Daylighting Performance of Subtropical Multi-Residential Towers
Simulations tools for design decisions

GARCIA-HANSEN, V.¹, KENNEDY, R.¹, SANDERS, P.¹, VARENDORFF, A¹.

¹Centre for Subtropical Design, Queensland University of Technology, Brisbane, Australia

ABSTRACT: During an intensive design-led workshop multidisciplinary design teams examined options for a sustainable multi-residential tower on an inner urban site in Brisbane (Australia). The main aim was to demonstrate the key principles of daylight to every habitable room and cross-ventilation to every apartment in the subtropical climate while responding to acceptable yield and price points. The four conceptual design proposals demonstrated a wide range of outcomes, with buildings ranging from 15 to 30 storeys. Daylight Factor (DF), view to the outside, and the avoidance of direct sunlight were the only quantitative and qualitative performance metrics used to implement daylighting to the proposed buildings during the charrette. This paper further assesses the daylighting performance of the four conceptual designs by utilizing Climate-based daylight modelling (CBDM), specifically Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). Results show that UDI 100-2000lux calculations provide more useful information on the daylighting design than DF. The percentage of the space with a UDI <100-2000lux larger than 50% ranged from 77% to 86% of the time for active occupant behaviour (occupancy from 6am to 6pm). The paper also highlights the architectural features that mostly affect daylighting design in subtropical climates.

Keywords: subtropical climate, daylighting, climate-based daylight metrics, high-rise residential towers, sustainable design

INTRODUCTION
The Centre for Subtropical Design at QUT partnered with a major property developer to explore models for high-rise multi-residential buildings suitable for the subtropical climate. An actual urban renewal site in Brisbane (Australia) was selected for the experiment. While the site has a northern aspect, the main views were deemed by the developer to be south toward the city’s CBD. The charrette, an intensive exploratory design research method by which experts collaborate to seek solutions to a specific problem, was utilised as the research methodology. Academics and several high profile architects collaborated to form ‘creative teams’, with members drawn from diverse disciplines. The main aim of the charrette was to develop designs that demonstrate the key principles of daylight to every habitable room and cross-ventilation to every apartment, while satisfying the developer’s expectations of yield. Over the course of two days, four different designs for buildings 20-30 storeys high were developed in response to the dual challenges of climate-responsiveness and cost-effectiveness as a development proposition.

The design teams proposed four low-energy exemplars for high-rise multi-residential buildings suitable for the subtropical climate. But while the proposals achieved good levels of thermal comfort, the daylight performance did not always comply with Green Star Daylight Factor (DF) requisites[1]. As daylighting design impacts not only on occupants’ health and wellbeing, but also on energy consumption, its considerations in the earlier stages of the design process and proper understanding of its performance are paramount. The paper particularly questions if the current metrics (DF) are the most appropriate to assess good daylighting design, especially in the tropics [2, 3]. To this end, the design proposals are further assessed under Climatic based daylighting modelling and results compared.

BACKGROUND
Over recent decades, multi-storey residential buildings in Brisbane have become increasingly energy-dependent and have largely been designed without any concern for ways to minimise energy consumption, or in particular response to the subtropical climate and lifestyle.

The form and layout of contemporary residential towers in Australia are influenced by market demand from an increasing number of one and two-person households seeking smaller apartments such as studios to one or two-bedroom dwellings. Typically a large number of small apartments are arranged around a lift core and double-loaded corridor, which is internalised and requires
artificial lighting and mechanical ventilation. Individual dwellings so arranged tend to be deeper in plan with low external-wall-to-floor-area ratios, which limit access to daylight. Utility areas such as bathrooms and laundries are neither day-lit nor naturally ventilated. In this scenario, the overall building is highly dependent on energy inputs for indoor climate control and lighting. The need for low-energy exemplars for high-rise multi-residential buildings suitable for the subtropical climate is strong for environmental, social and economic reasons.

During the charrette, IES Virtual environment[4] was used to allow quick feedback in early stages of the design process for assessment of the designs’ expected performance in thermal comfort; effectiveness of natural ventilation; availability of daylighting; predicted energy rating of individual units; whole of building energy consumption; renewable energy; CO$_2$ equivalent emissions; acoustic amenity; and average water consumption. The metrics that closely responded to the main aims of the charrette (natural ventilation and daylighting) were:

1. **Thermal comfort** compliance with ASHRAE Standard 55-2004 Acceptable operative temperature ranges for naturally conditioned spaces; and

2. **Daylighting** compliance with the requirements for GBCA Green Star accreditation for multi unit residential [1]: 1) a DF of 2% for kitchens and DF 1.5% for living areas; or 2) minimum illuminances of 200lux for kitchens and 150 for living areas. GBCA awards points as follows: 1 point is awarded where 95% of the kitchens and 60% of the living areas meet the criteria. 2 points are awarded where 95% of the kitchens and 90% of the living areas meet the criteria.

**CASE STUDIES**

The four design proposals are presented below as case studies.

**Case study 1: Point access tower**
This design arranges eight apartments per floor around two separate lift cores and lobbies (Fig.1 top). The cores are not fully-enclosed, allowing all apartments to be naturally ventilated. The majority of dwellings have dual aspect to the north, and south to the major city view. Gardens on each level provide ‘green’ foreground views for all residents despite being many floors above ground.

**Case study 2: Gallery access tower**
This design was conceptualised as a variation on the single-loaded ‘gallery’ access model to maximise cross-ventilation and ‘permeability’. Two lift cores are linked by a freestanding circulation zone connected to the main tower by walkways (Fig.1). The gallery is on the southern side of the building and was conceived as semi-enclosed communal outdoor space, which could be occupied for a variety of purposes as well as circulation. The apartments feature generous balcony areas.

**Case study 3: Point access single-loaded tower**
In the typical floor plan of this case study, apartments are arranged around a central core and a naturally ventilated single-loaded corridor. The facade is characterised by vertical fins which extend past the line of the facade, designed expressly to create a ‘roughness’ in order to reduce turbulence at height and provide comfortable conditions on balconies. The configuration of this design utilises minimises external wall-to-floor ratio of apartments in order to offset capital expenditure on integrated innovative building systems including on-site energy generation and community gardens.

*Fig.1: Case studies*
Case study 4: ‘Skip stop’ double-loaded corridor tower
In a departure from the ‘slab’ format where all apartments are on single levels, Case 4 adopts the ‘skip stop’ corridor type with a series of interlocking two-level apartments arranged around a double-loaded corridor on every third floor. A variation on the type originally pioneered by Le Corbusier in the Unite d’Habitation in Marseille, this type has advantages for developers as it literally halves the extent of floor area dedicated to shared circulation, thus providing more saleable floor area. This case also contrasts with Cases 1, 2, and 3 in its efficient ability to achieve cross ventilation without reliance on an external core; however, bathrooms typically require mechanical ventilation and riser systems.

CHARRETT OUTCOMES
The thermal comfort and daylighting information produced by the teams during the charrette presented diverse levels of accuracy (Table 1).

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Thermal comfort and DF for towers</th>
<th>Average DF of typical apartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80% acceptability for 98% of the year</td>
<td>No less than 2% for 75% of kitchens area No less than 1.5% for 60% of living areas</td>
</tr>
<tr>
<td>2</td>
<td>80% acceptability for 88% of the year</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>80% acceptability for 90% of the year</td>
<td>2.5% up to 3 meters</td>
</tr>
<tr>
<td>4</td>
<td>80% acceptability for 75% of the year. Outside comfort levels during winter months</td>
<td>1.5% for 60% of the living area</td>
</tr>
</tbody>
</table>

Table 1 shows IES analysis provided by the teams during the charrette. In general the proposals achieved good levels of thermal comfort and compliance with ASHRAE 55, however, daylighting results did not always comply with GBCA Green Star values for DF.

METHODOLOGY
Daylighting Factor (DF), defined as the ratio of internal illuminance to the external illuminance under a CIE overcast sky [6], is a metric that takes no account of the sun’s position and radiance, and it is insensitive to climate and orientation [7]. Because DF uses an overcast or uniform sky it is assumed that the results would produce a worst case scenario, however, in bright sky and warm weather conditions as those present in Brisbane, a worse situation may be when direct sunlight enters the space, as this condition may create visual discomfort and thermal gains [2]. In addition, DF is a static measurement taken for a particular time and day, and as a result, not representative of lighting conditions throughout the day and the year. A better approach to the analysis of daylighting in building design is the use of Climate-based daylight modelling (CBDM). CBDM is the prediction of luminous quantities using realistic sun and sky conditions derived from standardized meteorological data (i.e. hourly values for a full year) [7]. These new metrics include among others Daylight Autonomy (DA), and Useful Daylight Illuminance (UDI)[8].

Daylight Autonomy is defined as “the percentage of the year in which an interior minimum illuminance threshold is met by daylight alone”[8]. The minimum for this research is based on the GBCA Green Star values: 150 for living spaces and 200 for kitchens [1].

Useful daylight illuminance was first proposed by Nabil and Mardaljevic [5]. It measures the occurrence throughout the year of a target range of illuminances (i.e. 100 to 2000 lux) achieved across the work plane. This range is considered to be useful for the occupant, neither too dark (>100lux) nor too bright (<2000lux). This threshold was determined through preferences on lighting level studies performed for office buildings[5]. According to Mardaljevic, in residential buildings this threshold could be increased to 2500lux [9]. The range could be further divided into [5]:
- Daylight illuminances less than 100 lux are considered insufficient to be the sole source of illumination (UDI fell short)
- Daylight illuminances in the range of 100-500lux are considered effective either as the sole source of illumination or in conjunction with artificial light (UDI achieved-supplementary)
- Daylight illuminances in the range of 500-2000 lux are often perceived either as desirable or at least tolerable (UDI achieved/autonomous)
- Daylight illuminances higher than 2000lux are likely to produce visual or thermal discomfort or both (UDI exceeded).

Daylight Simulation
For further assessment of daylighting performance of the conceptual designs, DIVA, a highly optimised daylighting and energy modeling plug in for Rhinoceros 3D was used. DIVA uses a NURBS (non uniform rational Bezier spline) modelling software and it is based on Daysim and Radiance simulation software. The modelling of daylight included:
- Average Daylight factor calculation. DIVA for Rhino uses the CIE overcast sky for DF calculation.
- DA of 150lux for living areas to be compared with Green Star requirements for living areas [1] and 200lux for kitchens. Occupancy file selected was 6am to 6pm.
- UDI with the ranges suggested by Nabil and Mardaljevic [5], where UDI achieved/autonomous is considered in the range of 500-2500 and UDI exceeded
is more than 2500lux. DIVA for Rhino uses Daysim, for the default range of 100 to 2000lux. However for the specific UDI ranges, some manual calculations are performed. When the simulations are run DIVA produces a text file containing all of the lighting levels received over the course of the year. From this data the specific UDI ranges are extracted from 6am to 6pm to determine the percentage of the time the lighting levels are between a certain range.

- Average daylighting illuminance levels for December 21st (summer), March 21st (spring) and June 21st (winter) for 8am, 10am, 12pm, 3pm and 5pm.

Digital models and typical apartments descriptions
Digital models from various other modelling packages were imported into Rhinoceros 3D for the simulations. The analysis for each case study includes typical apartments consisting of a living area with kitchen, two bedrooms, bathrooms and amenities.

The four case studies present four different architectural solutions that result in varied approaches to the collection of natural illumination for the typical two-bedroom apartments. All the designs have sought to have openings to both north (equatorial) and south (non equatorial) orientations.

- Case 1 has north-south openings, with deep balconies (4.30m); Living area faces both north and south; one bedroom faces north, and one faces south; floor to ceiling height: 3m.
- Case 2 presents a similar distribution to the previous example, however the balconies are shallower (north balcony 3m and south balcony 2.2m); south façade has daylight obstructions from the circulation gallery; living area has north and south openings; and one bedroom, faces north and the other one south. The floor to ceiling height is 3.5m.
- Case 3 two-bedroom apartments are placed at the ends of the floors, providing openings with three different orientations, NE and NW for living areas and SW for bedrooms.
- Case 4 presents an interlocking composition providing views and openings to both north and south for the living area, and north or south for the bedrooms.

In the models, internal surfaces were assigned diffuse reflectance values typical of ceiling, walls and floor, i.e. 0.80, 0.50 and 0.20 respectively. All windows were modeled as clear simple-pane a transmittance of 0.88.

Sky description
For the different analyses the following data is used: 1- CIE overcast sky for DF; 2- Weather file energyplus .epw for Brisbane for DA and UDI and 3- CIE clear sky with sun for mean illuminance levels.

Fig. 2: Apartments’ location in the different towers

RESULTS
Table 2 presents the results for the analysis of Daylight Factor, Mean DA, DA_{150lux} (50%), Mean UDI and area of building with UDI 100-2000lux larger than 50%. These metrics are assessed at the working plane throughout the floor area of the apartments.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>1.5%</td>
<td>1.3%</td>
<td>3%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Mean DA</td>
<td>56%</td>
<td>63%</td>
<td>67%</td>
<td>73%</td>
</tr>
<tr>
<td>DA_{150lux} (50%)</td>
<td>67%</td>
<td>76%</td>
<td>73%</td>
<td>88%</td>
</tr>
<tr>
<td>Mean UDI</td>
<td>62%</td>
<td>71%</td>
<td>71%</td>
<td>74%</td>
</tr>
<tr>
<td>UDI_{100-2000lux} larger than 50%</td>
<td>77%</td>
<td>86%</td>
<td>83%</td>
<td>84%</td>
</tr>
</tbody>
</table>

The results show that Case 1 achieves an average DF of 1.5% which meets Green Star benchmarks for living areas, however, calculating the DA for 150lux shows that these daylighting levels would only be achieved 56% of
the time. Calculating UDI increases the performance to 62% for the 100lux to 2000lux range. Case 1 has the lowest UDI of the four towers.

On the other hand, Case 2 has a very low DF, below that recommended by Green Star. However, a typical apartment is reaching DA of 150lux 63% of the year; achieves DA of 76% in 50% of the area; and mean UDI (achieved) of 71%, as 29% of the time the apartment will be outside the UDI range. The percentage of space with UDI Achieved of 50% or greater, is 83%

Higher average DF of 3% and 2.4% are achieved for Cases 3 and 4, respectively. Although these comply with Green Star, when a further investigation by calculating DA, levels of 150lux or higher reveals that the designs achieve 67% and 73% of the time. In terms for UDI achieved 100-2000lux, Cases 2, 3 and 4 perform very closely (71%, 71% and 74% respectively), while Case 1 achieved a UDI of 100-2000lux 62% of the time.

Distribution of UDI
To better understand the results from UDI, the grid with UDI distribution is presented for the four plans (Fig.3) and UDI break down shown in Table 3. Low percentages of UDI Achieved, in blue, are usually found in bathrooms and circulation areas that do not have direct solar access. This means these areas have a UDI Fell Short, with daylighting levels under 100lux. Medium percentage of occupied hours around 50%, is visible closer to windows where the issue is the UDI Exceeded (more than 2000lux), as for example, NW oriented windows in the Case 3 building, when direct sunlight enters the building. It also represents a lower percentage of UDI Achieved in the middle section of the living spaces, for example, Cases 1 and 2 (Fig.3) where the depth of the building has an effect on the lux levels achieved. Higher values of UDI Achieved in orange are found with approximately 1.5 to 2.0 m distance from the openings to up to 4 to 6 m in depth.

Table 3: Useful daylight illuminance break down

<table>
<thead>
<tr>
<th>UDI</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100lux Fell Short</td>
<td>35%</td>
<td>26%</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td>&gt;100 &amp; &lt;500lux Achieved (suppl.)</td>
<td>48%</td>
<td>53%</td>
<td>37%</td>
<td>46%</td>
</tr>
<tr>
<td>&gt;500 &amp; &lt;2500lux Achieved (autonomous)</td>
<td>15%</td>
<td>20%</td>
<td>36%</td>
<td>27%</td>
</tr>
<tr>
<td>&gt;2500lux exceeded</td>
<td>2%</td>
<td>1%</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>

So, while Case 1 and Case 2 exemplars have greater levels of UDI Fell Short, Case 4 and Case 3 have greater issues with UDI being exceeded; but they also have a greater percentage between the >500 to 2500 range that may not need electrical lighting supplied.

Average illuminance levels
Table 4 takes a closer look at average illuminance levels and confirms Case 1 as having the lowest levels achieved in the break down of the UDI into Fell Short, Achieved and Exceeded. Most apartments have greater levels of daylight in winter, as there is more sunlight penetration.

Table 4: Simulated daylight illuminances

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average daylight illuminances ± standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>277±108</td>
<td>364±121</td>
<td>1273±1053</td>
<td>540±260</td>
</tr>
<tr>
<td>Autumn</td>
<td>241±96</td>
<td>365±141</td>
<td>1083±599</td>
<td>615±284</td>
</tr>
<tr>
<td>Winter</td>
<td>799±1090</td>
<td>574±344</td>
<td>1149±748</td>
<td>2555±2010</td>
</tr>
</tbody>
</table>

DISCUSSION
The following architectural features in the case studies have the greatest effect on the distribution and annual occurrence of the UDI metrics:

- **Deep balconies**: in the case of Case 1 (4m balconies) most UDI falls in the supplementary bracket (48%) and increases UDI Fell Short.
- **Floor to ceiling heights**: Case 1 and Case 3 have floor to ceiling height of 3 m, Case 4 has same height but a double high balcony which increases daylight penetration and Case 2 height is 3.5 m.
- Living Room proportions (including balconies); width to length ratios: Case 1 is 1:4.7, Case 2 is 1:3.6, Case 3 1:2.9 and Case 4 is 1:4.5, generally resulting in deep plan buildings. However, as most of the living areas are illuminated from two sides their daylight penetration is increased. On the other hand, if openings were placed only one side would have a greater effect on UDI distribution.

- Windows placement; Case 3 is the only one with windows on three facades, with some of these windows placed on the NW façade. This inclusion increases UDI autonomy by a slight margin as West orientation also increases UDI Exceeded around those windows (Fig. 3 Case 3). The SW bedrooms also have problems.

Although Climate based daylight modelling provides more information on how different architectural features like orientation, room proportions, floor to ceiling heights and depths of balconies affect daylight quality, as mentioned by Mardaljevic [7] there is still no consensus on targets for guidelines. Mardaljevic suggests that a good indicator for good daylighting is UDI, which measures the degree of occurrence of illuminances in the range 500 to 2500lux, since this range “provides adequate illumination for the majority of tasks; is associated with a very low probability for the switching-on of electric lights; and, the higher values in this range are now believed to have beneficial effects for both productivity and long-term health” [5]. The apartment that best performs is the Case 3, with a degree of occurrence of UDI 500 to 2500lux 36% of the time. However when reviewing Case 3’s performance, the fact that the apartment simulated has three facades needs to be taken into consideration. From the other three proposals, with only two orientations, Case 4 achieves 27%, Case 2 20% and Case 1 15%.

CONCLUSIONS

In an intensive two-day charrette four multi-disciplinary teams aimed to design new forms of high-rise residential buildings that provide comfortable, affordable and sustainable housing choices that would respond to the subtropical climate on a site in Brisbane (Australia). One of the main aims was to provide daylight to every habitable room and cross-ventilation to every apartment while still responding to yield requirements and price points. The final designs proposed single loaded type apartments that benefit cross ventilation but in general create deep plan buildings, not conducive to good daylighting. DF analysis carried out during the charrette showed in general that the apartments did not meet Green Star targets or would only be awarded one point for daylighting design. To further assess the quality of the daylight solutions CBDM is used. UDI autonomous, which measures the degree of occurrence of illuminances in the range 500 to 2500lux is used as an indicator for good daylighting. The apartment that performs best is Case 3, with a degree of occurrence of UDI autonomy 36% of the time. However, this apartment has openings in three facades. From the other three proposals, with only two orientations. Case 4 achieved 27%, Case 2 20% and Case 1 15%. All the apartments have similar areas, but issues of orientations, openings, floor to ceiling height, room proportions, and balconies depths varied greatly. Of the proposals with only north and south orientations, Case 4 (interlocking design) performs better than the other two without sacrificing balcony area, or increasing overall building height. Finally, the study shows that CBDM metrics can provide a more in depth analysis of daylighting performance of buildings, than current metrics (DF), and highlights the potential of their use especially during early stages of a design proposal.

ACKNOWLEDGEMENTS

The authors acknowledge the contributions of the design teams from Cottee Parker Architects, Cox Rayner Architects, DBI Design, and QUT School of Design. We also acknowledge Vivas Lend Lease (charrette partner), Shane Thompson (charrette facilitator), and Richard Hassell (charrette mentor).

REFERENCES