved from http//www.nabers.co.au

Pan, Y. et al. (2007). “Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai”, in *Energy and Buildings*,39, pp. 651-657

Wolfgang, F. & Schnieders, V., et al. (2005). “Re-inventing air heating: convenient and comfortable within the frame of the Passive House concept”, in *Energy and Buildings,* 37**,** pp. 1186-1203.