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The Effect of Geometric Shape and Building Orientation on Minimising Solar Insolation on High-Rise Buildings in Hot Humid Climate

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Abstract: High-rise buildings are experiencing overheating condition in hot humid climate. For a high-rise built form, vertical surfaces are the most critical to the impact of solar radiation. This study examines the effect of geometric shapes on the total solar insolation received by high-rise buildings. Two generic building shapes (square and circular) have been studied with variations in width-to-length ratio (W/L ratio) and building orientation using the computer simulation program ECOTECT V5.2. The results revealed that the circular shape with W/L ratio 1:1 is the most optimum shape in minimising total solar insolation. The square shape with W/L ratio 1:1 in a north-south orientation receives the lowest annual total solar insolation compared to other square shapes. This optimum shape (CC 1:1) receives the highest amount of solar insolation on the east-orientated wall, followed by the south-, west- and north-orientated walls respectively. This study guides designers on choosing optimum geometric shape and appropriate orientation for high-rise buildings.

Keywords: Solar insolation, High-rise, Geometric shape

INTRODUCTION

Malaysia (located between 1ºN to 7ºN and 100ºE to 120ºE) is in the tropical region. It is undeniable that she faces a lot of problems in terms of solar radiation. Therefore it is important to prevent solar radiation from reaching onto building surfaces. The high-rise building envelope experiences much greater impacts of external temperatures and global solar radiation than low-rise or medium-rise buildings. Ismail (1996) and Krishan (1995) suggested that low-rise buildings can be easily shaded by the roof and vegetation.

According to Yeang (1996), architecture design of high-rise has remained unchanged since its invention. Its technology and engineering have become far better and much more sophisticated, but most of the high-rise buildings constructed today remain fundamentally similar in term of their built configuration. Conventional high-rise is like a concealed box (geometry form) that segregates users from the external natural environment. Users of the high-rise buildings live in an artificially controlled

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environment and these artificial environments are expected to fulfil the basic needs of users such as lighting, ventilation and thermal comfort. In fulfilling these requirements, high energy on mechanical system is used; thereby increasing energy consumption of office buildings.

Energy studies of commercial buildings in Southeast Asia were initiated under the ASEAN-USAID Building Energy Conservation project (Loewen and Busch, 1992). The results showed that office buildings in this region have an energy consumption of 233kWh/m^2/yr on average. Comparison among the countries revealed that Malaysia has the highest energy consumption (269kWh/m^2/yr) among the office buildings surveyed. According to MS1525:2001 (Department of Standard Malaysia, 2001) code of practice for non-residential buildings on energy efficiency and use of renewable energy, the non residential building should comply with an annual energy consumption of less than 135kWh/m^2/yr. But the previous energy audit by ASEAN-USAID 1992 shows that the average energy consumption for office building is almost 100% more than the new requirements. It is a challenge for the government agencies, architects and engineers to reduce energy consumption particularly in office buildings.

In order to reduce this energy load, understanding the overall architectural design features of existing high-rise office buildings in hot tropics is important. Efforts to reduce cooling load can be done by blocking and filtering solar radiation from entering the building. Solar radiation is the most major contributor to heat gain in buildings. The prediction of average solar insolation for any day, month, season or year is needed in estimating the cooling load arising from radiation received on walls or transmission through windows. Solar insolation refers to the total amount of cumulative incident solar radiation on a point or surface over a specified period. Understanding the characteristic of solar insolation strikes on different geometric shapes and orientations are crucial.

OBJECTIVE OF THE STUDY

The main objective of this study is to investigate the influence of solar insolation on vertical surfaces of high-rise building and the relationship between its geometric shapes to total solar insolation. Thus, appropriate solar shading design strategies can be explored later in order to minimise further the impact of solar radiation on external facade for high-rise buildings.

METHODOLOGY

The study is carried out using computer simulation. The sequence of the simulation approach, from the selection of program, construction of models and procedure of simulation are discussed as below.

Energy Simulation Program

ECOTECT (ECOTECT Version 5.2b, 2002) is a software package with a unique approach to conceptualise building design. It couples an intuitive 3-D design interface with a comprehensive set of performance analysis functions and interactive information display. For this study, ECOTECT V5.2 is used to simulate data for cumulative incident solar radiation on vertical surfaces on a daily and monthly basis. The simulation can display the graphical distribution patterns and availability of solar insolation over the surfaces of an entire building. All simulations are calculated based on the available hourly direct and diffuse horizontal solar irradiance data from ECOTECT Weather Tool for Kuala Lumpur, Malaysia (3.7°N, 101.7°E).

Preparation of Base Models

Study of high-rise building shape in Kuala Lumpur city

Two studies were conducted on existing high-rise buildings in the city centre of Kuala Lumpur. The first study detailed out the geometric form with various width-to-length (W/L) ratios and the approximate floor area for the high-rise building. The second study established a checklist of general configuration for high-rise buildings in Kuala Lumpur.

The first study is conducted based on satellite images from the website GoogleEarth.com (http://earth.google.com/downloads.html) for the city of Kuala Lumpur and the images were then transferred to the AutoCAD programme. These satellite images are measured in AutoCAD drawings and it provided approximate dimensions of any parcel, thus 155 high-rise buildings with varied geometric shapes are determined based on the aerial view of the city (Figure 1). Based on the shapes, the W/L ratio and approximate floor area are defined (refer to Table 1). Parallelepiped shapes that are square and rectangular shapes are the preferred geometric shape which comprises 83.2%, followed by circular and other shapes which only comprise 7.7 and 9.0%, respectively of the high-rise buildings in Kuala Lumpur. Among all parallelepiped shapes, rectangular shapes with W/L ratio below 1:2 are the most desired building shape, followed by the square shape (W/L ratio 1:1). The average gross floor area (GFA) for high-rise building is 1243 m^2.

A checklist of high-rise buildings in Kuala Lumpur had been downloaded from website www.emporis.com. This checklist provides basic information on 150 existing high-rise buildings with minimum height of 20 storeys. The information given included the overall building's height, number of floors and year of completion. The mode of frequency for number of floors is 30 storeys while the average floor to floor height is 4.0 m.

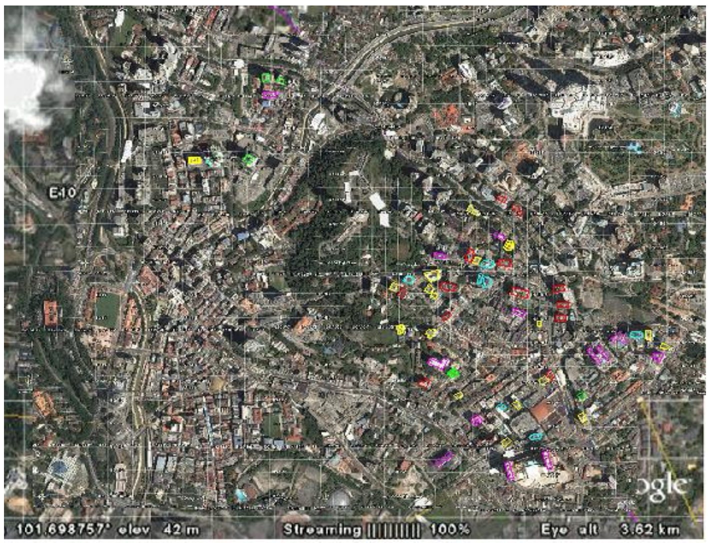

Figure 1. Generic Plan from Study for High-Rise Buildings in the City Centre of Kuala Lumpur
Source: Satellite Images from Google Earth, Accessed 24 April 2006

Table 1. Generic Geometric Shape of High-Rise Buildings in the City Centre of Kuala Lumpur

Generic shape	W/L ratio	No. of building	%
Square	1 : 1	28	18.1
Rectangular	1 : 2	52	33.5
	1 : 3	27	17.4
	> 1 : 3	22	14.2
Circular	1 : 1	3	1.9
Ellipse	1 : 2	4	2.6
	1 : 3	4	2.6
	> 1 : 3	1	0.6
Others	-	14	9.1

Generic high-rise office building shape

A study conducted by Lam and Goodsall (1994) found out that the configuration of generic office building in Hong Kong is similar with high-rise office buildings in Kuala Lumpur, except that its average building height is 40 storeys and floor to floor height is 3.8 m. A base case reference building form was developed from previous discussion. In order to investigate the effect of geometric shapes, two basic geometric shapes that include square and circular shapes were established according to the descriptions in Table 2.

Table 2. Description of Base Case Reference for Generic Office Building

Location	**Kuala Lumpur (3.7°N, 101.7°E)**
Floor area	GFA: 1225 m^2 per floor (GFA is same for all base models.)
Height	120 m (prismatic) (Building height is same for all base models)
Volume	147,000 m^3 (non-monolithic building – volume are separated)
Floor to floor height	4 m
Floor efficiency	Average tenants efficiency: 81.6%

This study focuses only on the cumulative incident solar radiation fall on the external surfaces of building before it enters the internal space of the building. All forms were considered as stand-alone building without overshadow from any adjacent buildings. Solar insolation received by the entire exposed surface was estimated as the sum of the solar radiation on its facades acting like flat solar collectors (Stasinopoulos, 1998). All forms were considered as opaque and zero reflectivity. This means that the exposed surface will receive solar radiation strike on it without any reflection.

Procedure of Simulation

The simulation procedure is divided into two main stages. Stage one simulates the annual total solar insolation on two basic geometric shapes with variations in W/L ratio and building orientation. In stage two, optimum shapes (for both basic shapes) with minimum annual total solar insolation were selected in order to investigate the relationship of insolation level on different orientated wall.

Base model 1: Geometric shape

Two basic geometric shapes with variations in W/L ratio and building orientation are simulated as describe in Table 3. The selection of W/L ratio are based on studies from Olgyay (1963) and Yeang (1994) which suggested that building form with W/L ratio 1:1.7 and 1:3 are the optimum ratio for tropical climate. So the geometric proportion of both basic geometric shapes was stretched according to the above stated W/L ratio (Figure 2). These shapes are modified to W/L ratio 1:1.7 and 1:3 but remain in the same typical floor area (GFA) and overall volume (V). The modified geometric is named based on its basic shape, for example CC 1:3 means circular shape with W/L ratio 1:3 which gives an ellipse. Therefore, exposed surfaces of every modified geometric shape will determine its capacity to receive solar insolation. Exposed surface-to-volume ratio (S/V ratio) for every modified geometric shape depends on the W/L ratio. Geometric shapes with higher value of W/L ratio contained lower value of S/V.

The main outcome of this simulation is to determine the capacity of every simulated building shape with variation in W/L ratio and building orientation. Thus, the optimum geometric shapes in minimising solar insolation were further investigated later.

Base model 2: Optimum shape

Further simulations on the effect of vertical surfaces of the optimum shape for both basic shapes were conducted. The building shape with the lowest annual total solar insolation (simulation result from base model 1) was chosen so that effects of solar insolation on different orientation can be studied. The annual and daily average solar insolation on the different orientated walls of that optimum shape at four design-days (Table 3) was compared. Selection of the four design-days determines that the sun's position is during solstice and equinox rather than representing the hottest day or extreme days of global solar radiation.

Table 3. Description of Building Parameter Variable

Base model 1	
Basic geometric shape	Square (SQ) and circular (CC)
W/L ratio	1:1, 1:1.7, 1:3
Building orientation	N-S, E-W, NE-SW & NW-SE
Base model 2	
Geometric shape	Optimum shape for both basic geometric shapes
Insolation on surface	4 major vertical surfaces (E, W, S and N)
4 design-days	21 March, 21 June, 21 September and 21 December on typical reference year

Note: E (East), W (West), S (South) and N (North)

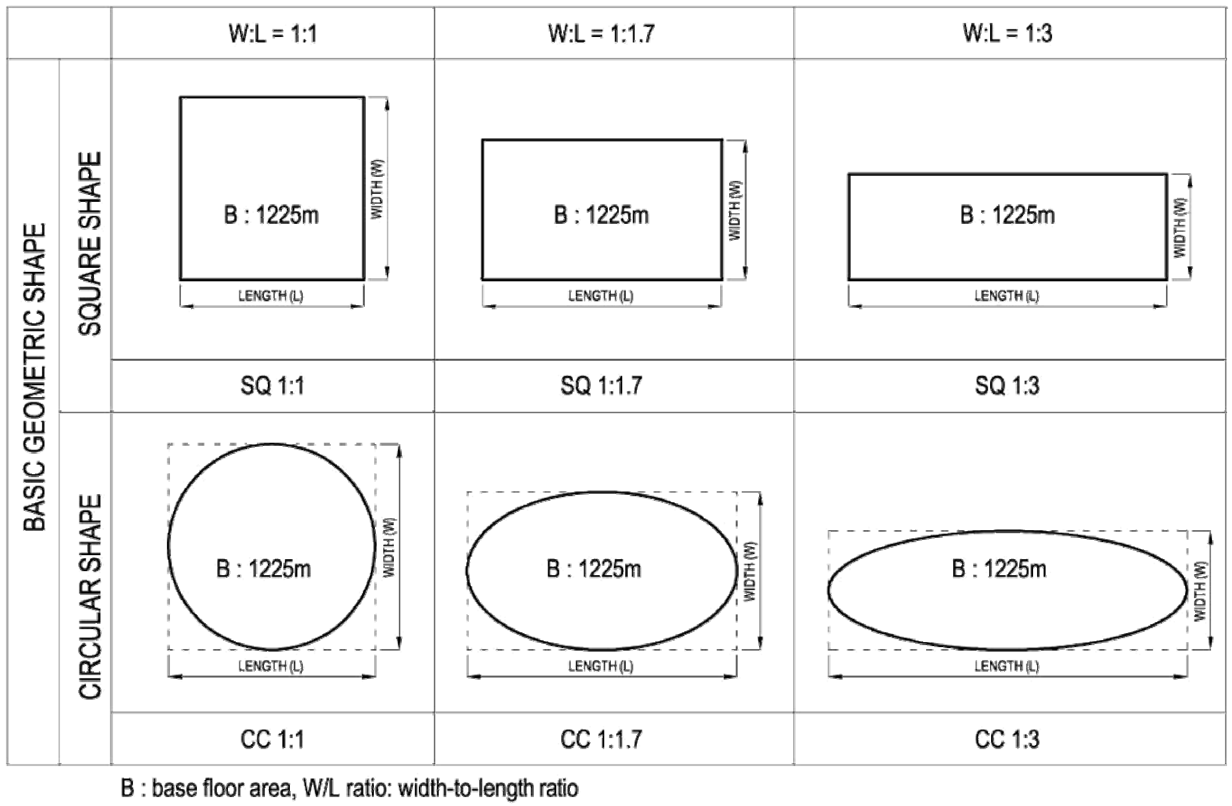

Figure 2. The Geometric Proportion of Two Basic Geometric Shapes

RESULT AND DISCUSSIONS

Geometric Shape

Different geometric shapes have different capacity to receive solar energy under the same conditions due to its geometric characteristics. For basic geometric shape, circular shape with W/L ratio 1:1 received lowest amount of solar insolation (9,296 mWh/year), followed by square shape (SQ 1:1) which received 10,503 mWh/year throughout the year as shown in Figure 3. Therefore, the circular shape is considered as the optimum shape in minimising the total solar insolation on high-rise buildings. In order to compare the effectiveness among building shapes, the total solar insolation received on circular shape is used as the base reference to other generic forms tested.

From all simulated building shapes, the rectangular shape with W/L ratio 1:3 and east-west (E-W) elongated orientation received the highest amount of solar insolation. It received 12,588 mWh/year which is 33% more than the optimum shape (circular shape CC 1:1). The results showed that circular shapes with W/L ratio 1:1.7 and 1:3 received 3–5 and 14–30% more total solar insolation respectively compared to the base case (circular CC 1:1). Square shape with W/L ratio 1:1, 1:1.7 and 1:3 received 11–13, 12–17 and 23–33% more total insolation respectively than the base case (Figure 3). Based on the shape, W/L ratio 1:3 of both square and circular shapes received more than 20–30% compared to optimum shape (CC 1:1). Slight increase (2–5%) of total solar insolation for all generic forms with W/L ratio 1:1 and 1:1.7 is shown compared to optimum shape.

The result indicated that main factors that determine the relationship between solar insolation level and building shape are W/L ratio and building orientation. Geometric shape with W/L ratio 1:1 contained the lowest value of S/V ratio; it received the lowest annual total solar insolation. Building orientation contributes greater impact to geometric shape with lower W/L ratio than higher W/L ratio, especially for east-west (E-W) elongated building shape.

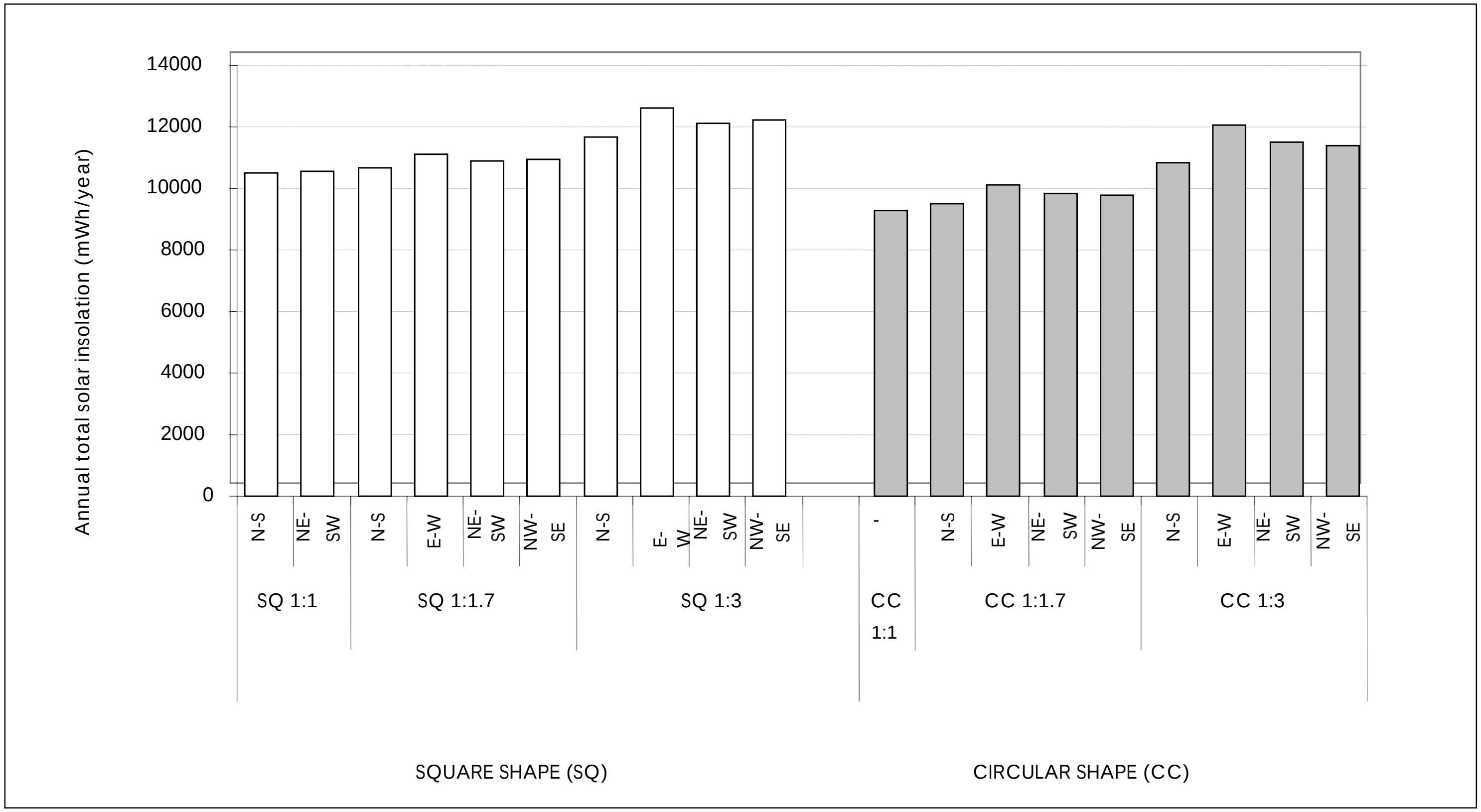

Figure 3. Comparison of the Capacity of Geometric Shapes to Receive Solar Insolation

Optimum Shape and Preferred Form

Further analysis focuses on the optimum shape for both basic geometric shapes. Based on the result from previous discussion circular shape with W/L ratio 1:1 (CC 1:1) and square shape with ratio W/L 1:1 (SQ 1:1) were selected.

Annual average solar insolation on main vertical surfaces

The results reveal that both optimum shapes (CC 1:1 and SQ 1:1) received the highest and lowest amount of solar insolation on wall facing east and north respectively (Table 4). In the square shape (SQ 1:1) model, the west wall received 3.1% higher than the average solar insolation for the south wall. While in the circular shape (CC 1:1) model, the south wall received slightly more (1.5%) solar insolation than the west wall, even though the west wall received the maximum intensity solar radiation than the south wall.

This may be due to longer solar exposure time on the south wall (average 7 hours) compared to the west wall (average 4 to 5 hours). Further frequent occurrence of evening showers may be another reason that might reduce the solar incident on the west façade. Othman et al. (1993) found that the frequency of occurrence of global solar radiation distribution pattern in Malaysia are as follow: 50% of partly cloudy day, 17% of afternoon rain, 16% of clear day, 14% of fully cloudy day and 3% of cloudy with occasional solar intensity above the solar constant (1400 W/m^2). This condition may lower the annual total solar insolation on the west wall.

Table 4. Annual Average Solar Insolation on Varied Wall Orientations on the Optimum Shapes for Both Basic Geometric Shapes

	Vertical surfaces (kWh/m^2)			
Circular (CC 1:1)	**East**	**West**	**South**	**North**
	1961	1595	1619	1565
Square (SQ 1:1)	**East**	**West**	**South**	**North**
	2211	1818	1763	1702

Daily average solar insolation on main vertical surfaces at four design-days

On the SQ 1:1 model, the north wall and south wall received the highest amount of daily average solar insolation on 21 June (3.59 kWh/m^2/day) and 21 Dec (5.52 kWh/m^2/day), respectively. While the east wall and west wall receive daily average solar insolation ranging from 2.72 to 5.26 kWh/m^2/day and 2.61 to 4.25 kWh/m^2/day, respectively on four design-days.

On the CC 1:1 model, the north and south wall also received the highest level of solar insolation on 21 June (3.17 kWh/m^2/day) and 21 Dec (5.0 kWh/m^2/day) respectively. While the east and west wall receive daily average insolation ranging from 2.31 to 3.98 kWh/m²/day and 2.35 to 4.76 kWh/m²/day, respectively on the four design-days. Most of the daily average solar insolation collected on CC 1:1 was lower than SQ 1:1(Tables 5 and 6). The results emphasize that the circular shape with varying wall orientations and curvatures can moderate the insolation level. It is parallel to the work by Ahmad and Gadi (2003) which states that the total solar insolation collected on curved roof is lower than flat roof for low-rise building in hot-arid climate.

Table 5. Daily Average Solar Insolation on Four Vertical Surfaces for Square Shape SQ1:1 on Four Design-Days

Design-days	Orientation (Wh/m²/day)			
	East	West	South	North
21 March	5260	4255	6984	2513
22 June	2722	2610	1743	3590
24 Sept	3306	3731	4733	2305
21 Dec	4441	2846	5524	1762

Table 6. Daily Average Solar Insolation on Four Vertical Surfaces for Circular Shape CC 1:1 on Four Design-Days

Design-days	Orientation (Wh/m²/day)			
	East	West	South	North
21 March	3585	4775	4910	3390
22 June	2311	2356	1523	3171
24 Sept	2687	3500	3829	2365
21 Dec	3979	2511	5000	1270

SUMMARY AND CONCLUSION

The aim of this study was to investigate the influence of solar radiation on vertical surfaces of high-rise building shapes and the effect of geometric shapes with variations of W/L ratios and building orientation towards minimising the total solar insolation. The main findings were summarized as follows:

a. For high-rise, the vertical wall is most critical, 86.6% of the annual total insolation is received from its vertical wall surfaces.

b. Circular shape with W/L ratio 1:1 is the optimum geometric shape (receiving the lowest amounts of annual total solar insolation) among all high-rise building shapes simulated in this study.

c. The highest level of daily average solar insolation is received on the east wall, followed by the south, west and north walls.

With appropriate attentions given to the geometric shapes and solar shading strategies, the impact of solar radiation on high-rise building envelopes can be reduced. Hence, it can be assumed that the energy consumption for cooling load in such high-rise building will be minimised.

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