Achieving High-Performance Building Design in the Tropics through Modelling and Simulation: A case study in Singapore

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Abstract

As part of a Scientific Planning and Support (SPS) initiative for designing buildings, a team of researchers from the Energy Research Institute @ Nanyang Technological University (ERI@N) in Singapore helped design a high performance building using extensive benchmarking, modelling and simulation studies. The building is designed to perform well beyond Singapore's highest energy efficiency standard – The Green Mark Platinum rating.

Designing high performance buildings in the tropics poses a unique set of challenges. Typical to the region, all non-residential buildings require robust air-conditioning and ventilation systems to fulfil high cooling demands (which typically comprises close to 50% of the building's total energy demand). The SPS team organized a Design Charrette to address problems such as (i) efficient cooling solutions, (ii) developing tropic-specific standards and schedules, (iii) separating latent and sensible cooling loads, (iv) increasing indoor thermal comfort, (v) passive air-distribution, (vi) centralized water cooling, (vii) intelligent chiller sizing and optimization, (viii) maximizing of natural ventilation and (ix) maximizing of natural lighting.

This paper presents the modelling and simulation results which were used to design energy efficient solutions specific to the problems faced in the tropics, as mentioned above.

1. Introduction

The building project – The North Spine Academic Building (NSAB) is a 25,000m² multi-tenanted, laboratory intensive academic building located at the Nanyang Technological University in Singapore. In line with the vision to meet high performance standards, the building owners fittingly chose to use the SPS team from ERI@N [Seshadri et al, 2013] to design and plan the building (Figure 1).

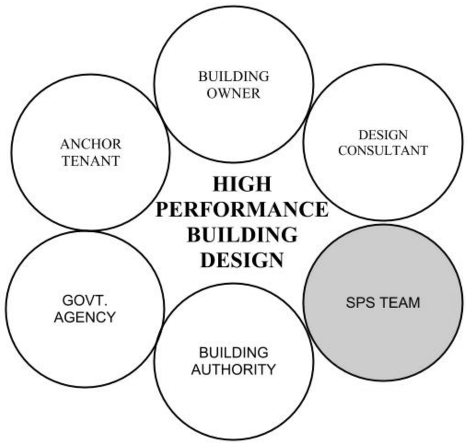

Fig. 1 – The Building Design Working Group [Seshadri et al., 2013]

The following points are a summary of the proposed approach to achieve the greenest building concept that will surpass Singapore's Building and Construction Authority (BCA) Green Mark (GM) v4.1 Platinum standard [BCA, 2013]. Further elaboration of the below mentioned points are in the following sections.

(i) Establish Key Performance Indicators (KPIs) for the building that targets BCA's Green Mark v4.1 Platinum standard and beyond
(ii) Passive Technology Recommendations : Building Orientation and Façade; Air-tightness of Building Envelope; Building Envelope material characteristics; and Day-lighting and Shading analysis

(iii) Active Technology Recommendations: Innovative cooling and ventilation; Building information management and Intelligent building controls; Building integrated power generation

(iv) Modelling and Simulation: Investigating design assumptions (weather data, internal loads and operational schedules); Building energy simulation for predicting energy performance using OpenStudio (OS) and EnergyPlus (E+); Air-Conditioning and Mechanical Ventilation (ACMV) simulation using TRNSYS; Airflow simulation for natural ventilation using ANSYS FLUENT; and Day lighting and shading simulation by using Ecotect Analysis and Radiance

2. Overall Building Design Performance

Compared to the BCA GreenMark established baseline standard (also referred to as building compliance), the NSAB design aims to make a 40% improvement in energy performance, 10% higher than the highest performance rating GM Platinum. Figure 2 shows a tentative (yet to be verified) proposed building performance of the different sub-systems.

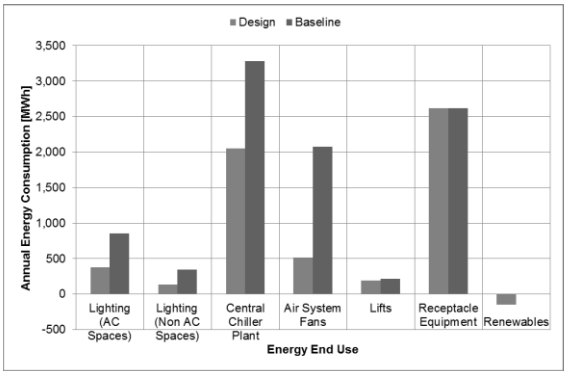

Fig. 2 – Predicted annual Energy Consumption (MWh) categorized into end-use according to design and baseline parameters

The notable improvements made to the baseline (code compliant) design were:

(i) Lowering average annual environmental heat gain from 50 W/m^2 to 17 W/m^2 by minimizing East-West facade gains, using double-glazed windows, high reflective paints, vertical greenery and appropriate shading.

(ii) Using a high-efficiency medium-temperature central chiller plant, energy-recovery de-humidification units and fan-less (passive) air distribution in rooms

(iii) Maximizing daylight, using energy efficient LED and task lighting

3. Benchmarking Input Data

3.1 Metering Equipment Loads

To accurately model the heat gains inside building spaces, it was necessary to meter the tenants' existing spaces: which included equipment, lighting and operational schedules of the tenants [Leung et al., 2012]. Hence, the design team avoided risking incorrect ACMV equipment sizing by not making assumptions regarding internal heat load calculations.

Figure 3 and Figure 4 represent a plug-load metering study, done on weekdays and weekends respectively, conducted by the authors over a 1 month period.

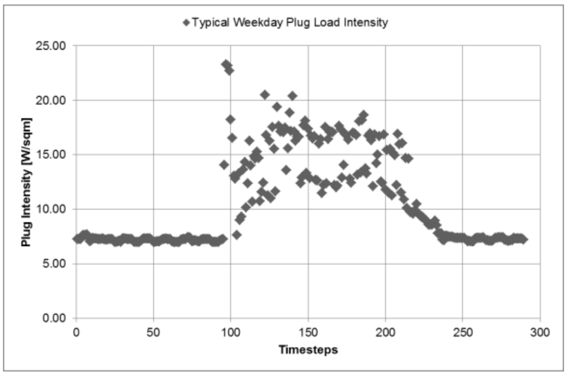

Fig. 3 – Metered weekday plug load intensity data for research office space during 01 to 31 Oct 2014 (Mon - Fri)

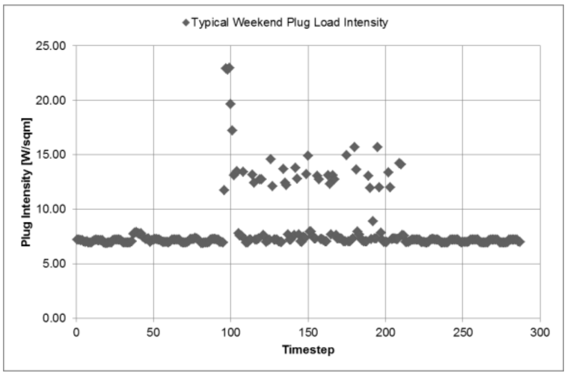

Fig. 4 – Metered weekend plug load intensity data for research office space during 01 to 31 Oct 2014 (Sat-Sun)

The above figures show that for research specific office spaces, the peak (0800 – 2000 hrs) equipment load was not significantly different from design assumptions [BCA, 2013]. But, the off-peak (2000-0800 hrs) plug load was higher than conventional office spaces. Upon further investigation, it was found that usage of high-performance processors (which could be accessed remotely) during off-peak hours was the reason for this unusually high load.

3.2 Laboratory Fume-hoods

Another example of accurately modelling equipment according to the operational performance was the laboratory fumehoods exercise. Laboratory fumehoods are responsible for high ventilation rates in labs and as such have to be controlled according to demand [Mathew, et al., 2007]. It was decided to quantify an occupancy sensor-control for fumehood-intensive laboratories. During the exercise, fumehood occupancy sensors, which were to be modelled for fumehood-intensive labs at NSAB, were installed at a test lab. The power consumption of the fumehood was measured for 1 month with the occupancy sensor and without. The results of the study, summarized in Figure 5, showed ~28.5% savings, marginally lower than 30% claimed by the equipment supplier based on previous case studies [White and Wu, 2014].

For modelling purposes, a 28.5% 'control-factor' was taken into account based on the exercise.

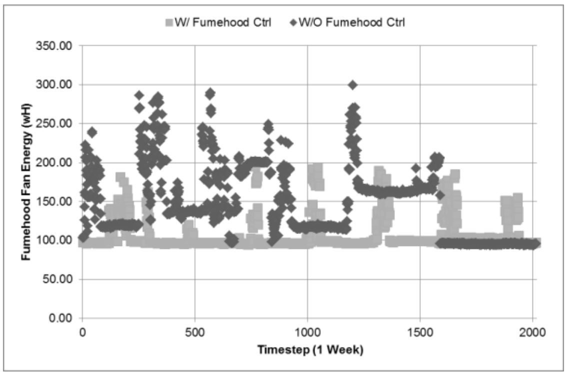

Fig. 5 – Laboratory Fumehood Operation with and without Occupancy Controls

4. ACMV Modelling

4.1 Central Chiller Plant

Instead of an exclusive chiller plant to supply chilled water to NSAB, it was decided to procure a central chiller plant to supply chilled water to NSAB and 2 of its surrounding buildings – the North Spine Learning Hub (NSLH) and Block N4. The SPS team was tasked to simulate the building loads and calculate the hourly annual cooling load demand of the 3 buildings.

Preliminary calculations showed that a total of 5 chillers were needed – Two 275 RT (Refrigerant Tons) Units (Unit 1, 2) for off-peak hours (2000 – 0800 hrs.) and Three 550 RT Units (Unit 3, 4, 5) for peak hours (0800 – 2000 hrs.). A simulation schematic is shown in Figure 6.

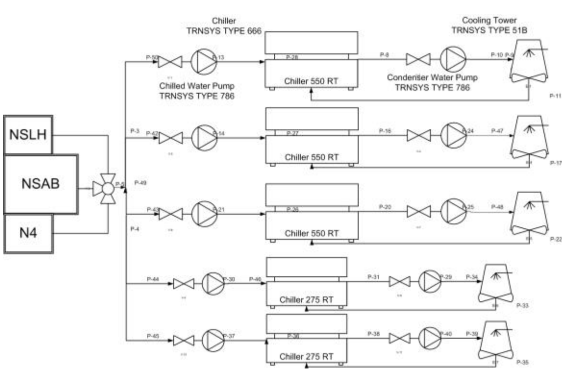

Fig. 6 – System modelling schematic for Central Chiller Plant

Annual cooling simulations from NSAB and NSLH, and metered data from Block N4, suggested that the chiller plant had to be sized to provide a maximum cooling demand of 2100 RT, as shown in Figure 7.

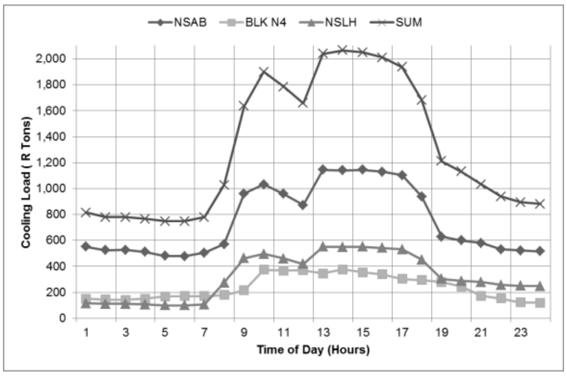

Fig. 7 – Annual maximum hourly cooling loads for the Central Chiller plant

4.2 Chiller Selection and Control Optimization

Even before the modelling exercise for the chiller plant was done, the modelling team offered their recommendations on best-efficiency chiller types based on their simulated performances for the total cooling loads.

Once the performance of the chillers, pumps and cooling towers were established, the modelling team set forth various control and optimization scenarios to maximize the frequency of best efficiency 'sweet-spots'. The two control methodologies [Wei, et al., 2014] which achieved the highest rated annual chiller plant performances were (i) schedule controlled operation and (ii) iterative control optimization.

The (i) schedule controlled operation method chooses when to switch ON and OFF Units 1-5. The schedule is based on maximum, minimum and average time-dependent cooling load demands. The individual, overall plant efficiency (global efficiency) and the operational frequency of the individual units are shown in Figure 8.

The (ii) iterative control operation method, an ideal-case operation, represents the best-possible chiller plant operation and the most difficult to achieve. The control operation tries to run each of the operating chillers at their individual best-efficiency 'sweet-spot' at all times. The individual, overall plant efficiency (global efficiency) and the operational frequency of the individual units are shown in Figure 9.

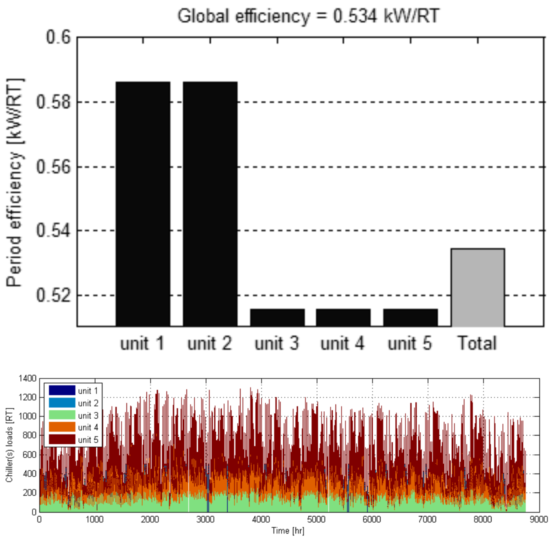

Fig. 8 – Annual Performance of the Chiller Plant using (i) schedule controlled operation: Individual unit performance (top) and frequency (below)

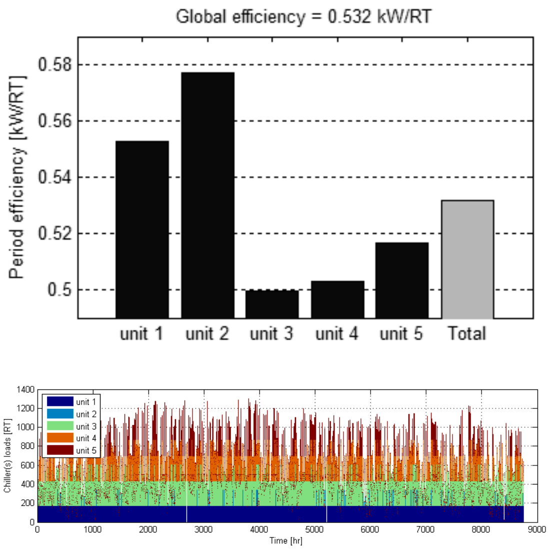

Fig. 9 – Annual Performance of the Chiller Plant using (ii) iterative control operation: Individual unit performance (top) and frequency (below)

It was concluded that the scheduled chiller plant control operation was sufficiently close to the ideal iterative control operation (differing by 0.002 kW/RT) and was chosen to operate the chiller plant.

4.3 Energy Recovery Units for Dedicated Outdoor Air System

Moisture control in the tropics is the biggest obstacle to achieving air-conditioning energy efficiency [Dong et al., 2005]. As is the case in most tropical locations, Singapore's daily relative humidity ranges from 65% to 95% [Dong et al., 2005]. As such, fresh air is cooled to low temperatures to control moisture before being supplied to the building spaces. This often results in over-cooling and thermal discomfort among occupants.

The above mentioned problems are magnified if spaces require high fresh air demands. Laboratory spaces require upwards of 6 L/s/sqm [Mathew, et al., 2007] of fresh air, as compared to 0.56 L/s/sqm [BCA, 2013] for conventional office spaces, which would make lab spaces even more susceptible to the above mentioned problems.

Hence, NSAB being a laboratory intensive building, it was decided to employ an energy-recovery mechanism to pre-cool the outdoor air, before the primary cooling stage, and re-heat the air-stream, after the primary cooling stage, using the incoming outdoor air to achieve optimal supply air conditions. This unit was designer to be a Dedicated Outdoor Air System (DOAS), with remaining zone sensible cooling demands met by Fan-Coil Units. A schematic of this Dehumidification Unit (DHU) is shown in Figure 10.

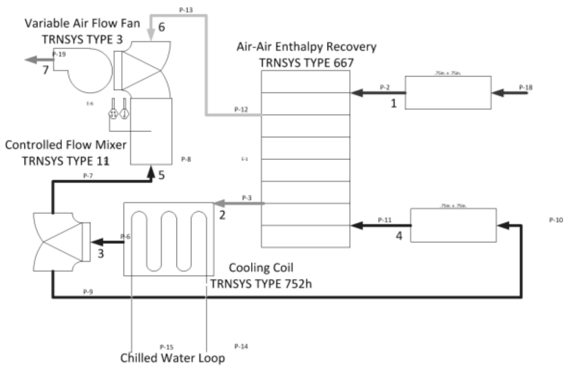

Fig. 10 – System modelling schematic for Dehumidification and Cooling using an air-air energy recovery unit (DHU)

A damper control was installed to maintain the supply air set-points by controlling the mixing of re-heated and non-reheated air. As shown in Figure 11 and Figure 12, the supply air conditions of 22^{0}C and 55% RH fluctuate by <0.2^{0}C and < 2.5% respectively, which is acceptable.

The cooling demand of the fresh air was simulated using a conventional AHU and the above mentioned DHU using energy recovery mechanism. It was found that the DHU energy performance was 13% better than conventional AHUs.

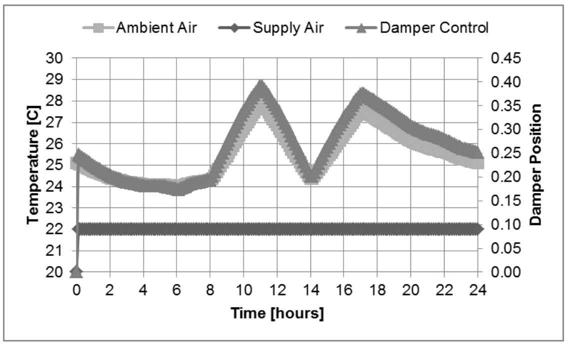

Fig. 11 – The DHU Damper control which maintains setpoint humidity of the conditioned Supply Air

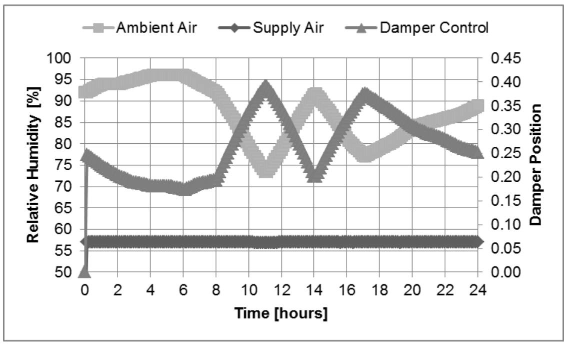

Fig. 12 – The DHU Damper control which maintains setpoint humidity of the conditioned Supply Air

5. Daylighting Simulations

5.1 Outdoor Areas

Daylighting for outdoor areas was done, using Ecotect Analysis and Radiance to establish the natural light levels and comfort in common spaces such as staircases, corridors and the plaza. Using results derived from daylight simulations the lighting engineers were able to identify areas which are expected to receive lower natural light levels (< 150 lux), and were able to make informed decisions on the locations of photo-sensors to activate electric lighting.

It was found that, despite being surrounded on all sides by buildings of equal height, only fully enclosed corridors were in danger of having low natural light levels and had to have photo sensors installed. Other common areas had good natural light levels between 0700hrs and 1800hrs every day. These areas only needed timer switches to switch electric lights on after 1800hrs and before 0700hrs.

Figure 13 and Figure 14 are examples of Radiance outdoor area simulations.

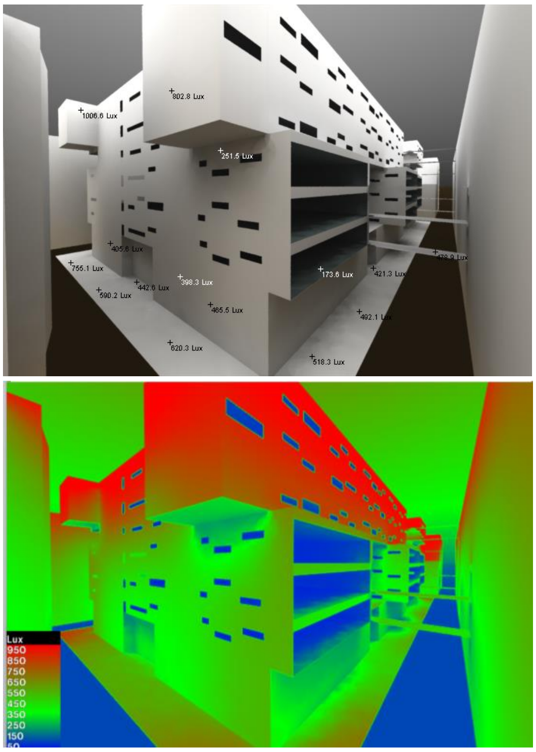

Fig. 13 – Outdoor Daylighting levels (Overcast) using Radiance

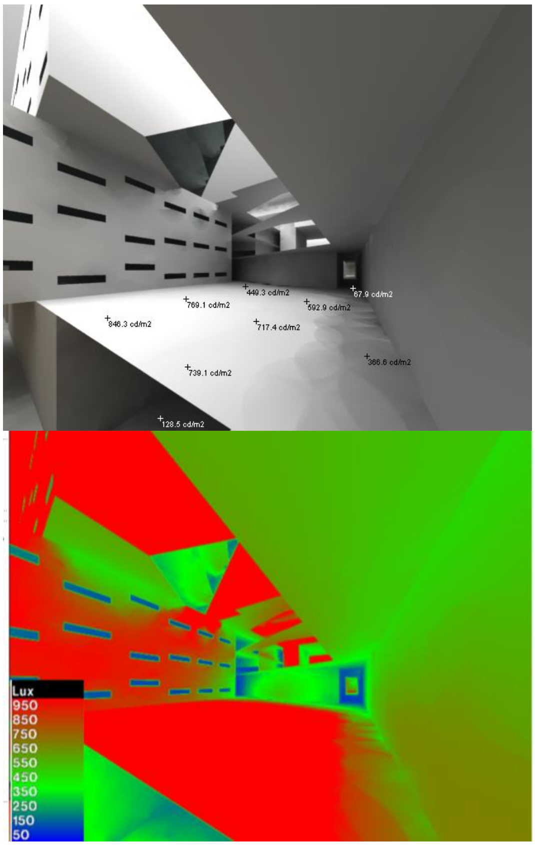

Fig. 14 – Outdoor Daylighting levels (Overcast) using Radiance

5.2 Indoor Areas

Daylighting for outdoor areas was done using Ecotect Analysis and Radiance, to establish the natural light levels and comfort in indoor air-conditioned spaces. Using results derived from daylight simulations the lighting engineers were able to measure daylight perimeters receiving good natural light levels (>500 lux) to install light sensors which could de-activate electric lighting [SPRING Singapore, 2006].

It was found that the daylight penetration in the indoor spaces was minimal due to the surrounding buildings that deflected direct solar radiation. Typical to tropical architecture, the East-West facades featured very little window area, and hence the daylight penetration was negligible (Figure 15). However, the North-South façade which featured higher window-wall ratio had better natural light levels, especially rooms with shop-front type of windows (Figure 16). Although limited, these rooms were able to receive 2.5 – 3m daylight penetration from the window.

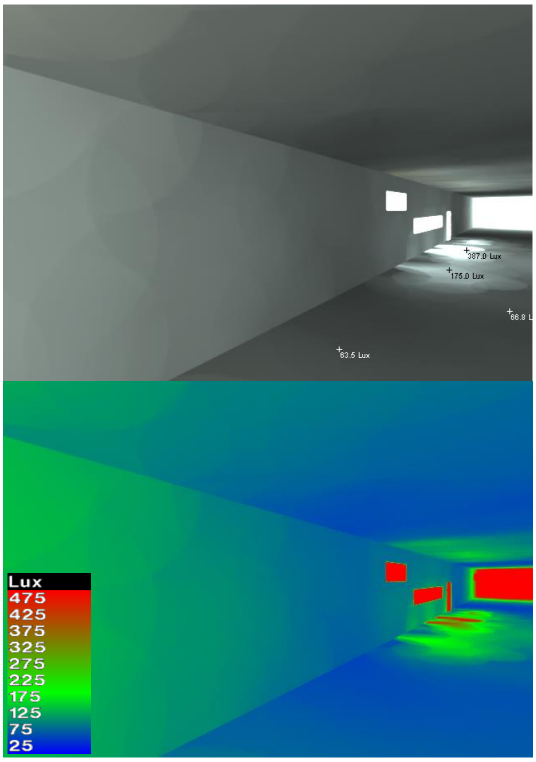

Fig. 15 – Indoor Daylighting levels (Overcast) to measure Daylight perimeter using Radiance for a Level 2 Space

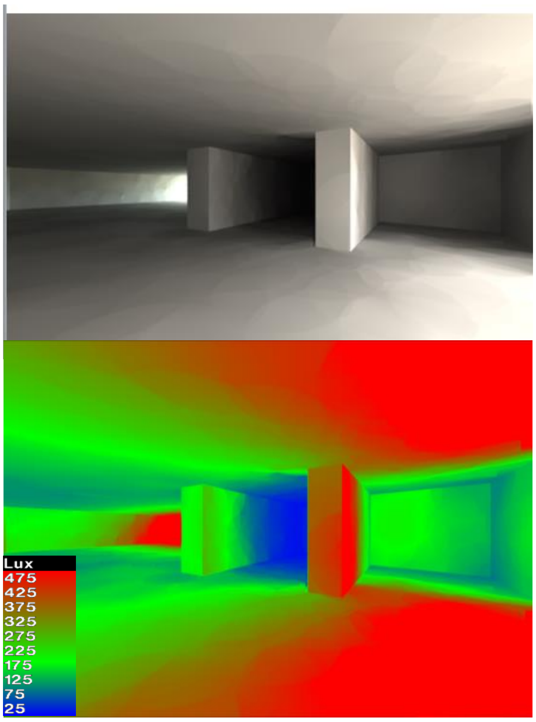

Fig. 16 – Indoor Daylighting levels (Overcast) to measure Daylight perimeter using Radiance for a Level 2 Space

5.3 Daylight Maximization Devices

It was concluded through previously described daylighting simulations that the surrounding building structures prevented deep penetration of sunlight into indoor spaces. Hence, the implementation of skylights and light shelves, popular daylight maximization devices, was considered. The SPS team measured the effect of these devices using another round of simulation exercises.

5.3.1. Solar Light Tubes

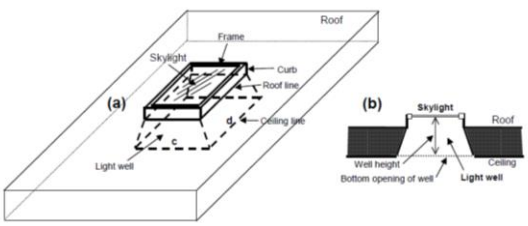

Fig. 17 – Roof-mounted sky lights [EnergyPlus, 2010]

Light tubes are light transmitting fenestration forming all, or a portion of, the roof of a building's space for daylighting purposes (Figure 17). A 2x2m grey glass panel, (0.65 Visible Light Transmittance) was used to model the light tube. A snapshot of the results is shown in Figure 18.

It was concluded that the light tube could increase the ambient lighting level inside the office space by 120 lux during a sunny day, as shown in Figure 18, but was also capable of causing excessive glare during 1200-1400 hrs. Owing to potential for glare and due to space constraints on the roof due to air-conditioning equipment, the light tubes were not employed.

0,0m | 5,0m

127	127	127	127
131	133	133	133
152	162	165	157
239	289	276	215
252	258	225	183
171	176	173	163
222	264	259	210
268	283	245	190
161	159	151	143
133	132	131	130

0, 20m | 5, 20m

0 lux — 500 lux

Fig. 18 – Increase in lighting levels due to sky lights at an office space on the highest level at 0900hrs on Dec 21st

5.3.2. Light Shelves

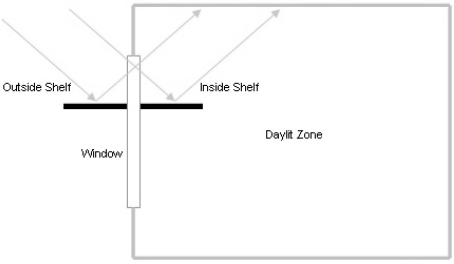

Fig. 19 – Daylight Re-direction louvers or Light Shelves [EnergyPlus, 2010]

Light Shelves re-direct daylight to the back of the room, hence distributing the amount of daylight that falls on the window plane to the indoor space (Figure 19). These devices are expected to extend the daylight perimeter and reduce electrical lighting energy consumption [Guglielmetti et al., 2011].

It was concluded that the daylight re-direction louvers were able to redistribute the daylight from the daylight perimeter zone to the back of the room, providing a comfortable ambient light for the entire space and increasing the average lighting level in the room by 20-80 lux depending on the time of the year. Figure 20 represents the distribution of daylight on Dec 21st at 1200hrs.

Light shelves which doubled up as shading devices were installed on the North-South façade.

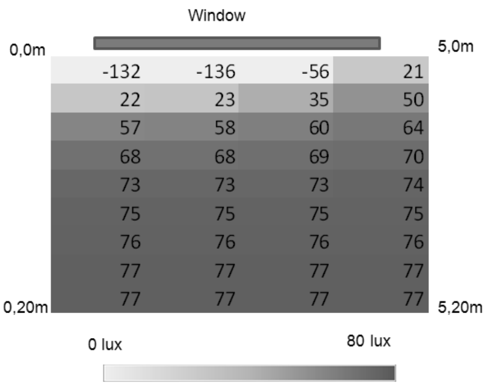

Fig. 20 – Increase in lighting levels due to light shelves at an office space on the highest level at 1200hrs on Dec 21st

6. Conclusion

The authors hope that this project and the results achieved will encourage more use of detailed modelling and simulation during the design phase of buildings, and provide best-practice guidelines for 'tropics-specific' building innovation.

It is also hoped that the technologies that were successfully designed and demonstrated in this project will be adopted and improvised as part of the efficient tropical architecture and system design. Particularly, (i) central cooling plants, (ii) separate latent and sensible cooling, (iii) energy recovery units, (iv) low velocity (fan-less) cooling, (v) daylight shelves and (vi) natural ventilation maximization are highly recommended. It should also be noted that accurate measurement of equipment, lighting and occupancy schedules contributes towards accurate sizing and indoor comfort.

The project concluded with all of the building KPIs achieved and justified the benefits of a research-oriented approach to building design.

References

BCA. 2013. "Green Mark for New Non-Residential Buildings Version NRB/4.1" http://www.bca.gov.sg/greenmark/others/gm_nonresi_v4.1.pdf

B. Dong, E.L. Siew, M. Sapar. 2005. "A holistic utility bill analysis method for baselining whole commercial building energy consumption in Singapore." Energy and Buildings (37): 167-174

R. Guglielmetti, J. Scheib, S.D. Pless and P. Torcellini. 2011. "Ënergy use intensity and its influence on the integrated daylighting design of a large net zero energy building". ASHRAE Winter Conference, Las Vegas, Nevada.

L. Komar, S. Darula. 2012. "Determination of the light tube efficiency for selected overcast sky types." Solar Energy (86): 157-163

Lawrence Berkeley National Laboratory. 2013. "EnergyPlus Engineering Reference." 208-211

M.C. Leung, C.F. Norman and T.T. Chow, "The use of occupancy space electrical power demand in building cooling load prediction." Energy and Buildings. (55): 151-163

P.A. Mathew, D.A. Sartor, G.C. Bell and D. Drummond. 2007. "Major energy efficiency opportunities in laboratories—Implications for health and safety". Journal of Chemical Health and Safety (14): 31-39

B. Seshadri, N.Y. Jadhav, M. Brychta and R. Singh. 2013."High-performance Building Design in Singapore: Scientific Planning and Support" Sustainable Buildings 2013, Singapore

SPRING Singapore. 2006. "SS 531 Code of practice for lighting of work places – Indoor"

X. Wei, G. Xu, A. Kusiak. 2014. "Modeling and Optimization of a chiller plant." Energy (73): 898-907

S. White and X. Wu. 2014. "Laboratories Fume Hoods with Automatic Sash Control System – A Case Study". Sustainable Laboratories Conference. Singapore