Preface

This study considers recent developments and implications of building taller towers. It discusses the impacts of increased height on lower footprints, structure, wind outcomes, energy consumption and environmental outcomes. In turn, these impacts affect architectural and urban design. The study makes observations that inform the growth strategy for Central Sydney.

Recent tall building developments typically reach an average of 250 metres in height.

Development of tall buildings has been growing overall. Notably, the proportion of new tall buildings accommodating office space has decreased. New tall office buildings have dropped from 68 to 47 percent. New tall buildings accommodating residential uses has increased to 47 percent.

The speculative power of residential development is likely a key driver for this trend. The implications for a future Sydney are significant given it ranks within the top ten of world cities in terms of tall building rental demand.

Building taller towers has significant implications for design and efficiency. Tower dimensions at street level can reach around 40 metres in length, up to 53 metres or towers of 400 metre heights. Taller towers result in less efficient floor plates due to structural and infrastructural constraints. At the lower levels, office tower cores can account for 28 percent of floor plane area whilst residential tower cores can reach 34 percent due to their tendency for smaller floor plates.

Larger floor plates at street level affect the public realm particularly when constrained by finer street grids such as Central Sydney. "valuable dimensions of city blocks can be compromised, as can the ability to provide usable public open space around the base of tall tower buildings.

Taller towers affect the environment of the city. Clustering towers can exacerbate the urban heat island effect in a city. Dense populations of tower structures absorb and retain heat. Tower structures themselves generate heat from occupants use. The ability for urban landscapes to dissipate heat at night is compromised due to limited exposure to open sky, in turn impacting on energy consumption.
Tall Buildings
The implications of increasing height
Tall Buildings

The implications of increasing height

This confidential report has been commissioned by the City of Sydney. The report presents a high level assessment of the implications of building tall towers higher in the urban realm.

There are many parameters that influence the design of tall buildings, and hence influence their impact on the city. Consequently, the report herein presents information which is considered typical and generic. This should be borne in mind when interpreting some of the data and recommendations.

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Tall Buildings | The Implications of Increasing Height

The following presents a summary of some of the key findings in this report:

Directions

- Tall buildings around the world are getting taller, such that now the average height of the tallest 100 buildings is 350m.
- The number of residential tall buildings has increased dramatically in recent years. Prior to 2000, only 1% of the then tallest buildings were residential, by 2010 this had increased to 15%.
- Towers are becoming more slender, driven by the increase in demand for residential towers and the desire to maximise the potential of small CBD sites. This has the tendency to increase cost and the need for devices such as tuned mass dampers.
- In Sydney there is the trend towards eccentric cores – Chifley being a good example. This influences the strategy for the structural design and how the building is serviced.
- The cost of tall buildings is significantly impacted by shape and geometry, site and regularity of floor plates, floor plate efficiency, structural solution, façade and floor plate ratio and the facade specification.
- The Knight Frank index, which ranks the demand for high rise around the world, ranks Sydney as 7th of world cities. This puts it ahead of Shanghai, Dubai and Chicago.

Components and Structure

- As buildings become taller, the footprint typically increases in size. The height to base width has a typical maxima of 8 or 9 but can increase to 12 as an extreme case, particularly for residential developments.
- As buildings become taller, the efficiency tends to reduce. For example, the plan area of a core can increase from 20% of lower level GFA for a 200m high building to 30% for one of 400m.
- The structural systems required for a tower change as the height increases. It is interesting to note that 75% of all tall buildings constructed globally over the height of 200m use an outrigger system.
- Perimeter framing or braced frames become more prevalent when using eccentric cores.
- Plant floors typically occur a between 20-28 storey intervals.
- For taller towers, the use of sky lobbies and shuttle lifts can greatly optimise the vertical transportation and minimise core area.
- The geology of Sydney is well suited to building taller compared to other cities in the world. This is due to the presence of rock at shallow depths.

Wind

- The extreme winds in Sydney are less than some of the ‘tall building cities’ around the world. This reduces the lateral design loads on towers. The less frequent ‘environmental wind’ is however higher and will require careful consideration in terms of environmental impact at ground level.
- Taller and more slender towers, particularly residential buildings, are more likely to need tuned mass dampers to control the comfort (accelerations) at the top of tall buildings.
- The build form on plan and elevation can greatly improve the dynamic performance of the building. Typically, towers which have more rounded corners, are non-extruded, or are tapered in elevation tend to perform better.
- Tall buildings do sway in the wind. The amount of deflection increases with height, whilst the limiting lateral deflection can vary, an internationally recognised limit is height of building divided by 500 (h/500) for a wind that occurs 1 in 50 years.

Energy and the Environment

- As buildings become taller, the energy they require per m² tends to increase. In general terms, the increase in operational energy is of the order of 5% for each 100m increase in height above 200m.
- The longest component contributing greatest to the increase in energy usage with height is the vertical transportation.
- Tall buildings have the potential to have a significant effect on the local environment. Most significant is the need to avoid urban canyons which impact on the environmental wind climate and heat load.
- As taller towers consume more energy per sq m. it is possible that this will make the energy targets in the Sydney 2030 plan more difficult to achieve. One solution is the need for a factor in the considerations of site area and greater uptake of public transport in the assessment.
**Cost of Tall Buildings**

*Appendix A* presents details of the cost of residential and commercial office towers. The data is based on buildings in London (reference 1). While the breakdown of costs between the individual components is applicable to construction in Sydney, the overall cost and ratio of cost between commercial and residential is likely to be different. The typical costs for tall buildings in Sydney are as follows (reference 2):

<table>
<thead>
<tr>
<th>Component</th>
<th>Low $/m²</th>
<th>High $/m²</th>
<th>Difference $/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>3,300</td>
<td>4,500</td>
<td>1200</td>
</tr>
<tr>
<td>Commercial</td>
<td>3,900</td>
<td>4,350</td>
<td>450</td>
</tr>
</tbody>
</table>

The key factors impacting the cost of high rise are summarised as follows:

- Size and geometry;
- Size and regularity of floor plate;
- Floor plate efficiency;
- Structural solution;
- Façade to floor plate ratio and façade specification/repeatability.

**Greening of Tall Buildings**

The greening of high rise buildings is becoming commonplace around the world. This is in part due to legislation. *Appendix B* presents a summary of examples of high rise buildings around the world where “vertical greening” has been used to good effect across a range of building types. The report presents the percentage of green coverage achieved for various buildings (reference 3).

**Move Towards Increased Slenderness**

There has been an increasing trend in recent years for buildings to become more slender, particularly residential apartments. Slenderness is defined as the height of a tower to the floor plate dimension on plan.

This has been driven by the demand for urban living and the premiums achievable to compensate for high cost of building slender. The photograph on the right shows some of the proposed towers in New York, highlighting their slenderness. Indeed these towers are referred to as New York’s “skinny towers”.

The aspect ratio (slenderness) of some of these towers is as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Aspect ratio (slenderness)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Madison, New York</td>
<td>1.12</td>
<td>188</td>
</tr>
<tr>
<td>432 Park Avenue, New York</td>
<td>1.24</td>
<td>433</td>
</tr>
<tr>
<td>11 West 57th Street, New York</td>
<td>1.24</td>
<td>438</td>
</tr>
</tbody>
</table>

Some examples in Australia include:

<table>
<thead>
<tr>
<th>Name</th>
<th>Aspect ratio (slenderness)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morant Tower, Brisbane, Qld</td>
<td>1.12</td>
<td>274</td>
</tr>
<tr>
<td>828 Flinders Street, Melbourne, Vic</td>
<td>1.15</td>
<td>88.3</td>
</tr>
</tbody>
</table>

It is expected that in meeting the demand for high rise residential development, the slenderness of apartment buildings will tend to increase.

There are a number of implications of buildings being more slender:

- A larger premium for structural costs (the building is potentially more flexible due to its slenderness and thereby requires a more material to increase stiffness).
- "The need to provide dampers in the building to improve comfort to occupants in wind later.
- Possible alternate solutions are necessary to address car parking issues.
Tall Buildings | The Implications of Increasing Height

Background information and directions

Increasing Height
There is a very pronounced global trend of increasing the height of tall buildings. The data in Appendix C (reference 4) presents statistics on specific global metrics including:
- Average height of top 100 buildings worldwide,
- Height increases relative to function,
- Geographic distribution with height,
- Timeline of height increases.

The data presented includes a timeline of all the buildings constructed in Australia over a height of 200m since 1960 compared to those constructed globally over a height of 300m.

It is evident from this that:
- The average height, at present, of the top 100 world’s tallest buildings is 350m
- Since 2000, there has been a significant increase in the proportion of mixed use towers. It should be noted that many of the mixed use towers are premier hotel components on the upper floors of Asian CBD commercial towers.
- Also since 2000, there has been a marked increase in the average height of the top 100 tallest buildings. This is primarily due to the high rise activity in the Middle East and China over the past 12 years and the large number of buildings in these locations above 300m. The opening of the Burj Khalifa tower in Dubai represented a significant increase in height of worlds tallest and fully illustrates the trend. See also Appendix C which refers to a summary of towers completed in 2011 only. The dominance of China and the Middle East is evident.
- From 1960 to 2000, 88% of the tallest 100 buildings were office buildings, and 12% were residential. By the end of 2010, the number of office buildings in the top 100 had reduced to 47% and the number of residential increased to 15%.

The Knight Frank Index
For completeness, included in Appendix D is the annual report from Knight Frank which provides background to some of the recent tall building trends. Based on a set of criteria, including rents, yields, building stock, demand for high rises and growth prospects, Sydney ranks 7th in the world ahead of Shanghai and other tall building centres like Chicago and Dubai.

Floor plates and eccentric cores.
The conventional configuration of office floor plate comprises a central core with an all-round lease span (depth) in the range of 11 – 14m. This configuration is very typical of commercial high rise in Asia.

The trend towards eccentric cores in Sydney also extends to residential developments due to the SEPP 65 requirements precluding south facing apartments. The inclusion of an eccentric core can have significant implications on the structural design, and the way in which the building is serviced.
- Twisting forces under lateral load promote the use for exterior frames (see later).
- The non-symmetrical distribution of vertical structure tends to cause taller towers to bend under gravity loading. This can introduce complexities in pre-setting during construction to compensate for these effects.
- The service runs from the core to the perimeter can be longer and this can influence the way in which the building is serviced.

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Impact of height...... 200, 300, 400

This part of the report considers the implications of constructing towers with heights of 200, 300 and 400m. It intentionally draws on the experience and precedent of towers constructed elsewhere. Where appropriate, graphical data is presented to define trends and typical information.

Base width

To meet with structural and comfort requirements, towers need to have a minimum lateral stiffness and strength. This is influenced by the type of structural system adopted, the materials used and most significantly by the aspect ratio of the tower. Aspect ratio is defined as the building height divided by the minimum base width dimension. A higher aspect ratio equates to a higher slenderness and potentially a more flexible tower. Drivers such as small plot size, desirable lease depths, floor plazza impact the aspect ratio adopted.

The following graph presents the approximate base dimension for residential and commercial building types. For these figures to be meaningful, the following assumptions have been made:
- Office tower, floor plates 1,500m² nett with floor to floor height of 4m
- Residential tower, floor plate 600 m² nett with floor to floor of 3m

It is noted that floor to floor dimensions in office buildings can typically vary over the range 3.8 - 3.3m, and for residential 2.8 - 3.2m. The figures chosen for this exercise are general assumptions for the purposes of comparison.

There is intentionally no data in the above graph for 400m high residential towers. This is because there are very few 400m plus solely residential towers. Towers of this height tend to be mixed use residential / office / hotel.

This plot shows a typical value for an aspect ratio of 8, but also includes a minimum value. This is recognising the trend to more slender towers and corresponds with some of the more slender extremes. In the case of residential buildings this minimum equates to an aspect ratio of 1:12 whilst for offices it equates to 1:10.

Cores Sizes

The size of cores for tall buildings vary significantly depending on the approach to vertical transportation, escape stairs and how the building is serviced. While the core will typically make a significant contribution to the strength and stiffness of the tower, invariably its size is dictated by the space requirements of the services and egress provision within. Indicative breakdown of services within the core for high rise commercial tower are as follows:

<table>
<thead>
<tr>
<th>Category</th>
<th>Approx. Percentage of Floor Plate Area</th>
<th>Approx. Percentage of Core Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Services</td>
<td>3.5%</td>
<td>10.5%</td>
</tr>
<tr>
<td>Fire stairs</td>
<td>2.0%</td>
<td>7%</td>
</tr>
<tr>
<td>Lifts</td>
<td>10.5%</td>
<td>35%</td>
</tr>
<tr>
<td>Lobbies</td>
<td>8%</td>
<td>24%</td>
</tr>
<tr>
<td>WCs</td>
<td>2.5%</td>
<td>8%</td>
</tr>
<tr>
<td>Total</td>
<td>26.5%</td>
<td>45%</td>
</tr>
</tbody>
</table>

The figures above exclude the 'structure' of the core. It is for this reason that the total is 85%. The residual area making up the core can be considered as structure and miscellaneous.

Plant floors

Typically there will be a plantroom every twenty (20) to twenty eight (28) floors. Plant floors will typically be between 5.5m and 6.0m floor to floor. Total building services plant requirement will be between 9.5 and 10.0% of gross floor area (GFA). Depending on the specifics of the design, there could be two plant floor level at 20-25 storey intervals, and it may be that the floor to floor height matches that of the typical floors (for reasons of external aesthetics).

External skin allowances

For typical towers NLA is measured to the inside face of the glazing. Overall glazing thickness is typically 20mm for a high rise tower. For most commercial towers, the mullions are inboard of the glazing to maximise the NLA. However, this is not always the case. In cases where the main part of the mullion is external to the glazing it could be expected to protrude 50-200mm beyond the external glazing face. In some cases where a high-performance accessible double skin cavity is used (ie. 1 Bligh Street) the glazing depth will be typical of 800mm.
Tall Buildings | The Implications of Increasing Height

Impact of height

Guangzhou West Tower - 439m
- Net Internal Area: Low Zone Floor Efficiency = 71%
- High Zone Floor Efficiency = 73%
- Core:

Hong Kong Nina Tower - 320m
- Net Internal Area: Low Zone Floor Efficiency = 72%
- High Zone Floor Efficiency = 78%
- Core:

Shanghai China Merchant Bank - 208m
- Net Internal Area: Low Zone Floor Efficiency = 74%
- High Zone Floor Efficiency = 79%
- Core:

Guangzhou R & F Mixed-Use Tower - 296m
- Net Internal Area: Low Zone Floor Efficiency = 74%
- High Zone Floor Efficiency = 77%
- Core:

Shenzhen Kingley Finance Tower - 442m
- Net Internal Area: Low Zone Floor Efficiency = 76%
- High Zone Floor Efficiency = 73%
- Core:

HWP Tianjin Complex - 432m
- Net Internal Area: Low Zone Floor Efficiency = 75%
- High Zone Floor Efficiency = 80%
- Core:
Tall Buildings | The Implications of Increasing Height

Impact of height

The above data comes from Arups database on towers in Asia. It comprises a range of structural systems (influenced by height) and also includes mixed use towers. The core area shown is that for the low levels of the tower, as opposed to that in the higher levels where the lifts "drop-off" and core sizes typically reduce.

The above shows the core area for some of the most internationally recognised towers, the data of which is also included in the graph opposite.
Tall Buildings | The Implications of Increasing Height

Impact of height

Typical Structural Systems
The following presents some of the typical structural systems that are likely to be adopted for the different heights of building.

Notes regarding the above diagrams:
- 75% of all tall buildings constructed globally over the height of 300m use an outrigger system.
- Outriggers are typically located at plant room levels. For a typical office building, the plant room floors are located at 20 to 25 floor intervals, depending on plumbing, mechanical systems adopted and local regulations.
- In 1960, 95% of the 100 tallest buildings were constructed in steel. By 2010, only 22% were constructed in steel. The remainder were constructed from concrete or concrete steel composite.
- Concrete is the preferred structural medium for residential buildings because of its inherent acoustic benefits and the reduced requirement for long floor spans compared to office buildings.
- Whilst externally braced or diagrid type structures have been used for office buildings, there is the obvious reluctance to use such systems for residential or hotel type towers.
- Regardless of the structural system, there is a preference for the use of reinforced concrete cores (as opposed to steel only) due to the efficiency and maturity of the climbform industry, the robustness of a reinforced concrete core (from a damage and means of escape perspective) and the acoustic benefits, mindful that cores typically obscure the plant and equipment.
Tall Buildings | The Implications of Increasing Height

Impact of height

Building to the Limit of Height

In setting a height limit for tall buildings, it is appropriate to consider what the construction implications are in constructing to that limit.

It is conventional to use tower cranes in high rise construction. These are used to move materials to and from the work front. It is inevitable therefore that such cranes project higher than the level under construction. In addition, there are other pieces of equipment such as material and people hoists, climbing forms which can also project beyond the level of construction.

When it comes to constructing to a defined upper height limit this can present a problem. To cost-effectively construct the highest point of permanent structure will usually involve the use of cranes and hoists as above, thereby breaching the height limit during the construction. As a solution, it is common practice to apply for a dispensation to breach an imposed limit for a restricted period which follows a very detailed set of procedures. These dispensations might only apply during daytime and in periods of good visibility. In Australia, and where the height limits are defined by CASA (Civil Aviation Safety Authority), any such reach will typically involve Federal Approval.

If, for any reason, there is no possibility to breach a height limit, even temporarily, then there does need to be careful consideration of the approach to construction. There are probably two main categories to consider:

- Towers with spires, and
- Towers with flat tops

Tower with spires, or masts, are probably the easiest to construct to a height, without exceeding the height limit. On the Petronas Towers in Malaysia, and the Burj Khalifa in Dubai, the masts were constructed at a lower level, below the height limit, using cranes for the installation of material and then the completed mast was jacked vertically into its permanent location. An image below shows part way through the jacking process with the mast progressing higher than the tower cranes.

It should be noted that this approach was adopted not because of the need to avoid breaching the height limit, but is more to do with the practicalities of construction. For the scale of masts envisaged in these towers, it is not sensible to build the tower cranes taller than the mast, jacking up the mast is cheaper and easier approach. In the case of more modest towers, with more modest masts/spires, it is expected that installation by tower crane would most cases remain a preferred and cost-effective approach. However, the jack-up method does provide a solution where a height breach is strictly not permitted.

Flat top towers do present a more difficult challenge. For there to be absolutely no encroachment above the finished constructed level during construction, it will be necessary to construct the uppermost floors and roof at a lower level, and then jack the completed floors into position. It is envisaged that to achieve this, the larger crane used to construct the bulk of the tower would be replaced at higher level by a small crane (potentially also used to dismantle the large crane) which did not encroach on the height limit. This smaller crane would facilitate the construction of the roof and highest floor slab at (say) 5m, or two storeys, below the height limit, before these completed floors are vertically jacked into their correct position, in a similar manner to that described above for the spire/mast. Compared to conventional construction, this is expected to be more costly, and as such we are not aware of this approach being adopted anywhere else in the world.

A more credible approach might be that for the construction of flat top towers there is a minor encroachment permitted. One that allows the placement of small cranes, or concrete pumps to enable the heavy material such as concrete tubes, placed in-situ – i.e. when the floor is in its final position. Such an encroachment might be only of the order of 2-3m, and for short periods during pouring. This would represent a significant reduction of duration and encroachment compared to conventional tower cranes and might be deemed more acceptable. In situations where absolutely no encroachment is permitted, a flat jack-up solution is considered as prohibitively expensive or not practical, then building to a maximum height which is 2-3m below the no-encroachment zone would be a sensible approach.
Tall Buildings | The Implications of Increasing Height

Impact of height

Typical Building Services Systems

Mechanical

Key issues in the consideration of mechanical systems:
- Air versus chilled water circulation
- Central plant
- Efficiency of risers sizing
- Stack Effect issues
- Environmental impact on the design
- Plant replacement and maintenance
- Tenant plant flexibility

Mechanical Plant (Commercial Buildings)

Taller buildings are more energy-intensive and require more power the taller the building becomes. The graphs on the right show the typical floor area requirements for different mechanical systems. One is all water system (e.g. chilled beam approach) whereas the other is all air without water or the office floors (e.g. Variable Air Volume (VAV) approach).
Vertical Risers
Typically as follows:
1. Mechanical Air - No variation with height assuming distributed plant.
2. Mechanical Water - Negligible difference with minor penalty due to hydraulic break.
3. Electrical - Penalty with height to reticulate HV up the building and communication.
4. Fire Services and Hydraulics - Penalty with height for multiple rising mains.

Total MEP Plant
Increase in total building area leads to:
1. Increased spatial efficiency of the mechanical central plant
2. Increased spatial efficiency of fire services central plant.

Total typical area of risers as a percentage of floor area.

Total MEP Plant area as a ratio of GFA
(Note: Above not tested)
Tall Buildings | The Implications of Increasing Height

Impact of height

Electrical

Basically the energy density for power on the footprint of land increases the taller you make the tower.

Commercial

These demands are for the same sized footprint for each usage type and hence the energy density for the piece of land gets significantly higher. Hence in high rise designated zones the relevant utility company may need to reinstate their network locally to meet the overall demand. For example in the City of London they upgraded their network and created a dedicated 33kV new service dedicated to large projects (ie. tall buildings) and they have already exceeded the available capacity.

With the increase in electricity demand the amount of space required for total electrical equipment (substations, switchboards, electrical risers, generators, common rooms, comms risers, land/aspect services but excludes lift shaft/plant areas) also increases. In terms of percentage the approximate electrical plant requirement would be as follows:

- a 200m commercial tower with 50 occupied floors and a footprint of 1500m² will give an electrical plant percentage of approx. 8.3%
- a 300m commercial tower with 75 occupied floors and a footprint of 1500m² will give an electrical plant percentage of approx. 3.5%
- a 400m commercial tower with 100 occupied floors and a footprint of 1500m² will give an electrical plant percentage of approx. 4.2%

This assumes a standard level of resilience and backup as would be required for a premium office space. So pretty much around 4-4.2% of building area for all options for commercial.

For residential there is a lower requirement or resilience so no generators and less resilient design in the infrastructure. The percentages below are for all electrical (i.e. substations, transformers, switchboards, risers tenant risers, comms risers etc but no generators and excludes lift shaft/plant areas)

- a 200m residential tower with 65 occupied floors and a footprint of 1000m² will give an electrical plant percentage of approx. 1.9%
- a 300m residential tower with 100 occupied floors and a footprint of 1000m² will give an electrical plant percentage of approx. 2.5%
- a 400m residential tower with 133 occupied floors and a footprint of 1000m² will give an electrical plant percentage of approx. 3.1%

Typical Substation Locations

For a commercial office electrical plant percentage will be approximately 4-4.2% of GFA.

For a residential tower electrical plant percentage will be between 1.9% to 3.1% for 200-400m towers respectively.
Tall Buildings | The Implications of Increasing Height

Impact of height

Vertical Transportation

The following section considers the impact on the design and specification of vertical transportation systems, as buildings become increasingly taller.

The development of vertical transportation technologies has been a key driver in the successful design of functional, high-rise buildings. A well-planned and designed vertical transportation system should enable the architectural requirements of the site while transporting people and goods seamlessly with minimal time and stress. To this end, we will consider the impact on vertical transportation designs in terms of:

- Performance
- Design Arrangements (Stacking)
- Equipment Technology
- Occupant Safety

Performance

Vertical transportation systems are designed to meet the performance levels as agreed with the building owner or developer. The main variables having influence over the design of vertical transportation systems include:

- Building height
- The number of occupied floors
- Building population
- Building type (Commercial, Residential, Hotel, Mixed use)
- Specific architectural requirements

For commercial buildings, the Property Council of Australia stipulates required performance levels for Premium, A and B Grade type developments. There is however no comparative body in Australia for residential buildings; therefore, we would reference The Chartered Institute of Building Service Engineers (CIBSE) Guide D - Transportation Systems in Buildings.

In commercial buildings, both the morning up-peak and mid-day two way traffic conditions are considered. For residential and hotel developments a 2-way traffic profile is assessed.

The performance of vertical transportation systems is defined in terms of:

**Handling Capacity (HC)** - The percentage of a building's population that can be transported by the elevator system, during the most demanding 5 minute period for the traffic profile under consideration.

**Average Waiting Interval (AWI)** - The average time between successive elevator arrivals at the main floor. Average interval is a good measure of the elevator systems quality of service when a conventional control system is being used.

**Average Waiting Time (AWT)** - The time period between when a passenger registers a landing call or joins a queue, until the responding elevator begins to open its doors at the boarding floor. This measure is applicable when Destination Control Service (DCS) is used.

Typical performance targets for commercial and residential buildings are summarised below.

### Residential

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Luxury</th>
<th>Normal</th>
<th>Low Income</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling Capacity (Two-way)</td>
<td>8%</td>
<td>6% to 8%</td>
<td>5% to 7%</td>
</tr>
<tr>
<td>Average Interval / Waiting Time (Up-peak)</td>
<td>45-50 seconds</td>
<td>50-60 seconds</td>
<td>50-70 seconds</td>
</tr>
</tbody>
</table>

### Population

<table>
<thead>
<tr>
<th></th>
<th>Studio</th>
<th>1 Bedroom</th>
<th>2 Bedroom</th>
<th>3 Bedroom</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td>1 person</td>
<td>1.5 persons</td>
<td>2 persons</td>
<td>3 persons</td>
</tr>
<tr>
<td></td>
<td>2 persons</td>
<td>3 persons</td>
<td>4 persons</td>
<td>6 persons</td>
</tr>
</tbody>
</table>

### Commercial

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Premium Grade</th>
<th>A Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling Capacity (Up-Peak)</td>
<td>&gt; 14% of total building population during peak 5 minute period</td>
<td>&gt; 13% of total building population during peak 5 minute period</td>
</tr>
<tr>
<td>Handling Capacity (Two-way)</td>
<td>&gt; 12% (15% incoming + 6% outgoing) of 80% of total building population during a 1 hour period</td>
<td>&gt; 11% (5.5% incoming + 5.5% outgoing) of 80% of total building population during a 1 hour period</td>
</tr>
<tr>
<td>Average Interval / Waiting Time (Up-peak)</td>
<td>&lt; 25 seconds</td>
<td>&lt; 30 seconds</td>
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<tr>
<td>Average Interval / Waiting Time (Two-way)</td>
<td>&lt; 35 seconds</td>
<td>&lt; 40 seconds</td>
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<tr>
<td>Car Loading</td>
<td>&lt; 80%</td>
<td></td>
</tr>
<tr>
<td>Occupancy</td>
<td>12/hr (per person) of total NLA</td>
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</tr>
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</table>

Tall Buildings | The Implications of Increasing Height

Impact of height

Design Arrangements (Stacking)

As towers increase in height, the vertical transportation design must respond to achieve the required performance and enable the seamless flow of tenants and visitors throughout the building.

While increasing the number, size and speed of elevators is possible, there comes a point where this is no longer an effective design strategy in order to maintain the floor plate efficiencies required to make a development viable. At this point, the design of vertical transportation systems must adopt design strategies and equipment technologies different to those the Sydney market may be familiar with.

To maximise floor plate efficiencies, elevators are arranged in groups. Subject to the number of elevators in each group (low, mid, high rise etc.) the below stacking arrangements are typical.

As commercial towers increase in height or where mixed use towers are being developed, sky lobbies can be introduced as depicted below. Sky lobbies require the use of shuttle elevators to transport passengers to the sky lobby where they transfer to local elevator groups.

Equipment Technology

As towers increase in height, it is necessary to consider the use of various equipment technologies to achieve the required performance levels. There are several equipment technologies that have been specifically developed to maximise the handling capacity of each elevator shaft. These include:

- Multi-car systems (Double Deck and TWIN Elevators)
- Destination Control Service

Double Deck elevators comprise two permanently connected passenger cars, positioned one above the other and connected to a common suspension and drive system. The upper and lower decks are therefore limited to serving two adjacent floors simultaneously.

The Twin system is unique to ThyssenKrupp and has 2 elevator cars running independently in the same elevator shaft. Each car has its own ropes, counterweight, safety, control and drive equipment while sharing common guide rails and landing entrance doors.

Multi-car elevator systems have been specifically developed to increase the handling capacity of each elevator shaft. This in turn provides the opportunity to reduce the overall number of elevator shafts while achieving comparable levels of service to a traditional single deck system.
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Impact of height

There are a number of similarities between Double Deck and TWIN elevator systems, with the most important being:
- Both require Destination Control Service to maximise efficiencies. On Double Deck elevators, DCS is used to minimise non-coincidental calls and on Twins to maintain safe operational distances between elevator cars;
- Both require dual lobby loading to allow the upper and lower cars to load simultaneously;
- Increase handling capacity of each elevator shaft;
- Fewer elevator shafts;
- In comparison to a conventional single deck system with all elevators serving from the ground floor, the use of multideck elevator systems combined with sky lobbies can reduce the core size by up to 30%.

When considering a multi-car vertical transportation system in conjunction with the use of sky lobbies the below stacking arrangements are made possible.

Occupant Safety

In many parts of the world, including East Asia, Europe and the Americas, the use of appropriately designed elevators is considered safe and reliable means of evacuation to support the use of fire stairs. In Australia, there are few developments where the use of elevator for evacuation has been considered or allowed. There are several emergencies which may result in a building, or a part of a building, needing to be evacuated. These emergencies include fire, earthquake, explosion, a security threat, impact, flooding, storm damage and chemical, gas or biological release. The likelihood of one or more of these occurrences leading to an evacuation will vary depending upon the location and the use of the building. For some of these emergencies it may be appropriate for an elevator to be used for evacuation, noting the warning sign displayed at each lift landing advising “do not use lifts if there is a fire” is with specific regard to fire.

There are several discussion papers regarding the use of elevators for evacuation in Australia. The most recent being the Information Handbook “Lifts Used During Evacuation”, from the Australian Building Codes Board (ABC). This is however a non-mandatory or regulatory document, with the formal position nominated in the current National Construction Code (NCC) being to prohibit the use of elevators in the event of a fire. The main drivers for using elevators for evacuation, which become increasingly critical as buildings increase in height include:
- Demographic changes with ageing populations and greater obesity leading to issues of fatigue when using fire stairs;
- An increase in different forms of disability, making use of stairs impossible or problematic for some persons. In Australia up to 29% of the population is considered to have some form of disability.
- The need to provide safe, equitable and dignified egress for all building occupants under Occupational Health and Safety (OHS) legislation.
- A desire for more rapid evacuation in the event of non-fire threats by using elevators and stairs in conjunction;
- A design ambition to provide better fire fighter access.

There are two primary design concepts for egress using elevators:
1. Transfer Refuge Floors - in this concept, building occupants travel down the fine stairs to a protected transfer/refuge area from where they are transported by shuttle elevators to a point of egress;
2. Direct Evacuation - in this concept, building occupants enter a protected lobby and directly into the elevator at each floor.

The International Organization for Standardization (ISO) is developing a standard specifically on requirements for lifts to be used in building evacuation. Some of the lift operational goals required are still under development and to ensure a harmonised approach, are being developed through the ISO process. In consideration of the above, it is possible for elevators to be used for the evacuation of occupants in emergency outside of a fire event. Should elevators be used in this way, the co-ordination of multiple engineering disciplines will be required to achieve:
- Building Structure designed to protect elevators from:
  - Smoke
  - Heat
  - Water
- Provision of a reliable power supply during evacuation.
Ultimately, an evacuation strategy using elevators, which does not negate or reduce the requirement or application of current life safety statutory requirements, could be a condition of consent for towers over a certain height or which have a particular set of characteristics.
Geology and Foundations

The 1:100,000 Geological Map of the Sydney Region indicates the city of Sydney is underlain by Hawkesbury Sandstone and Ashfield Shale.
- The CBD is typically founded on Hawkesbury Sandstone.
- Ashfield Shale is present to the south of the CBD in the areas of Hyde Park, Central Station and Campsie. Ashfield Shale overlies the Hawkesbury Sandstone.
- Quaternary alluvium deposits and reclaimed land (fill) are present at the harbour edges and within some bay. Prominent intrusions of quaternary alluvium deposits extend from Darling Harbour north of Central Station then Surry Hills and Moore Park. Depths to rock can be in the order of 10 to 23m.
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Below Ground

The presence of fractures and defects, including major structures such as faults and dykes, may reduce allowable bearing capacities for foundations, increase groundwater inflow, and present instable conditions for vertical excavation faces. The "Map and selected details of near vertical structural features in the Sydney CBD" indicates the presence and whereabouts of these geological features with the Sydney CBD.

In accordance with Pelisi et al., typical allowable bearing pressures for Sandstone Class III/III/III in the order of 0.8MPa to 1.2MPa and for Shale Class III/III/III 3.5MPa to 5MPa. The classification system is based on the rock strength, defect spacing, and allowable stress of which all three must be satisfied.

The Sandstone and Shale prevalent in Sydney across the CBD and beyond, provides good founding material for high rise towers (higher than the present limit) and results in foundation solutions which are significantly more cost-effective compared to those of other tall building cities around the world.

Numerous high rise buildings up to 245m exist in the Sydney CBD, each of these buildings typically comprise of multi-storey subterranean car parking or basements. The depth of these structures are normally sufficient to encounter competent rock at full excavation level permitting the use of spread footings for present building foundation loads. Where this is not the case piled foundation solutions of varying diameters can be adopted where compressive loads cannot be achieved by spread footings or required founding material is at depth or below groundwater. Where buildings or groundwater exert tension or uplift loads on foundations these can be resisted by permanent ground anchors or tension piles socketed into the rock.

During excavation the release of high in-situ horizontal stresses within the rock results in ground movement that may affect adjacent properties, existing foundations, existing and future underground infrastructures. Assessment of the impacts of ground movement is normally a development condition of City of Sydney and to also satisfy TNSW and other relevant stakeholder requirements.

Groundwater is present and needs to be considered for the selection of drained or tanked basements.

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Basement Parking

As the area of a site increases, more efficient car parking layouts can be provided resulting in a high number of parking spaces per level. However, the number of spaces is greatly affected by a number of factors including, but not limited to:
- Service vehicle manoeuvring and loading;
- Circulation roads and ramps;
- Access to driveway and locations;
- Slope of site;
- Area required for general building services (i.e. substations, storage, refuse area, bike store, lift core); and

This results in a range of parking spaces able to be provided for different site areas as shown below.

As one would expect, the number of car parking spaces becomes inefficient as the site area reduces. For small sites, there is a limiting width of site necessary in order to achieve a core, full round core circulation, and parking bays either side. This minimum site width equates to 23m plus the width of core plus perimeter wall thickness and tolerances. Some sites that are being developed for residential buildings greater than 250m do not achieve this criteria. As a consequence, the number of car parks achieved per level is very low and car stacking solutions have to be considered.
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The Impact of Wind

Wind Speeds
Below presents a graph of the approximate relative gust wind speeds of a number of tall building cities around the world. It should be noted that different countries trust the ultimate wind condition used to design for the safety of buildings, quite differently. Thus, the relative magnitude of wind loads adopted in design might differ compared to that shown below.

It is evident however that, compared to other tall building cities around the world, the wind climate in Sydney is no particularly onerous. It would not be a factor in limiting the building height.

It should be noted that one characteristic of the wind in Sydney is that the serviceability wind, i.e. the magnitude of the regularly occurring wind is relatively high compared to other cities. As a consequence it is likely that making buildings comfortable, as discussed later, is likely to be the key consideration in the design.

Deflections, movements, accelerations
One of the key considerations in the design of tall towers is the extent by which they move laterally under wind and the need to ensure the comfort of occupants within. Key to achieving a comfortable environment is to make sure that the accelerations on the occupied floors are within acceptable limits.

The graph below shows the typical deflection limits adopted for tall buildings. This is based on a value of h/300 for a 50 year return period wind. It should be noted that this is not a mandated limit, and as such there is some variation from these typical limits depending on the specifics of the building. For a 60m high building, it is credible that the building will deflect 800mm from vertical under extreme winds.
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The Impact of Wind

The comfort requirements limit the lateral accelerations to acceptable levels when the building operates under wind loading. The graph below shows a number of internationally recognised limiting criteria. Some of the criteria depend on the dynamic period of the building, recognising that humans are less sensitive to a given acceleration if the period is longer. Some of the criteria also consider an acceptable limit as being that where the person objects if fall within a 2%-10% range.

A very simple rule of thumb, and one that is sufficient for the nature of this study is that the following acceleration limits should apply:
- Commercial Buildings: 20 mg
- Hotels: 15 mg
- Residential: 10 mg

‘mg’ is millig, or put another way, 10 mg is 1% of the acceleration due to gravity.

The significant issue is that the acceleration limits for residential are significantly more stringent than that for an office building. There are a number of reasons for this:
- Where a person owns the property, as in a high rise apartment, there is increased awareness and anxiety of movements and 'things that might be wrong'. Less so if it is a place where you visit to work.
- People are more sensitive to accelerations when they are relaxed, lying down - i.e. typically at home.

The limiting of accelerations is often a key driver of the design of residential apartments, and can have a big implication on office buildings which are mixed use and have a hotel or penthouse type accommodation in the top floors.

Ways to reduce the acceleration include:
- Make the building stiffer
- Change the shape (make less slender)
- Increase the mass of the building (to increase period)
- Increase the damping

An approach to reducing accelerations, which is becoming increasingly more common, is to incorporate dampers into the building. Common in residential towers in Australia is to use Tuned Liquid Dampers (see figure). The system relies on the 'tuned' sloshing of water within large tanks to dissipate energy and increase damping. For residential towers of 30m high, with an aspect ratio of 12, it could be expected that two such tanks would be required at the top of the building, each 20m long, 6m wide and 6m high (2 storeys).
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The Impact of Wind

Effect of Tower Shape

The plan shape of a tower will greatly influence the wind loading. As a general rule:
- A square shape is not ideal.
- Sharp corners are best avoided.
- Channeled or rounded corners greatly reduce wind loading.
- Overall rounded forms typically behave better.

The shape of a tower in elevation is also a factor in influencing its performance under wind. In the case of tall towers, or towers with high slenderness, departures from a pure extruded form can greatly improve the dynamic response by 'confusing the wind' and reducing the effects of vortex shedding. A gentle taper over the height of the building is effective in this respect, or as an extreme, a non-symmetric elevational profile. The world's tallest tower, the Burj Khalifa in Dubai, uses this latter effect to benefit the performance of the tower and the comfort of occupants within.

Effect of Tower location

Towers in CBD locations typically benefit from the 'cluster effect' - i.e. beneficial wind shielding due to the close proximity of similar sized towers. It should be noted however that this is not always the case. The plan form of certain buildings (triangular being a good example), can have a disturbing effect on immediately adjacent towers.

What should be avoided are significant tall towers being located 5D apart (where D is a case of tower width) and with little obstruction in between. This approximate dimension is the classic stand-off distance where vortex shedding of one tower directly impacts the other. The impact on the behaviour of the affected tower is potentially very significant.

The above is a little simplistic, as the biggest influence on loading and dynamics of a tower more often than not created by its proximity to other towers, prevailing wind direction and the like. 
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Fire and Life Safety

Building Code of Australia (BCA) currently treats all buildings of the same class of use >50m effective height in the same way, i.e., identical minimum prescriptive and the same performance requirements for:
- fire resistance, compartmentalisation and protection of openings
- access and egress
- services and equipment

Australian Building Codes Board is driving more economy in construction and encourage performance-based fire engineering alternative solutions. BCA 2016 will become fully performance based, with less emphasis on simple prescriptive or Deemed to Satisfy (DTS) rules.

However, historical practice has frequently adopted minimum “deemed to satisfy” BCA prescriptive provisions the design of tall buildings rather than extensive use of performance-based fire engineering risk assessment. Hence, typically tall buildings >50m have adopted DTS fire resistance level requirements of 150 minutes for office areas and 90 minutes for residential areas, independent of building height.

Likewise, typical tall office buildings of 1500m2 GFA have two exit stairs and residential buildings 1000m2 commonly have two exits. There have been a few engineered buildings with a single exit stair, however, current trends are against these solutions due to lack of redundancy for fire brigade access.

Therefore, the future trend in fire safety design of very tall buildings is that simple prescriptive DTS rules may no longer be considered adequate. Instead, a Fire Safety Strategy is required to be developed by addressing key aspects of the building, its fire hazards, fire safety systems and the related design approaches, aimed at meeting fire safety goals and objectives.

For very tall buildings (>200m height) Arup would recommend building owners to obtain a fire safety strategy from a professional fire safety engineer in order to ensure the most appropriate design for occupant safety and protection of adjacent properties. Building owners and their insurers also have additional requirements which can influence the fire safety design, e.g.
- property protection
- business continuity
- security against malicious attack
- marketing image

A fire safety strategy for a very tall building starts with establishing the fire and life safety goals and objectives in conjunction with overall design objectives. Key considerations will likely be:
- the building will house a large number of occupants
- occupants will have limited evacuation options
- the building needs to remain standing for the time necessary to protect occupants in place or safely evacuate them
- fire fighters will have limited access opportunities
- potential hazards include natural fire hazards and deliberate events
- potential accidental or deliberate failures of fire safety systems

Once the fire safety strategy has been established, the architect and client can then proceed with confidence with the Concept Design.
Tall Buildings | The Implications of Increasing Height

Environmental, Light and Energy

Energy Use for typical towers

For commercial buildings energy use is typically split between tenant power and lighting and base building services such as air conditioning, ventilation, hot water and lift energy. As a tower increases in height the most significant differences in energy use per sqm are lift energy and pumping. Based on current commercial systems design with state of the art efficiency and technologies such as lift energy reclaims the variation in energy per sqm of 5% is expected per extra 100m height in Sydney.

For residential buildings the lift energy is a higher proportion. The second major impact for residential towers are degree of air-conditioning hours. Most residential tenancies are designed to use natural ventilation for the majority of the year. Mid to low rise towers wind pressures are appropriate to ventilate the building. For taller towers wind pressures increase and have the potential to change the ability to ventilate the tenancy, as a result of disturbing wind patterns residents in taller buildings may choose air conditioning to condition premises rather than natural ventilation. Typical residential energy use estimates are shown for increase in lift energy and reliance on air conditioning.

Sydney 2020 Discussion

The Sydney 2020 plan advocates a net reduction in carbon and energy however it is a typical outcome that the taller the tower the more energy they consume per sqm. They become less efficient per person than more efficient. The net outcome is that it becomes harder for Sydney to reach the 2050 energy targets. One solution might be to develop energy or carbon and water footprints based on site area. Further peak demand footprints may be considered to help reduce impacts to distribution and support infrastructure that greater demands generate.

Discussion

One of the major differences in energy use for towers is lifting energy. How does a 300m high tower compare to building more 100m high towers?

For one 300m tower, it is estimated that lifting energy increases by approximately 5kwh/m² per annum for a tower occupied typically at 1 person per 12 sqm. Thus 60kwh/person per annum.

Assuming 3 x 100m (say) spaced an average 100m apart. Using simple efficiency of car energy usage of 20kWh/10km we see that the additional horizontal travel per person is 20/10000 = 0.2 kWh.

In conclusion lift energy of a tower is not offset by horizontal travel required to build the same area for a low rise solution. As a result it is more energy efficient to space low rise towers apart assuming public transport systems are efficient.

The second key discussion point is that as towers get taller the NLA efficiency decreases as lift banks take up more space as do mechanical risers. Normalizing for these times we see the following energy impacts.

Embodied Energy

The embodied energy of construction is closely related to cost and volume of construction as it is typically associated with mass. The embodied energy for construction based on energy scopes that include mining of raw materials, processing and manufacture (scope 1-3) for a typical highrise tower add to roughly 2000 MJ m² which when considered over a 50 years design life.
Environmental Impacts
As towers increase in height, they have the following key environmental impacts on the public ground plane:
- Wind impacts
- Overshadowing
- Thermal load
- Daylight.

These environmental changes may have the following impacts on public space:
- Warmer areas and heat island effects
- Colder windier areas
- Changes in tree canopy due to changes in microclimate

Some areas may experience a combination of increased heat island effect and warming of the ground plane, increase evaporation, decrease in general wind speed.

While others may see increases in localized cooling wind speeds and decrease in heat island due to overshadowing.

This following is based primarily on public space and ground plane issues. It is worth noting that different building programs will also have different environmental requirements. For example, residential towers like sunlight with design guidelines nominating minimum number of hours key for areas of residential apartments should receive sunlight and ventilation whereas commercial towers try to reject sun and heat and are generally sealed away from ventilation.

Heat Island Effect
Due to high density urban development high rise cities suffer from the Urban Heat Island (UHI) effect. Urban areas are significantly warmer than the rural surroundings. As a result of the UHI effect, the number of very hot days and hot nights can increase dramatically. This leads to uncomfortable urban living, heat stress and related health problems, and an increase in energy consumption. There is a need to consider this in the planning and design of our city.

Buildings in cities are mostly constructed of concrete and reflective glass. They have higher thermal capacity than the natural environment, and therefore store a lot of heat during daytime. The heat that is stored elevating urban temperature. At night, tall buildings block the urban area's sky view and hence limit the ability to release the heat back into the atmosphere, thus elevate the night time temperature.

Secondly, the tall buildings disrupt and show the natural wind patterns especially deep in canyons created by buildings. This reduces the ability to flush out stored heat load. The residual heat carries forward to the next day and the vicious circle continues. As a result the city generates its own urban climatic conditions that are different from the rural and natural areas. Cities typically gain more heat than they lose resulting in Urban Heat Island effects (UHI).

The image below shows the difference in heat flows for Urban and Rural locations. In Urban areas incoming solar radiation is scattered by buildings, the subsequent reradiated energy is absorbed by buildings so finds it harder to escape. In addition the building themselves reject heat associated with the occupancy and their equipment. This all increases the temperature of the urban area. The rural areas however can reradiate energy to the sky more effectively as well as utilizing the foliage albedo effect to reflect energy as well as absorb excess thermal radiation.

When considering the cities who's life energy or carbon footprint at the embodied energy of a building may contribute 20% to 30% of the entire whole of lifetime energy. Operational energy contributes the bulk of rest of the energy however embodied energy in infrastructure is also a contributor. The image shows typical whole of life energy of cities. Based on typical energy uses of city systems, cities with tall buildings have a bigger whole of life energy impact due to the points discussed previously, namely lift energy, floor plate efficiencies and limits to ability to utilise natural systems.
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Environmental, Light and Energy

Wind

Sydney has a wind environment that has lower gust speeds than other cities with tall buildings as seen earlier in the report. The mean or average wind speeds however are higher than these cities with the exception of Hong Kong. Refer to table on page 15 - Comparison of Design Wind Speed profiles for major Cities. Tall buildings affect the wind environment in two ways. Generally, they increase surface roughness of the area and reduce wind speeds in urban canyons when spaced closely together. Tall towers however also act as tall sails that can capture and funnel wind. As wind speeds are greater higher away from the ground, these towers then have the potential to funnel higher wind speeds down to ground level. Thus tall buildings will reduce general wind speeds at ground level but simultaneously increase it in some areas. Sydney’s wind environment can be characterised with summer cooling breezes from the North and North East while colder stronger winds come from the West and South.

Thermal Loads

Downward reflected solar load increases thermal load. Of particular note for modern towers is the use of glass and the use of high performance glazing. Modern glass is highly reflective to thermal radiation. With glass the reflectivity is relatively specular and as result it is directional. This means that solar load is reflected downward till it is caught by intra-reflections deep in the urban canyon. The ability to achieve this energy to the sky and atmosphere is related to the degree of sky that can be seen to radiate to (Sky view) and wind driven air movement. In Urban canyons both these items are limited thus heat loads will be captured deep in urban canyons.

Finally heat island and wind driven air movement have big impacts on tree and shrub growths. Plant selection and sensitive planting needs to be well considered in urban canyons.

Scientifically, urban air flow depends on Building Height/Street Width (H/W) ratio

H/W > 4 not effective
H/W of 3 less effective
H/W of 2 effective

Discussion

Hong Kong has developed studies and planning issues on Heat island effects in the publication Urban Climatic Map and Standard for Wind Environment - Feasibility Study: Stakeholders Engagement Report. This study discusses concepts of Thermal Load impacts and Dynamic Potential.

Thermal Load is affected by issues such as:
- Building thermal reflectance,
- Building spacing, massing and orientation,
- Internal building loads (lights, equipment, people),
- And tree canopy ratio.
- "These defines the spatial heat balance.

Dynamic Potential is associated with ground height plane variations. This affects wind speeds, its heat flux potential, and physiological comfort. It is affected primarily by: massing, existing air paths, open spaces and ground coverages. The dynamic potential of the urban space can be mapped by using topographic and land use data. Hong Kong studies generated maps of sensitive areas that closed areas ranging from areas with low thermal load and high dynamic potential to remove heat impacts to areas with high thermal load and low dynamic potential. Further consideration to this type of mapping not the associated climate resilience should be considered when establishing tools or recommendations around urban microclimate impacts of tall buildings.

Strategies to Mitigate Thermal Load and Improve Dynamic Potential

It should also be noted that tall buildings cast long shadows. These generate localized impacts around tall buildings that decrease heat island as thermal loads are reduced. Urban comfort conditions in these areas can be further compromised by local increases in wind speed due to down draft from all towers. In summary, tall buildings can affect various microclimates that may be exacerbated thermal discomfort due to both heating and cooling.

Any development of high rise buildings should consider the existing microclimate and Urban Heat Island and set out sensitivity maps and comfort benchmarks that includes wind and thermal effects.
Daylight

There are no code requirements to provide minimum levels of daylight to developments in Australia. There is no case in which “poor” daylight performance could be considered as ‘breaking the law’.

Internationally, there are several documents proposing “good practice” daylight performance. This includes the British Standard 8206 part 2: 1992 - “Lighting for buildings: Code of practice for daylighting”. This document sets targets for daylight penetration into residential dwellings in terms of the Average Daylight Factor. The Green Star sustainability good practice tool calls up similar metrics.

There is also BREEAM – “Site layout planning for daylight and sunlight a guide to ‘good practice’”. The BREEAM document provides advice on the planning of the external environment to provide good daylighting and sunlighting within buildings and in the open spaces between them. The document does not address high rise construction impact between the principles will remain the same in urban settings and have also been used for projects such as the Athelas village in London. This document sets targets for Vertical Sky Components (VSC).

The key Daylighting Metrics typically used for considering daylight in urban spaces are then:
- **Average Daylight Factor**
- **Vertical Sky Component**

**Average Daylight Factor (ADF)**

The level of daylight penetration into a room is measured by use of the ADF. The daylight factor requires computer simulation and can be applied to a variety of functional types such as domestic, commercial and retail spaces. Each of these spaces, or parts of these spaces, will usually have a target ADF as good practice and it is recommended that any consideration of high rise development consider developing these targets.

The **VSC** is a measure of daylight received on the outside of a window (or where a window could be placed). A lower value of VSC is a good metric to use for massing. Appropriate VSC targets for urban areas should be investigated for Sydney. Targets around 25% have been considered for British projects.

Most daylight and sunlight considerations are based on human occupation requirements however the prevalence of Photovoltaic technology should be considered in future considerations to rights to light.

### Design Recommendations

<table>
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<tr>
<th>Aspect</th>
<th>ALT</th>
<th>Light Shelves</th>
<th>Daylight Reducers</th>
<th>Minimum Floor Plate Depth</th>
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<td>10</td>
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<td>South</td>
<td>0.1 - 0.5</td>
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<td>9</td>
</tr>
<tr>
<td>West</td>
<td>0.1 - 0.5</td>
<td>✔</td>
<td>✔</td>
<td>10</td>
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</tbody>
</table>

Sydney has a mix of overcast, intermediate and clear skies. Areas with bright daylight levels appear up to 5 m forwards. Brighter areas appear up to 2 m along the southern facade. The UDI depth is generally 7 to 8 m for the lower ceiling configurations and between 8 and 10 m for the higher ceiling configurations.

For the lower ceiling configuration the UDI depth does generally not increase with external light shelves and daylight redirectors. All locations with a higher ceiling configuration benefit from having light shelves and daylight redirectors. The UDI depth can be increased by approximately 1 m. Light shelves alone do not significantly increase the UDI depth for any of the facades.

Although very similar, the UDI along the eastern and western facade is slightly less for the simulation with the cumulative direct + diffuse sky, as the influence of the sun increases the bright area but does not significantly reduce the dark area. This suggests that shading devices may be appropriate along those facades.
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Environmental, Light and Energy

Other potential impacts

Ground plane issues
As the number of people occupying the building increase the energy demands of the site increase. This is particularly true for single program building, for example commercial. The infrastructure services outside the building footprint to support this increase density include:
- Electrical distribution and substations
- Water and Sewer reticulation
- Gas reticulation and boosters
- Communication systems
- Roads, Bike lanes, pedestrian walkways and public transport.

The augmentation of these systems to support greater development is by third party providers and part of economic development. This augmentation may present disruption to public space during construction and enhancement of this infrastructure. For example electrical distribution and connections may need to upgraded local to the building but also back to zone substations. Similarly, sewerage pipes may need to be increased in size and capacity to remove larger blackwater flows.

It may also add to congestion of the ground plane with back of house connections to infrastructure such as access to sub stations, carparks and loading bays. This limits the ground plane activation.

Substations
Currently buildings that require substations are required to have one at road level however they may apply to place 2 basement substations one floor down from road level as long as there is access to replace transformers. This affects the ground plane. Tall buildings often require 2 or 3 substations. These additional substations may be located up the building as long as there is one at ground or basement level. However it is sometimes cheaper to have them all at the ground plane having significant impact on the ground plane. This should be considered when developing the building ground plane impacts.

Pollution
Increased congestion on roads may be limited by limiting the number of car parking spaces, however additional usage of roads for supply and removal of goods and waste, taxis and occasional pick up and drop off will also increase, this leads to a net increase in pollution in the city environs.
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References

4. Council of Tall Buildings and Urban Habitat (CTBUH), Website, Skyscraper Centre Database.
6. Chartered Institution of Building Services Engineers (CIBSE) - Guide D
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Appendix 3 | Green Walls in High Rise Buildings
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Appendix C | Average Height of World Tall Buildings

The Average Height of the Tallest Buildings

- The average height of the 100 tallest buildings in existence around the world that year
- The average height of all 200m+ buildings completed that year

Tall Buildings 200 Meters or Taller Completed Each Year from 1960 to 2016

2014 Completions: 200m+ Buildings by City

100 tallest buildings by function
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TOWERING

ABOVE THE REST

From New York to Shanghai, companies want exciting new work places to inspire staff, while more people want to live near work. The skyscraper is seen as the best way to achieve these goals.

- JAMES ROBERTS
Chief Economist, Knight Frank

Skyscrapers are a rising tide in the modern global city. London has added 22 new skyscrapers (a building over 200 feet high) since the 9/11 terrorist attack, compared to 17 in the preceding five years. While New York added four new towers in 2014 alone, including the newest World Trade Center. This trend is expected to continue, as Deloitte has built nearly 800 skyscrapers since 2000, and Shanghai has 98.

The new architecture for skyscrapers is typically one of steel structures. Less common are cement changes in high-floor offices, particularly in offices located in high-rise buildings.

In the past, offices were typically viewed as places where companies worked and communicated with other companies. However, an important element of the design was the ability to support the work. Today, spaces are designed to fit the office around the work, and offices support the work. Tall buildings today are more than just offices; they are places to live and work.

The need for new work places has increased in recent years, with more people wanting to live near work. The skyscraper is often seen as the best way to achieve these goals.

1. The office as a place to live.
   - Bette Western
   - The office is a place to live, with views of the city and close to public transport.

2. The office as a place to work.
   - Bette Western
   - The office is a place to work, with a place to sit, and a place to work.

3. The office as a place to socialize.
   - Bette Western
   - The office is a place to socialize, with a kitchen and a place to relax.

4. The office as a place to collaborate.
   - Bette Western
   - The office is a place to collaborate, with a place to work and a place to socialize.

5. The office as a place to innovate.
   - Bette Western
   - The office is a place to innovate, with a place to think and a place to create.

6. The office as a place to learn.
   - Bette Western
   - The office is a place to learn, with a library and a place to study.

The future of the skyscraper is in flux, with new technologies and changing work practices. The skyscraper is no longer just a place to work, but a place to live, work, and socialize.

- CONTINUED ON — 11-07
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Another important factor, according to Amane, is the number of floors a building can occupy. This is seen in the concentration of retail and office space. The tallest building in the world, the Burj Khalifa, has almost 100 floors. The building's interior design and technology contribute to its sustainability. The building is equipped with solar panels, wind turbines, and water recycling systems. These systems reduce the building's carbon footprint and contribute to its sustainability.

The Shanghai Tower, on the other hand, is designed to be energy-efficient. The building is equipped with energy-saving lighting and HVAC systems. The building's design also helps to reduce heat gain and loss, which helps to reduce energy consumption. The building is also equipped with solar panels on the roof, which generate electricity for the building.

The Guangzhou International Finance Centre, located in Guangzhou, China, is another example of a sustainable high-rise building. The building is designed to be energy-efficient and to reduce its carbon footprint. The building is equipped with solar panels, wind turbines, and water recycling systems. The building's design also helps to reduce heat gain and loss, which helps to reduce energy consumption. The building is also equipped with energy-saving lighting and HVAC systems.

The Jingumae Hills, located in Tokyo, Japan, is another example of a sustainable high-rise building. The building is designed to be energy-efficient and to reduce its carbon footprint. The building is equipped with solar panels, wind turbines, and water recycling systems. The building's design also helps to reduce heat gain and loss, which helps to reduce energy consumption. The building is also equipped with energy-saving lighting and HVAC systems.

The Burj Khalifa, located in Dubai, UAE, is another example of a sustainable high-rise building. The building is designed to be energy-efficient and to reduce its carbon footprint. The building is equipped with solar panels, wind turbines, and water recycling systems. The building's design also helps to reduce heat gain and loss, which helps to reduce energy consumption. The building is also equipped with energy-saving lighting and HVAC systems.

The Shanghai Tower, located in Shanghai, China, is another example of a sustainable high-rise building. The building is designed to be energy-efficient and to reduce its carbon footprint. The building is equipped with solar panels, wind turbines, and water recycling systems. The building's design also helps to reduce heat gain and loss, which helps to reduce energy consumption. The building is also equipped with energy-saving lighting and HVAC systems.
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CONTINUED FROM — 1ST FLOOR
further 14,000 ft² waivers. This is equal to 320,000 sq ft of retail at Brookfield Place, and World Trade Center South.

The new office models containing non-traditional office spaces, with more technology and creative firms moving in, according to New, the publisher of Revenue, the leading firm for One World Trade Center. Other firms include creative agency, MRD Creative, and tech companies High Gears, Gmocha, and ABD, demonstrating the changing tenants profiles, which are now more associated with finance.

Tungsten Morningside Heights Station are some of the new clusters of skyscrapers being developed. This is due to the high demand for office space, which is always developing by Oxford Properties and Related Companies. This consists of three art-deco buildings and two residential towers. According to New, the new building project at 405 W 112 St, which is currently under construction, is the tallest building ever built in the financial and commercial industry. As the new World Trade Center, it's currently under development, with the financial and commercial industry that previously dominated Manhattan and surrounding areas.

As with the previous skyscrapers, the current building in progress is the 512,000 sq ft, which is currently under construction, with plans for 700 residential units and 250,000 sq ft of office space.

La Defense in Paris has also seen a surge in the number of office occupiers, with 50% of the new buildings in the region being occupied by office space. In the UK, London's skyline is expected to see a surge in office space as well, with 500,000 sq ft of new office space expected to be completed by 2025.

The increasing demand for office space in the US and Europe is due to a combination of factors, including a surge in technology companies, demand for office space by creative agencies, and the desire for a more collaborative workspace.

In conclusion, the rise in office space demand is not only due to economic growth but also due to the changing needs of the workforce. As companies continue to adapt to the digital age, the demand for office space will continue to rise, leading to the development of new skyscrapers and the renovation of existing ones.
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In 2009, there were 19% of the world’s tallest buildings in China. Today, 79% of them are. Of which are in the USA
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Hong Kong remains the world’s leading city for skyscrapers, but New York is closing fast. While Asia may be building faster, economic recovery in the US is buoying demand for towers from investors and tenants in the big North American cities.

Knight Frank’s latest skyscraper index has been extended to take into account additional measures of city-specific significance, such as the presence of high-rise towers and their architectural impact. The index uses a combination of factors, including skyscraper office space and height, as well as qualitative assessments of national and local business, the number of high-rise towers, and the skyscrapers in the city.

The previous index had Hong Kong, the number one city with a score of 9,1, followed by New York with a score of 8.5. In the new index, Hong Kong continues to lead, followed by New York, with scores of 9 and 8.5, respectively. The new index includes additional cities, such as London, Paris, and Tokyo, among others, providing a more comprehensive view of the skyscraper landscape.

The index also considers the impact of skyscrapers on the city’s economy, including the creation of jobs, the attraction of businesses, and the contribution to the overall economic growth. It highlights the importance of skyscrapers in shaping the identity of a city and its skyline, as well as the role they play in the urban development and growth.

In conclusion, skyscrapers continue to be a driving force in the global economy, contributing to the growth of cities and the development of new business opportunities. The new index provides a valuable tool for understanding the evolution of the skyscraper landscape and the impact of these structures on the cities they inhabit.
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[Diagram and text about tall buildings and their implications]
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5 FUTURE TRENDS

When a city grows, it can do so either laterally by spreading out, or vertically by building skyscrapers thus converting air into land. Below we identify five trends that will encourage the Global Cities to go upwards, making skyscrapers an essential component of urban growth.

01 NEW TECHNOLOGY
Architects and engineers are now using higher, ever increasing technologies to create the buildings that can both hold people and be more efficient. With new dream cities going up around the world, more efficient use of energy is now being considered. This includes using less energy to create cleaner, more sustainable buildings. As a result, the use of renewable energy technology is now a must for modern architecture.

02 MIGRATION
Migration, globalization, and growing economic opportunities are bringing about rapid urban growth across the globe. The UK is expected to see the number of migrants in London increase by 50% in the next decade. The EU is expected to see an increase of 25% in the next 20 years, with 15 million people expected to return from their studies and jobs. By 2030, the emerging middle class cities are expected to see a rapid increase in the number of businesses and jobs, leading to an increase in the number of people living and working in these cities.

03 BUSINESS CULTURE
The rise of the internet and electronic banking, coupled with businesses operating globally, has made it easier for businesses to operate across borders. In many cases, this has led to a decrease in the need for physical offices. This has led to a shift towards more flexible, smaller office spaces. In addition, businesses are now able to work from anywhere, even from home, which has further increased the demand for flexible office spaces.

04 LIVING SPACES
As more people move into urban areas, the demand for living spaces is increasing. This is especially true for those who are looking to move from rural areas to the city. In many cases, the cost of living in rural areas is higher than in urban areas, which makes it more affordable to live in the city. In addition, urban areas offer more opportunities for social interaction and access to amenities.

05 COMMUNITY
While many urban areas offer the same services as rural areas, the city is a place where people can come together and interact. In addition, urban areas offer more opportunities for social interaction and access to amenities. While many urban areas offer the same services as rural areas, the city is a place where people can come together and interact. In addition, urban areas offer more opportunities for social interaction and access to amenities.
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ABOUT THE GROUP

Knight Frank and Newmark Grabb Knight Frank, together, is a thoroughly integrated market-leading global real estate advisor.

The combined group have more than 8,500 property professionals, with more than 25,000 offices worldwide, advising global commercial and residential customers. Three unique titles: Knight Frank, Newmark, and Grubb & Ellis, each with its own distinct heritage and expertise, are now under the unified banner of Knight Frank, combining the best of three worlds and offering a truly global service.

Our global platform enables us to offer clients dedicated services from a single point in London and New York City. Together, we are able to provide the most comprehensive, tailored service for our clients globally.

Our global network enables us to offer clients dedicated services from a single point in London and New York City. Together, we are able to provide the most comprehensive, tailored service for our clients globally.

We have a highly developed and reliable global network that connects our clients to the full range of services we offer, including advisory, transactional, and management services. Our clients benefit from the expertise of our global team, which is dedicated to providing the highest level of service possible.

The combination of our global network, research capabilities, and extensive relationships across all sectors of the market enables us to provide our clients with comprehensive solutions that meet their needs.

Our team includes some of the most experienced and knowledgeable professionals in the industry, and we are committed to providing the best possible service to our clients.

The combination of our global network, research capabilities, and extensive relationships across all sectors of the market enables us to provide our clients with comprehensive solutions that meet their needs.
Tall Buildings | The Implications of Increasing Height

Appendix 3 | Let There Be Light

Let There Be Light

Introduction
This study considers daylight conditions on a generic office floor plate located in different cities around the world. It compares various facade configurations in these cities and the impact they have on internal daylight. The study is based on similar studies undertaken by ARUP for the Architectural Works Bogotá (Australasia) over the past three years.

The daylight quality of perimeter office space should take into account the daylight intensity, glare and external views. All of these factors relate directly to occupant well-being and can affect work productivity. Studies suggest that, if combined with higher levels of indoor environmental quality and individual comfort control, daylight and plans strategies can increase occupant's likelihood to improve by 1.9% for one year period.

The present study focuses its analysis on daylight penetration into the floor plate, as an important part of a larger study that tries to analyze the other factors. It is crucial, however, to emphasize the importance of considering design features such as glare minimization, solar and view access in conjunction with daylight intensity when finding the right configuration of floor plate and facades configurations to achieve ideal conditions for occupants well-being within commercial office spaces.

The study compares the Useful Daylight Illuminance (UDI), explained later in the document, for a standard office floor plate with different facade configurations and efficient light transmission values (VLT) in various cities around the world. For each city the outcomes of the study is represented on a separate page. In the way, when designing a building in a city that has been analyzed, this page can be extracted and used during the early design stages. The preliminary design recommendations that are given relate to floor plate depth, preferred facade configuration and recommended VLT range.

Method
The daylight penetration analysis involved the following procedure:
- Analysis of climatic data and sky type or each specific location.
- Modelling of a typical floor plate and each facade configuration that is tested.
- Computer simulation with Radiance software for each facade configuration and different VLT properties.
- Analysis of the results.

Useful Daylight Illuminance

The Useful Daylight Illuminance (UDI) is defined in study by Raish and Mardaljev (2008). It is designed to aid the interpretation of climatic-based analysis of daylight illumination and as an alternative to the Daylight Factor (DF) approach.

The UDI informs not only the minimum useful daylight levels but also the likelihood of exceeding daylight levels that may result in visible discomfort and unwanted solar gains. The UDI is capable of assessing the provision of daylight, as well as solar penetration and daylight levels below the minimum targeted requirements. Useful daylight illumination, according to Raish and Mardaljev's studies, is defined as the illuminance that falls within the range 100-2000 lux. The range is based on a comprehensive review of the latest data from studies of occupants' behaviour under daylight conditions. ARUP's daylight study has adopted a UDI range of 250-2000 lux, as 250 lux is considered the minimum useful amount of daylight desired in an office space.

The colours on the images represent a daylight intensity of:
- 250 to 625 lux, defined as useful daylight (green),
- Less than 250 lux defined as dark areas or zones (black), and
- More than 2000 lux, defined as excessive daylight with potential to cause visual and thermal discomfort (red).

Based on the approach described above it was possible to analyze the amount of useful daylight within the space and daylight penetration depending on the sky conditions and the facade configuration.

Superimposing the gridlines and the skyband of UDI ranges reveals excessive brightness, which should be avoided by minimizing the risk of glare. In general, a good daylight is the depth of the green zone. Areas of excessive brightness, in the red zones, may be dealt with by reducing the light transmission of the glass or by using blinds. This will have the effect of lowering the green section closer to the facade and potentially increasing its size.

The analysis can be used to inform initial selection of VLT, shading configurations, building forms and internal planning and layout.

Purpose
The document can be used during the early design stages of projects. It will give insight to the typical daylight conditions in various cities around the world. It also gives preliminary design recommendations on the use of light shelves, floor plate depth and the VLT of the glazing. The study has focused on the design of office floors, but can be applied to various other building types.

Please note that the recommendations given are preliminary and need verification during later design stages.


ARUP

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**Let There Be Light**

**Skies**

The sun is the source of light and all daylight is light coming from the sun. The sky illuminates, which can also be called the sky brightness, is the light intensity of the sky. Light coming from the sky is called diffuse daylight. Technically, this is light from the sun being reflected by the sky. Its intensity is highly dependent on the properties of the atmosphere, the cloud distribution, the type of clouds and the location of the sun. Typically, diffuse daylight is considered to have a positive impact on the office environment as it lights the interior without creating too much contrast or light intensity, generally creating a pleasant environment. However, if the sky is really bright, sometimes it can create glare as a result of diffuse daylight. In addition to the diffuse daylight, there is direct sunlight that comes directly from the sun and reaches its receiver without obstructions. Direct sunlight is very intense and often causes glare or thermal discomfort. Typically, direct sunlight does not have a positive effect on office interiors because of these issues. Illuminance should not be confused with luminance, which describes the amount of light coming from a point in a given direction or a given area. Generally, luminance can be thought of as brightness.

The assessment for each city is based on the information in the weather files available at the EnergyPlus website for that city (http://www.energyplus.net/buildingsizesamples). This information is collected from weather stations throughout the world and formatted by the United States Department of Energy for use in climate analysis. These files contain hourly information about the sky conditions and the illuminance levels at a certain location. This includes information about the horizontal and vertical sky brightness as well as the cloud distribution for every hour of a typical year.

The information in these files was used to generate an annual average sky model within a script developed by ARUP. The sky files were generated based on an occupancy schedule from 6 am to 6 pm.

In the weather files, skies are classified as one of three types based on the amount of cloud cover: clear, partly cloudy, or overcast. In this case, the luminance profile for each sky type is given. The relative luminance distribution has a 1 to 3 horizontal axis ratio and only varies with the attitude of the sky at the center of the sky, which we are concerned.

**Overcast Sky** - The Standard Overcast Sky (CIE, 1998) defines the luminance distribution for a sky and uniformly overcast sky with stratus type clouds. In this case, the luminance profile is the same as that of the stratus sky. The relative luminance distribution has a 1 to 3 horizontal axis ratio and only varies with the attitude of the sky at the center of the sky which we are concerned.

**Clear Sky** - The Standard Clear Sky (CIE, 1973) represents the luminance distribution for a perfectly clear (cloudless) sky. This model is based on the theoretical diffuse characteristics of the earth's atmosphere.

**Intermediate Sky** - This describes an intermediate sky condition between overcast and clear sky types where the sun is partially obscured by clouds.

An annual average sky model was developed for each location taking into account sky type distribution. Both direct and diffuse components are accounted for based on hourly adaption data for each city. This approach results in a final sky model for each location that reflects daylight illuminance levels as an average condition through the year. This ensures that the design of the canopy and floor plate is capable of responding to the most common sky conditions during the year.

The above images show the sky models that were created. Two sky models were made: one that includes the direct sun component, (cumulative direct + cumulative diffuse sky) and one with the diffuse component only (cumulative diffuse sky). The direct + diffuse sky is used to assess the different facade configurations. The cumulative diffuse sky is used to determine the recommended floor plate depth and U-value of the glass.

**Sky Distribution Graph for Shanghai**

**Cumulative diffuse + direct sky**

**Cumulative diffuse sky**

**Sky files generated with different types of weather files for Beijing**
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Appendix E | Let There Be Light

Let There Be Light

Sky Brightness

Overcast Cloudcover Clear

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Recessed ceiling

With recessed ceilings, part of the sky will be visible further inwards and thus the amount of daylight that penetrates the floor plate will likely increase. Generally, daylight conditions will improve the deeper into the floor plate. Recessed ceilings, however, tend to have a deeper and shallower ceiling, which may negatively affect the daylight penetration. Therefore, additional light sources should be considered.

Light Shelves

Light shelves are an effective way of increasing daylight penetration along the perimeter zone while at the same time improving natural ventilation further into the floor plate. Sunlight is reflected off the shelf into the ceiling and diffusely dispersed into the office. Light shelves can greatly improve daylight conditions by lightening up the ceiling and in this way the space will be perceived as brighter.

As the Let There Be Light study only takes into account the daylight intensity in the horizontal plane, the full benefits of light shelves are not reflected in the results presented here. However, the benefits of external shading devices are reflected in the study.

Daylight Redirectors

Daylight redirectors are an even more efficient way of reflecting sunlight onto the ceiling and walls, further into the floor plate. Like light shelves, daylight redirectors can greatly improve daylight conditions by lightening up the ceiling and walls.

As the 'Let There Be Light' study only considers the daylight intensity in the horizontal plane, the full benefit of using daylight redirectors is not included.
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Let There Be Light

Facade configurations
Six different facade configurations are modelled with the cumulative skies created as described on page 2 and shown on page 3. The purpose of the analysis is to demonstrate that different facade options and floor plate configurations are capable of optimising daylight for different locations. The six facade types were modelled around a square floor plate of 50 by 50 meters with a 10 by 10 meter core in the centre.

The following facade options were modeled:

- **Type 1**
  - 2.7 m ceiling height;
  - Glass (0.4 to 2.7 m) with a VLT of 0.65;
  - A 500 mm wide light shelf at the outside at 2.2 m height;

- **Type 2**
  - 2.7 m ceiling height;
  - Glass (0.4 to 2.7 m) with a VLT of 0.65;
  - A 500 mm wide light shelf at the outside at 2.2 m height;

- **Type 3**
  - 2.7 m ceiling height;
  - Glass (0.4 to 2.2 m) with a VLT of 0.44;
  - A 500 mm wide light shelf at the outside at 2.2 m height;
  - Light refractions (2.2 to 2.7 m) in front of glass with a VLT of 0.7C;

- **Type 4**
  - 3.2 m ceiling height;
  - Glass (0.4 to 3.2 m) with a VLT of 0.65;

- **Type 5**
  - 3.2 m ceiling height, three meters deep into the floor plate;
  - Glass (0.4 to 3.2 m) with a VLT of 0.65;
  - A 500 mm wide light shelf at the outside at 2.2 m height;

- **Type 6**
  - 2.7 m ceiling height;
  - Glass (0.4 to 2.2 m) with a VLT of 0.39;
  - A 500 mm wide light shelf at the outside at 2.2 m height;
  - Light refractions (2.2 to 3.2 m) in front of glass with a VLT of 0.7C;

ARUP

<table>
<thead>
<tr>
<th>Type</th>
<th>Ceiling Height</th>
<th>Light Shelves</th>
<th>Daylight Refractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 2</td>
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<tr>
<td>Type 6</td>
<td>3.2</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

The results are displayed in a graph showing the floor plate of model with the area that is considered to be too bright, the area with useful daylight and the area that is considered to be too dark (see the figure below). The northern facade is along the top. A grid of 5 by 5 meters is overlaid on the floor plate to allow the simulations to be interrogated. In relation to facade option efficiency in delivering useful daylight based on local climate and orientation.

May 2010