THE USE OF MULTIPLE BUILDING PERFORMANCE SIMULATION TOOLS DURING THE DESIGN PROCESS – A CASE STUDY IN SINGAPORE

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ABSTRACT

This paper discusses the use of multiple building performance simulation tools to support the design of a state-of-the-art intelligent library building in Singapore. Building performance simulation tools that include energy analysis program, computational fluid dynamics (CFD) and daylighting models are utilized throughout the design process to evaluate various proposed design schemes, to study the impact of multiple design parameters and to assess the potential of certain design strategies and proposed systems on energy, ventilation, thermal comfort as well as day-lighting performance of the building. The paper also highlights the difficulties encountered during the process and recommendations to overcome the difficulties are discussed.

INTRODUCTION

The design and evaluation of the environmental quality of buildings has become increasingly complex over time. Such complexity arises from the rapid advances in technology, changing perception and demands of building owners, operators and tenants as well as the increasing importance of the building as a facilitator of building occupant control, productivity and information interchange. One of the challenges in the design process is to understand the interaction between various aspects of building performance and their implications on complex building control systems. This paper discusses the use of multiple building performance simulation tools for the evaluation of design concepts and options at the early design phase for a state-of-the-art intelligent library building in Singapore. This new National Library Board Building is designed by Ken Yeang using the bioclimatic approach to provide a building which is environmentally friendly (Yeang 1999). Most of all, it will provide an excellent indoor environment that could be achieved with the use of sophisticated control and environmental technology. The building is located just outside the Central Business District (CBD) in Singapore (see Figure 1). The site is bounded by two major roads, Victoria street and North Bridge road and two side roads Bain street and Middle Road. In order to fulfill the objectives of the design, multiple computational simulation tools are utilized throught out the design process to evaluate multiple proposed design schemes, to study the impact of various design parameters and to assess the potential of certain design strategies and proposed systems. The types of building performance simulation tools used include:

Figure 1: Site location of the new NLB building

- DOE2 energy simulation,
- FLUENT computational fluid dynamics (CFD) simulation and
- LUMINA daylighting simulation.

DOE2 ENERGY SIMULATION

The energy simulation using DOE2 (DOE2 1994) covers mainly the comparative study of two proposed design schemes, the "Plaza Scheme" and the "Street Scheme".

The performance indicators for comparison include:

- Energy consumption (kWh/m^2/year)
- Overall Thermal Transfer Value (OTTV) (W/m^2)
- Space temperatures (^{o}C)
- Space relative humidity (%)

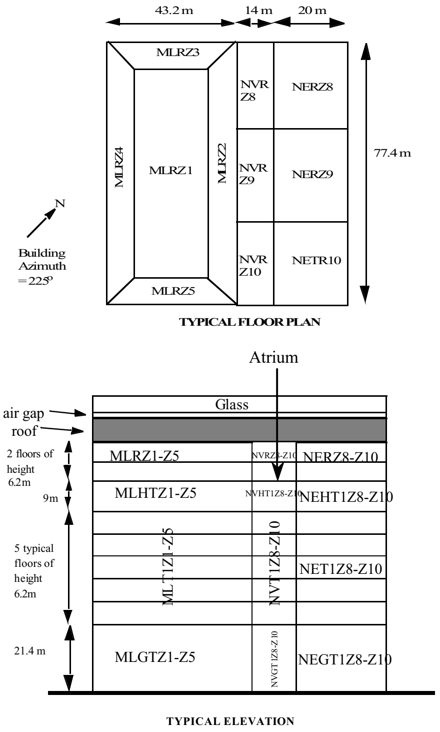
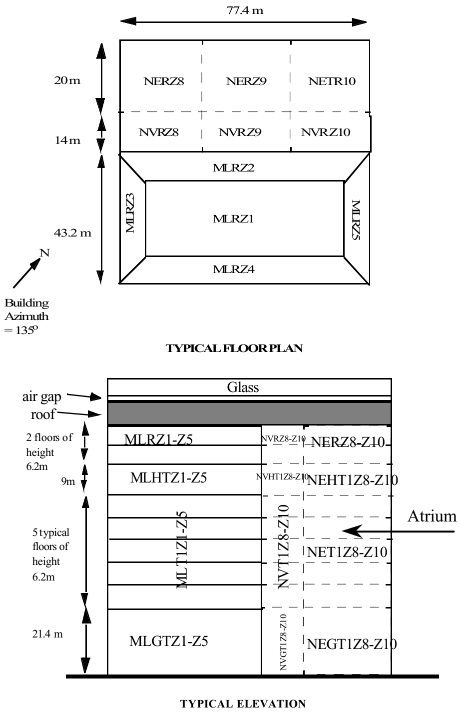


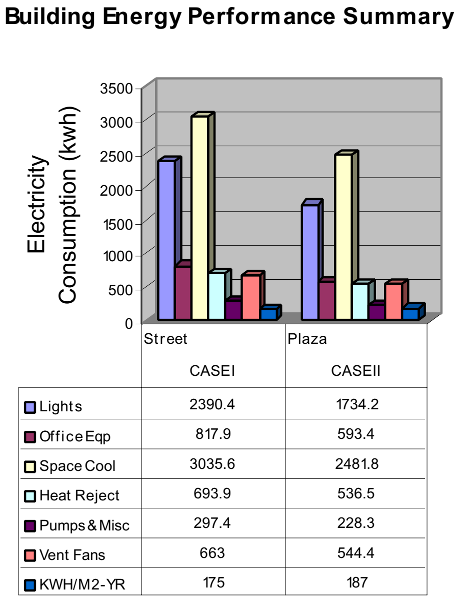
Figure 2: DOE2 modelling of Street



NOTE: ASSUME ADABATIC WALLS IN ATRIUM AND NE BLOCK

Figure 3: DOE2 modelling of Plaza Scheme

The geometric configuration for the two schemes are shown in Figures 2 and 3. The Street Scheme consists of two main blocks (ML and NE) separated by an atrium. The atrium is modelled as a naturally ventilated zone. The ground floor MLGTZ1-Z5 is modelled as a mechanically ventilated zone without cooling. The Plaza Scheme consists of only one main block (ML). The rest of the zones (NV and NE) are considered as an atrium and modelled as multiple zones with adiabatic walls. The ground floor zones NVGT1Z8 – Z10 and NEGT1Z8 – Z10 are modelled as air conditioned zones with set point temperature of 24°C but the upper zones are modelled with set point temperatures of 26.7°C since these are the unoccupied zones.



	Street CASEI	Plaza CASEII
■ Lights	2390.4	1734.2
■ Office Eqp	817.9	593.4
■ Space Cool	3035.6	2481.8
■ Heat Reject	693.9	536.5
■ Pumps & Misc	297.4	228.3
■ Vent Fans	663	544.4
■ KWH/M2-YR	175	187

Figure 4: Energy performance of the two design schemes

Figure 4 shows the energy performance of the two schemes. The simulation results showed that the Street Scheme performs better than the Plaza Scheme in terms of energy efficiency (175 Kwh/m^2/year and 187 Kwh/m^2/year respectively). Similarly, the Street Scheme has an OTTV value of 38.6 W/m^2 compared to 54 W/m^2 for the Plaza Scheme. The permissible value in Singapore is 45 W/m^2. The solar heat gain for the Plaza Scheme is much higher than that for the Street Scheme. This is attributed to the orientation of the building with a large area of glass facade facing the Victoria Street (north-west). The space temperatures and relative humidity, are similar in both schemes.

Based on a survey of 104 office buildings in Singapore, the energy efficiency target of 175 Kwh/m^2/year represents a performance standard comparable to the 23.5 percentile of the surveyed buildings (see Figure 5).

The DOE2 energy simulations are also conducted to study the effects of glazing for the Street Scheme. Two studies were conducted by varying only the glazing specification as follows:

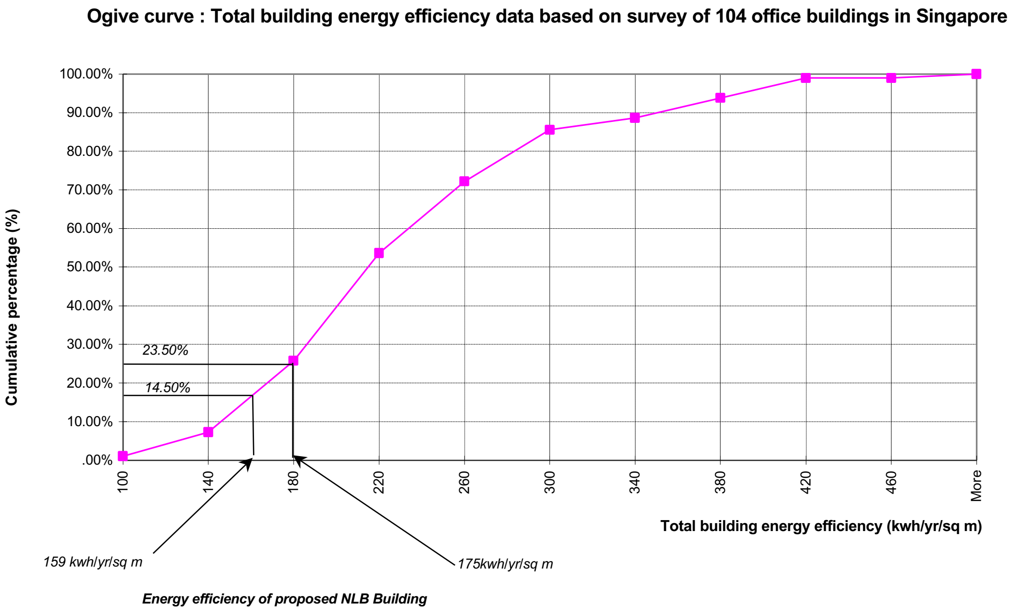


Figure 5: Energy performance target of the design scheme

- **Case 1:** low-e double glazing of 6.4mm thick with 12.7mm air gap, shading coefficient = 0.59, emissivity = 0.1 on surface 2, clear glass;
- **Case 2:** low-e double glazing of 6.4mm thick with 12.7mm air gap, shading coefficient = 0.36, emissivity = 0.1 on surface 2, green tinted glass.

No shading device has been included and the glazed area is assumed to be 80% of the total façade area. The energy efficiency for Case 1 is 175.5 kwh/m^2/yr but the OTTV value of 56 W/m^2 exceeded the permissible 45 W/m^2 . The energy efficiency for Case 2 is better at 159 kwh/m^2/yr and the OTTV value of 38 W/m^2 meets the regulatory requirements.

For good visual performance, tinted glazing is not recommended. To improve the OTTV value for Case 1 to an acceptable level, two possible alternative design specifications may be adopted:

(i) reduce the area of glazing;
(ii) select a lower emissivity value for the coating.

As an estimate, selecting a low-e double glazing with emissivity = 0.05 and shading coefficient = 0.43, will likely meet the OTTV requirement.

COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION

This CFD study compares the two proposed design schemes in terms of air velocity profile and temperature distribution for the atrium. Further simulations are conducted to understand the impact of the use mechanical ventilation on thermal comfort for both schemes. Table 1 shows the boundary conditions used for the CFD simulations. The details of the velocity profile at the atrium for both schemes are shown in Figures 6 and 7.

Table 1: Boundary conditions for CFD simulation.

Design Scheme	Plaza	Street
Wall	Exposed : temperature = 28 °C Unexposed : temperature = 24 °C All walls are assumed to be 'concrete' wall (concrete properties : r = 2400 kg/m3, c = 1100 J/kgK, k = 1.5 W/mK). All temperatures are defined as inside surface temperature.	
Exhaust	Square (1m x 1m) Located at the roof. Total no. : 13 Velocity = 4 m/s vertical [With this velocity, the flow rate is 52 m3/s, and the ACH=0.686]	Square (1m x 1m) Located at the roof. Total no. : 20 Velocity = 3 m/s vertical [With this velocity, the flow rate is 60 m3/s, and the ACH=1.9]
Inlet	Rectangular opening (2m height, 3m width) Located at two side walls at the floor level. Total no. : 6 Defined as 'pressure-inlet' at atmospheric pressure level.	
Human Heat Source	Assumed to be 1 person per 10 m^2 and 140W/person = 14 W/m^2 Convective part of the heat is assumed to be 50 % = 7 W/m^2 Defined as a uniform heat source throughout the floor.	

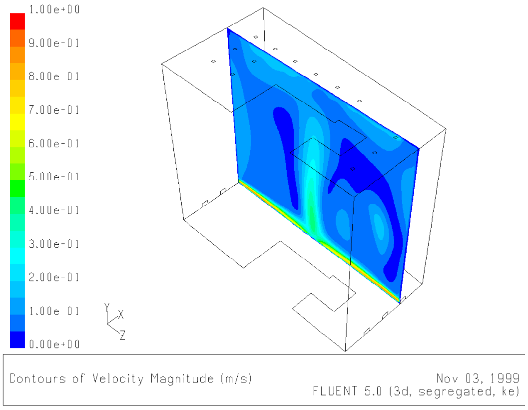


Figure 6 : Velocity distribution in Plaza Scheme

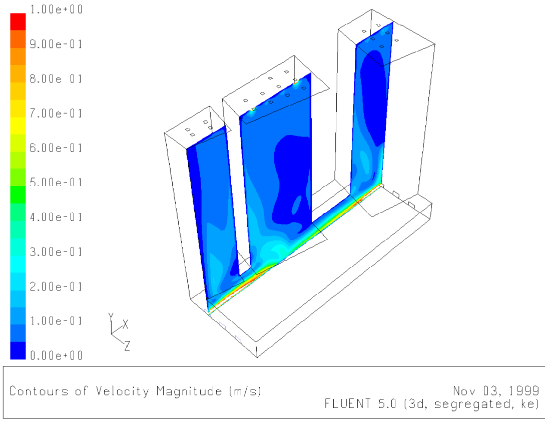


Figure 7: Velocity distribution in Street Scheme

A comparison of the velocity profile as well as temperature distribution shows that the performance is better for the Street Scheme. At the floor level near the inlet openings, the temperature is about 25°C with velocity of up to 1m/s or higher. At the section in the middle of the space, the temperature is around 26 – 27°C and the velocities vary from 0.1 to 0.6 m/s. For the Plaza scheme, the temperature is around 27°C with velocity of up to 1m/s at the floor level near the inlet openings. At the section in the middle of the space, the temperature is around 28 – 30°C with velocities vary from 0.1 to 0.4 m/s.

In order to explore the feasibility of utilizing natural ventilation at the plaza space, it is essential that the thermal comfort condition of the space be assessed. A literature search revealed that there is an Equatorial Comfort Index (an enhancement of the original Singapore Index) (ECI) developed by C.G. Webb, which may be used as a performance benchmark (Webb 1957). The highest index value corresponds to an environmental state where 68% (maximum) of the subjects felt comfortable.

The thermal comfort analysis involves a two-stage process. First, wind speeds have to be established through wind tunnel testing of a 1:200 scale model (see Figure 8). Wind speeds at the entrance and exit of the atrium at various levels are measured. This data is then used as input boundary conditions for the computational fluid dynamics (CFD) simulation to derive the static air temperature and air velocity distribution across the space.

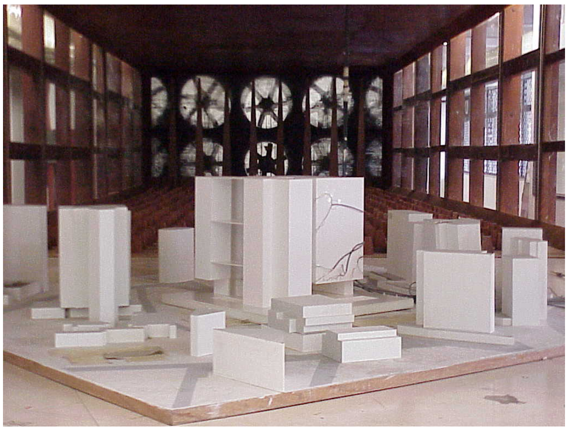


Figure 8: Use of wind tunnel to establish the boundary conditions for CFD simulations

Two simulation studies are conducted by varying only the occupancy value as follows:

- **Case 1:** 1 person/10m^2 (or total population of approx. 220);
- **Case 2:** total population of 900 persons

The results show that the difference in air temperature distribution between Cases 1 and 2 is generally no more than 1°C in most parts. The air velocity distribution varies quite significantly across the space, generally from 1 m/s to as high as 4.5 m/s in certain spots. Given the assumed prevailing wind direction, the fully enclosed link bridges act as a barrier which deflects the wind downwards and accelerates the flow along the "Street" towards Victoria Street. The CFD simulation study also shows that there is negligible air movement in the vertical core between the link bridges under naturally ventilated conditions.

The Equatorial Comfort Index is applicable to a maximum air velocity of 1.5m/s. Similarly, the well-known Fanger's comfort indices given as Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) (Fanger 1970) are also based on such a velocity range for indoor condition. For air velocities beyond this range, there is no established comfort measure, particularly in outdoor conditions in the tropics. Nonetheless, assuming that Fanger's equations are acceptable for higher velocities, PMV and PPD values have been computed for a grid of points across the naturally ventilated plaza area. (see Figure 9 and Table 2)

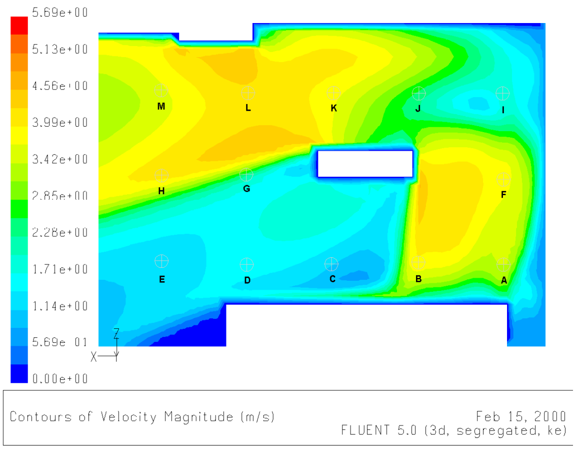


Figure 9: Air Velocity Contours at 1m Height (Plan View)

Table 2: PMV and PPD Values for Several Locations

	Velocity (m/s)	**Temperature (^{o}C)**	**Humidity = 80%**	
			PMV	**PPD**
A	3.237	28.44	1.4	44.9
B	3.856	28.07	1.2	37.6
C	1.092	28.03	1.4	45.2
D	1.395	28.03	1.4	43.4
E	1.257	28.02	1.4	43.9
F	3.695	27.94	1.2	35.7
G	2.460	27.92	1.3	37.9
H	4.047	28.04	1.2	36.8
I	1.741	28.06	1.3	42.4
J	2.571	28.04	1.3	39.5
K	3.801	28.08	1.3	37.8
L	4.179	28.08	1.2	37.3
M	3.586	28.06	1.3	37.8

It shows that the PPD ranges from 35.7 to 45.2. The higher percentage satisfied (i.e, 100 - 35.7 = 64.3 %) is comparable to the maximum percentage of satisfied subjects (68%) under the Equatorial Comfort Index. Further parametric analyses have been conducted to show the sensitivity of PMV and PPD variations for different air temperature and humidity values, given the simulated air velocity for the four selected points.

This study has established that there is generally good airflow through the plaza space at the occupied zone in level 1. However, the air velocity distribution is not uniform. The objective of the next phase of detailed design study would be to avoid area of high air velocities in the Plaza. Assuming that the link bridges would remain fully enclosed above the Street, an element such as a canopy at the base of the lowest link bridge to deflect the downdraft would help. Similar elements should also be introduced at the perimeter of the main library block along Victoria Street and North Bridge Road, given that the prevailing wind is mainly in the north-south direction. These elements should also serve as effective screens against potential driving rain into the Plaza area.

The target for thermal comfort is to achieve the equivalent of the highest index value in the ECI stated above. For wind velocities at or below 1.5 m/s, both the ECI and Fanger's formulation can provide the corresponding combination of air velocity, air temperature and humidity that would yield such a predicted level of satisfaction.

DAYLIGHTING SIMULATION

A set of generic design data for horizontal shading device is developed specifically for the four facades of the NLB Building using a simulation tool SOLARIS (Figure 10). It provides a quantitative measure of the shading efficiency of different height of façade/depth of shade ratios (h/d) in terms of percentage of shaded areas (Figure 11) as well as solar radiation (computed as kWh/m^2) incident of the façade (Figure 12). The self-shade condition represents shading that occurs simply by virtue of the façade orientation (e.g., an east façade will not receive any direct solar radiation in the afternoon period). The results indicate that the Victoria Street and Middle Road facades are generally more exposed to incident solar radiation all year round than the North Bridge Road and Bain Street facades. The data shows clearly that introducing any horizontal shading will reduce the incident radiation on all facades.

Daylighting simulations are also conducted by researchers at Carnegie Mellon University, USA, using LUMINA (Pal and Mahdavi 1999) to study the daylight illuminance distribution as well as the daylight glare index (DGI). Four "typical" spaces were modeled, viz. ,

1. Facing Victoria Street – 4.0m and 8.0m floor to ceiling height
2. Facing North Bridge Road – 4.0 and 8.0 m floor to ceiling height

The weather data used is based on the average values of 5-year measured data for Singapore. Three types of glazing were selected for study (Table 3).

Table 3: Properties of the three types of glazing

Glass Type	**Viracon Glass VE1.2M**	**Viracon Glass VE1-55**	**Viracon Glass VE1-40**
Transmitt-ance	Visible -70% Solar – 32% UV – 10%	Visible –47% Solar – 16% UV – 22%	Visible -36% Solar – 20% UV – 10%
Reflecta-nce	Vis_Out - 51% Vis_ In – 12% Solar – 31%	Vis_Out –11% Vis_ In – 16% Solar – 22%	Vis_Out - 15% Vis_ In – 19% Solar – 25%
ASHRAE U – Value	Winter – 0.33 Summer – 0.28	Wint – 0.31 Sum – 0.32	Winter – 0.31 Summer – 0.32
Shading Cooeff.	0.43	0.4	0.31
Reflection heat gain	90	70	67
SHGC	0.37	0.34	0.27

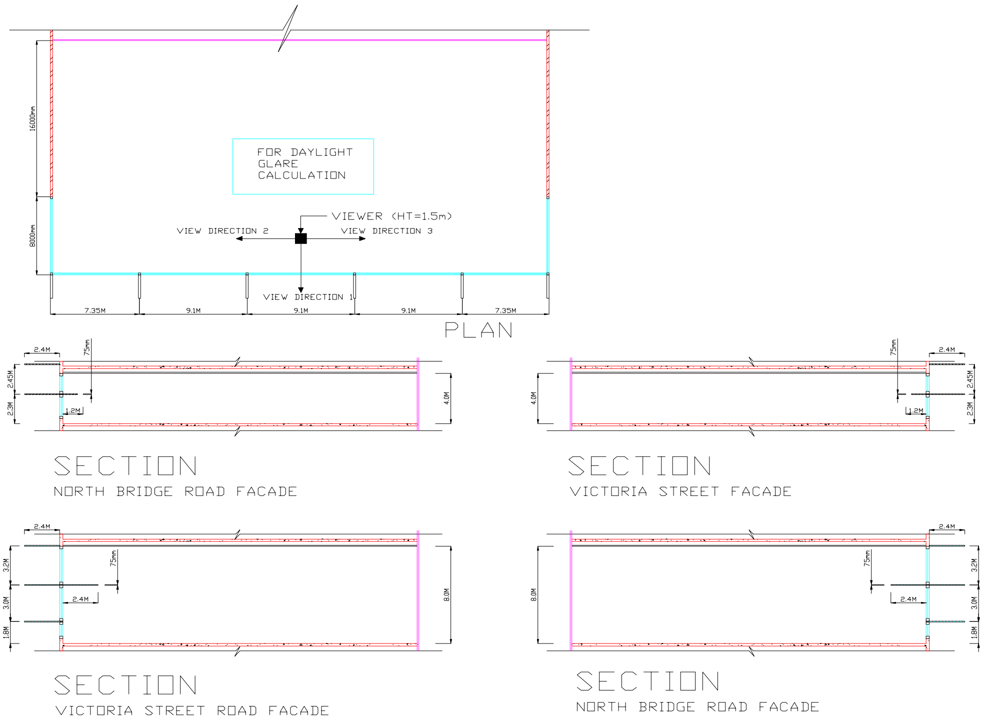


Figure 10: Typical plan and section of the facade

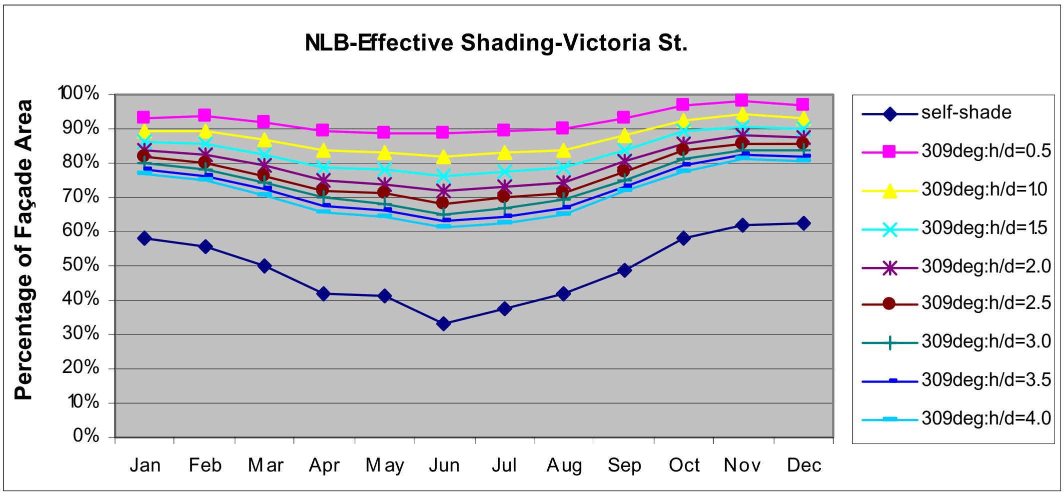


Figure 11: Percentage of the façade area shaded for each month

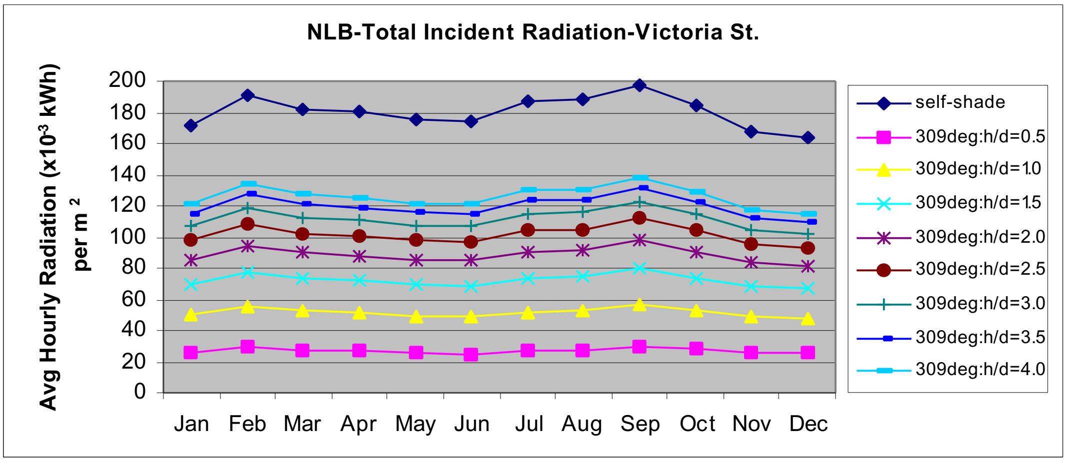


Figure 12: Hourly solar radiation incident on the façade for each month

Figure 13 shows the plot of a typical daylight glare index for different time range using a specific glazing type for a certain floor to ceiling height.

The predicted Daylight Glare Index values (DGI) for all simulated cases are generally within the acceptable level of about 8. The DGI tends to be relatively higher for spaces with higher floor to ceiling dimensions (i.e. 8.0m). As expected, the DGI is also higher for the window glazing Type 1 (with higher light transmittance value) compared to the other 2 types. However, the range of variations at each time period remains quite small amongst the 3 glazing types.

The typical daylight illumination level and distribution pattern is shown in Figures 14 and 15.

The results show that the larger floor to ceiling height (corresponding to a larger glazed area) naturally admits more daylight which also penetrates deeper into the library space.

The spaces facing North Bridge Road will experience very high illumination levels in the morning hours in the January (ranging from a maximum of 7000 lux for Type 1 gazing to 4300 lux for Type 3 glazing. Some additional form of 'temporary' shading will still be necessary during these end of year periods. At all other times, the values appear to be generally acceptable. If 500 lux is to be taken as the target illumination levels, the distance from the façade where this is achievable varies between 18m (Jan, 10am) to about 4m (July, 3pm).

The general illumination levels in the spaces facing Victoria Street are much lower than those facing North Bridge Road. Peak values are between 1500 to 2000 lux for Type 1 glazing (8.0m floor to ceiling height). The 500 lux contour occurs between 5m (Jan, 10am) and about 12m (Apr, 3pm). These results suggest that the shading devices are over provided, in terms of their dimensions, for the Victoria Street façade. Some reduction in the depth of the shades will help to improve the levels and distribution of daylight in these spaces.

Figure 13: Plot of daylight glare values against time

Considering the overall results, Type 1 glazing can be recommended for daylighting purposes. Glazing with higher daylight transmittance value will provide better visual performance. However, this needs to be checked against OTTV requirements and energy performance. It is unavoidable that some form of temporary shading may be required at certain times of the day in certain months (especially in the North Bridge Road façade). The simulation study has not taken into consideration the surrounding buildings which may shield certain parts of the building from direct sun at times.

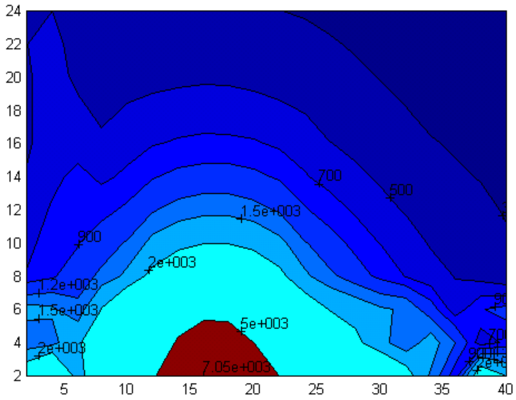


Figure 14: Illuminanace distribution for facade facing North Bridge Road on Jan 15 at 10 am, with floor to floor height = 9.7m and ceiling height = 8.0m. Window Type 1.

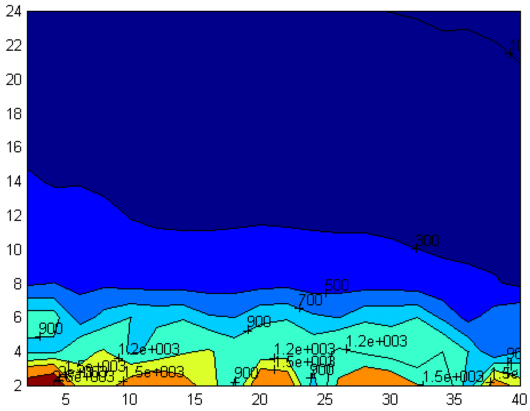


Figure 15: Illuminance distribution for facade facing North Bridge Road on Jan 15 at 12pm, with floor to floor height = 9.7m and ceiling height = 8.0m. Window Type1

CONCLUSIONS

This paper discusses the use of multiple performance simulation tools to evaluate the design concepts and options during the early design phase of a state-of-the-art intelligent library building. The performance simulation tools prove to be valuable in evaluating the various alternative schematic design proposals. They also help to study the impact of various design parameters and proposed systems on the various performance mandates such as energy, thermal comfort, visual quality, etc. However, the use of multiple stand-alone performance simulation tools do have certain limitations. For example, simple alterations by the designers can result in very time comsuming re-modelling of the building for each of the simulation tools used. To maintain model data consistency across multiple simulation domains is also challenging. Very often, the boundary conditions for the stand-alone simulations are determined by the respective design requirements which are frequently inconsistent or in conflict with one another especially during the early design stage. This difficulty is further compounded by the fact that the different simulations may be conducted by different groups of people where such consistency check may not be carried out all the time.

Furthermore, any change in the design specification can affect one or more environmental performance domains. This complex inter-relationship cannot be easily or effectively evaluated. To overcome these difficulties, the logical approach is to utilize an integrated building model. Research work is in progress in this respect which include efforts such as SEMPER (Mahdavi et al. 2000), ESPr (Hand et al. 1999), BDA (Papamichael 1999) etc. These approaches aim to allow the utilization of multiple simulation tools on a common building representation model to facilitate the investigation of integrated building perfromance.

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