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Energy-efficient Tall buildings design strategies: A holistic approach

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Abstract

The number of tall buildings is increasing as a result of the advances in construction technologies and the rising land prices. These buildings are characterised by their high energy consumption compared to other building types as they rely intensively on mechanical HVAC systems due to the extreme weather conditions associated with the increase in height. However, they present a great opportunity for energy savings. In recent years, it has been noticed the increasing interest in geometry and form of tall buildings, as a result of the evolution of parametric modelling and 3D visualisation tools, on the expense of the environmental aspect. This paper discusses factors affecting the energy consumption in the tall buildings. Through an extensive analysis of Literature, active and passive energy efficient strategies adopted in tall building at various building stages are identified. In addition, the role of architectural design parameters, such as building form, orientation and envelope on the tall building energy performance are highlighted. Finally, a set of guidelines and environmental design strategies to be considered in different phases in order to achieve energy-efficient tall buildings are proposed. These strategies have been categorised into four stages namely early design, conceptualisation, and documentation and operational. A 3D modelling approach was used to visualise and illustrate the proposed strategies in different stages.

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Keywords: Energy efficiency, design strategies, tall buildings, visualisation

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1. Introduction

The number of high-rise and tall buildings has increased in recent years. Several factors have resulted in the emergence of this building type. It became a desired and typical building type whenever the land characteristics are suitable and the construction laws and legislations allow building. These building types are distinguished with their high energy consumption compared to other building typologies as they rely mainly on mechanical heating, cooling, transporting people and equipment to the higher levels. A study that compared several case studies on tall buildings and found that although the success of these buildings in implementing energy efficiency strategies yet there is a great potential in achieving higher energy efficiency in tall buildings through an integrated approach [1]. For high-rise buildings, a study developed design-based strategies towards low energy. Three areas of improvement were addressed building shape, orientation and glazing opening [2]. This paper presents different type of tall buildings and the relationship between building height and energy consumption. Factors affecting energy consumption in tall buildings are introduced. Finally, it suggests an approach to reduce the operational energy use and generate. This strategy combines various techniques design, conceptualization, architectural features and systems related.

Nomenclature

BMS	Building management System
PV	Photovoltaic
HHW	Heating Hot Water
HVAC	Heating, Ventilation and Air Conditioning
CTBUH	Council of Tall Building and Urban Habitat

1.1. Building Heights classification

Tall buildings can be classified into three types: Tall, Supertall and Megatall Buildings.

Tall buildings are those with average height of 50 to 300 meters. This buildings type constitutes 90% of the total tall buildings worldwide e.g. CCTV headquarters, China and Comcast centre, Philadelphia. Supertall buildings have an average height of 300 to 600 meters. They represent 10% of the total tall buildings around the world. Whereas Megatall buildings are those with height more than 600 meters and they represent a small percentage 0.05% of the total high-rise buildings. Figure 1 compares five high-rise buildings within the three building types.

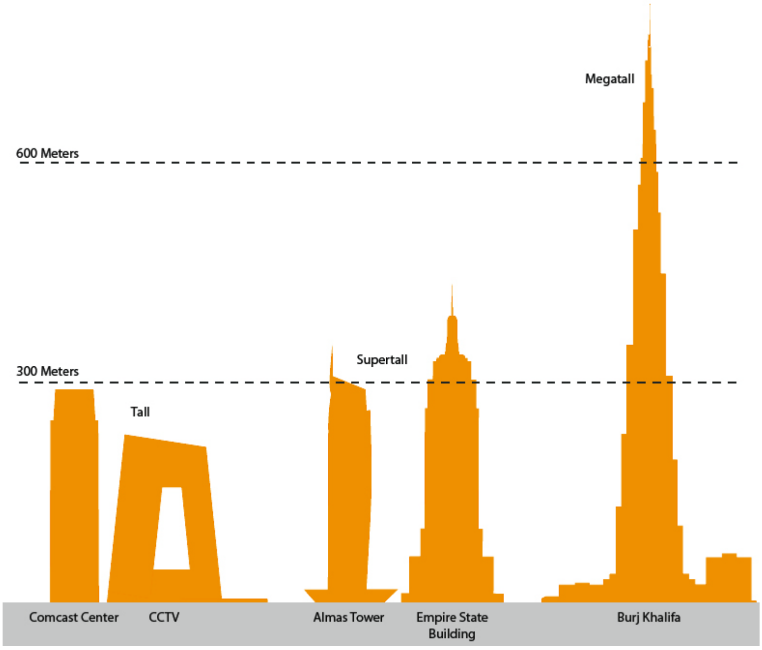


Fig. 1 Classification of buildings based on height

1.2. Energy consumption in tall buildings

There are several factors that affect the energy consumption in tall buildings. The degree of importance of these factors varies between buildings. Generally, they can be classified into architectural, human, technology and natural factors.

1.2.1 Architectural factors

They are the factors related to the building design and its components. They can have a positive or a negative impact on the energy consumption of the building. The architectural factors include; building functions, spatial relations, building shape, height and envelope.

Building function determines the number of user and occupants and thus has a direct impact on its energy consumption. For instance, commercial and retail use has a high density of users which will result in more energy consumption for vertical transport systems, heating, cooling in addition to the thermal loads from the equipment, machines and lighting. On the other hand, in residential use such as hotels, the energy consumption is much lower compared to the retail one.

- *Spatial relations*

Placing functions with high occupancy rates at lower levels decreases the energy consumption required in vertical transport systems. In addition, Having the spaces that need more natural light oriented towards the north direction in the northern hemisphere leads to a decrease in the energy consumption required to shift the thermal load from the artificial lighting [3]. A good spatial design for the building spaces that has a strong adjacency relationship will result in reducing the area needed for vertical and horizontal transport elements which will lead to a decrease in the energy required for lighting, ventilating and cooling of these areas.

- *Building Shape*

Different building geometry has affects their solar exposure as some shapes receives more solar radiation than others resulting in higher cooling loads inside the building [4]. In addition, some shapes improve the natural daylight and ventilation flow inside the building that will decrease the thermal and ventilation load inside the building [5].

- *Building Envelope*

Building envelope controls the building internal environment against the external climatic conditions such as the amount of solar radiation, temperature, humidity and wind getting into the building. The envelope materials with their different thermal properties such as solar insulation, thermal mass and heat transfer has a great impact on the energy consumption inside the building [6].

- *Building height*

Tall buildings are usually higher and isolated from the urban pattern of the surrounding built environment. This results in increasing the energy use for mechanical heating and cooling water, and transporting materials and users pumps for higher levels [7]. In Hong Kong a study on 25 buildings has shown the increase in the energy consumption associated with the increase height [8]. Figure 2 shows a comparison between building at different heights and their relative energy consumption per unit floor area.

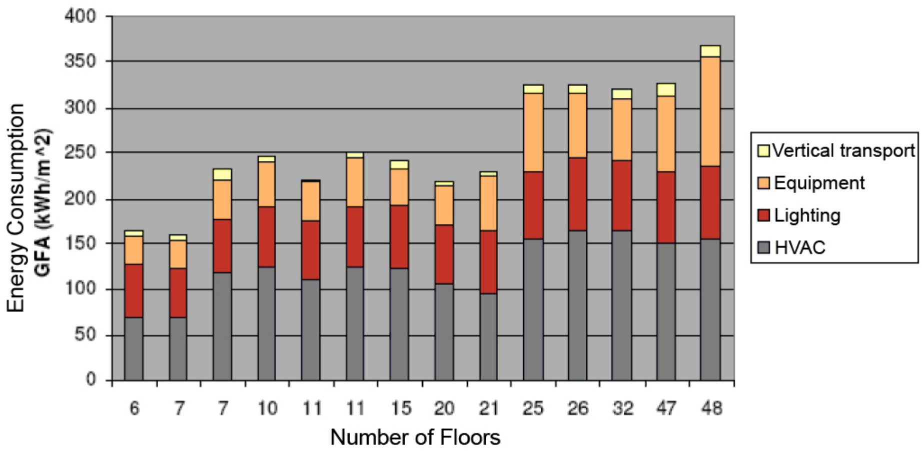


Fig. 2 Energy consumption per unit floor area associated with building height

1.2.2 Human factors

They are the factors related to the human being building owner, users. It is comprised of four categories as follows: Laws and legislations, occupants' behaviour, cultural and economic.

1.2.3 Technology factors

The advances in technology in recent years that promotes luxury and prosperity in different facets of life have led to a huge increase in the energy consumption. However, some technologies assisted in achieving buildings energy efficiency such as building management systems (BMS).

1.2.4 Natural factors

It occurs without any involvement from the human side. The nature of the site places some constraints on the building designer to neglect the environmental design principles. For example a coastal site with sea views dictates maximising the number of internal spaces overlooking that view which might have a negative impact on the energy consumption. Similarly, in the central business districts CBDs where the rising land prices, owners try to densify as many activities as possible in one building such as having a mixed commercial, residential and administration purposes on the same site which reduce the possibility of harnessing natural ventilation and lighting for many spaces and increases the energy consumption.

Climate plays an important role in tall building energy consumption. Tall buildings are exposed to various micro-climatic conditions that changes gradually with the increase of the building height above the sea [9]. In tall buildings, levels that are higher than the urban canopy receive more direct solar radiation than those below as the levels within the urban canopy can receive some shading throughout the day from the adjacent buildings. Higher levels are also exposed to additional indirect solar radiation from the reflections on the rooftop of the adjacent buildings that are lower in height [10]. However, in the areas which have larger number of tall buildings the shading increases and the solar radiation effect decreases. In addition, there is a decrease in the air temperature so-called Temperature Lapse Rate, increase in Wind speed, air pressure and air infiltration rate on the facades facing the wind and decrease in humidity [3].Tall buildings have a higher rate of heat loss in clear sky and it decreases when it is cloudy. Also, Levels above the urban canopy have a higher rate of heat loss during nights [11].

2. Method

An extensive review of the scientific articles has been conducted such as those from the Council on Tall Buildings and urban Habitat. Case studies on tall buildings were compared to stand on the environmental design strategies applied in each case. By analyzing those articles case studies factors and methods affect the energy consumption in tall buildings are highlighted. Energy efficiency strategies employed are introduced. The factors, methods and strategies have been categorized into different phases. Finally, an integrated approach to achieve energy efficiency in tall building through the suggested phases is proposed.

3. Results and discussion

3.1. Design strategies for energy-efficient tall buildings

The environmental strategies are classified into four phases; early design, conecptualisation, documentation and operational phase. Due to the space limitation this paper only two phases will be covered in details in this paper, namely early design and conceptualisation. Figure 3 presents the framework for energy efficiency strategy in tall buildings

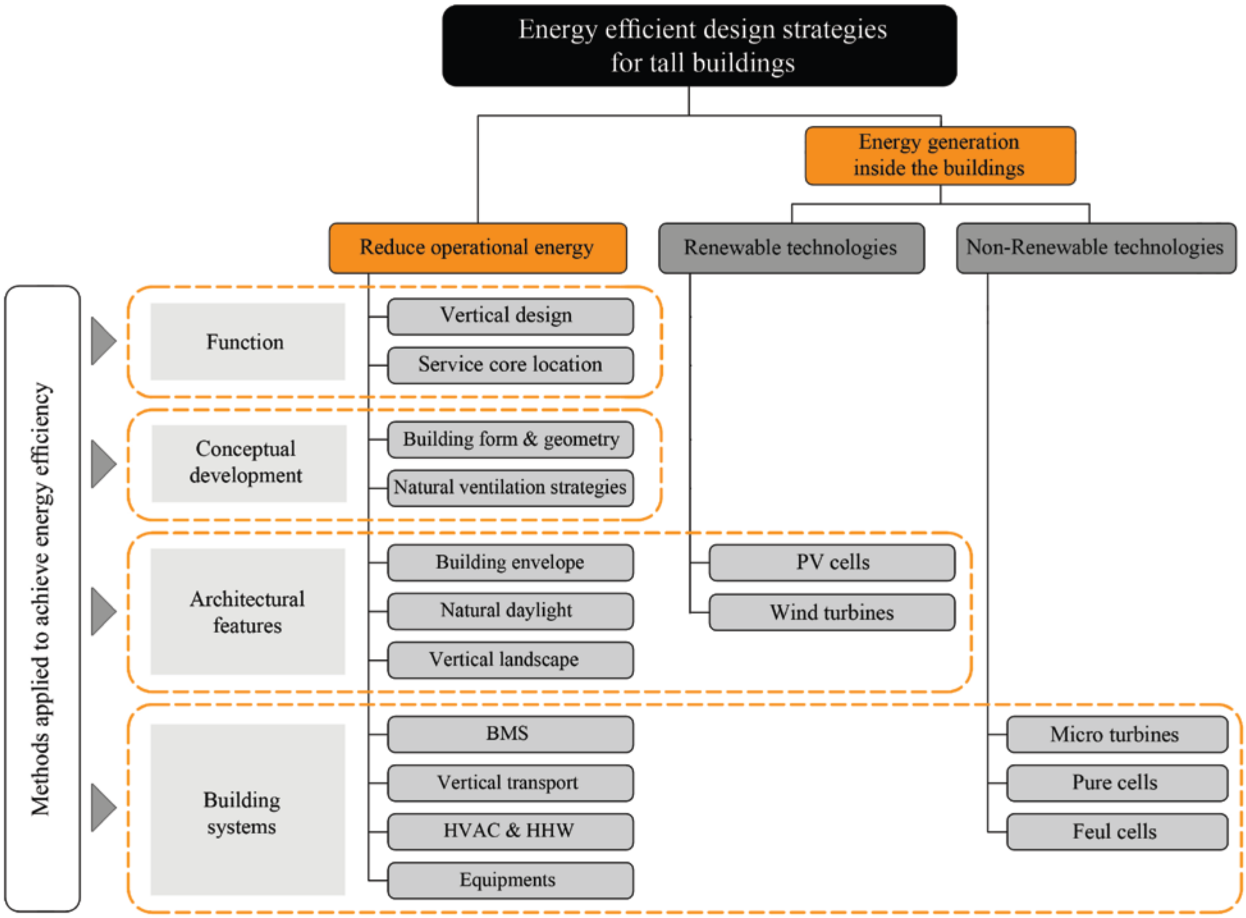


Fig. 3 Energy efficiency framework in tall buildings

3.1.1 Early design phase and zoning (Design programme)

- *Vertical design*

In hot climate areas, functions that require high energy consumption for cooling shall be placed on higher level to get advantage of low air temperature and reduce the cooling load. This in case those levels are located above the urban canopy. In cold climates functions that require high energy consumption for heating shall be placed on lower levels to reduce the heating load as shown in Figure 4.

In the districts that include high number of tall buildings, whereby the entire building lies under the urban canopy, the rate of heat loss decreases with the increase in height. Thus the function with high occupancy rate should be placed on the lower level of the building as shown in Figure 4.

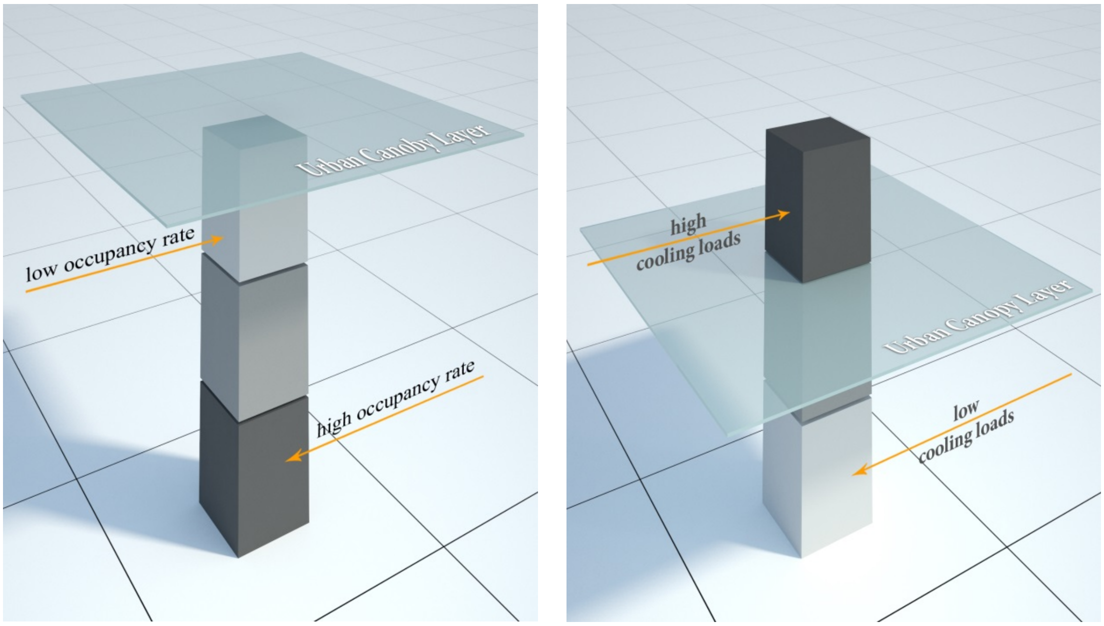


Fig. 4 Vertical distribution of buildings functions relative to the urban canopy

- *Building services core location*

The building services' core on the building outer envelope assists in providing natural ventilation and daylight for the lifts lobby, staircases and toilets. In addition it helps in creating void in the building centre that can be used as a central atrium that will increase the natural ventilation and daylight for the internal building spaces (Figure 5). The location of the building core should be placed on the façade with the high solar radiations exposure in hot climate and with cold wind in cold climates to decrease the cooling and heating loads. In temperate climates, where the facades are not exposed to very cold or hot climate, the services' core can split and placed on the corners of the building. This will increase the surface area of the buildings exposed to natural lighting and decrease the cooling loads resulting from the use of artificial lighting (Figure 5).

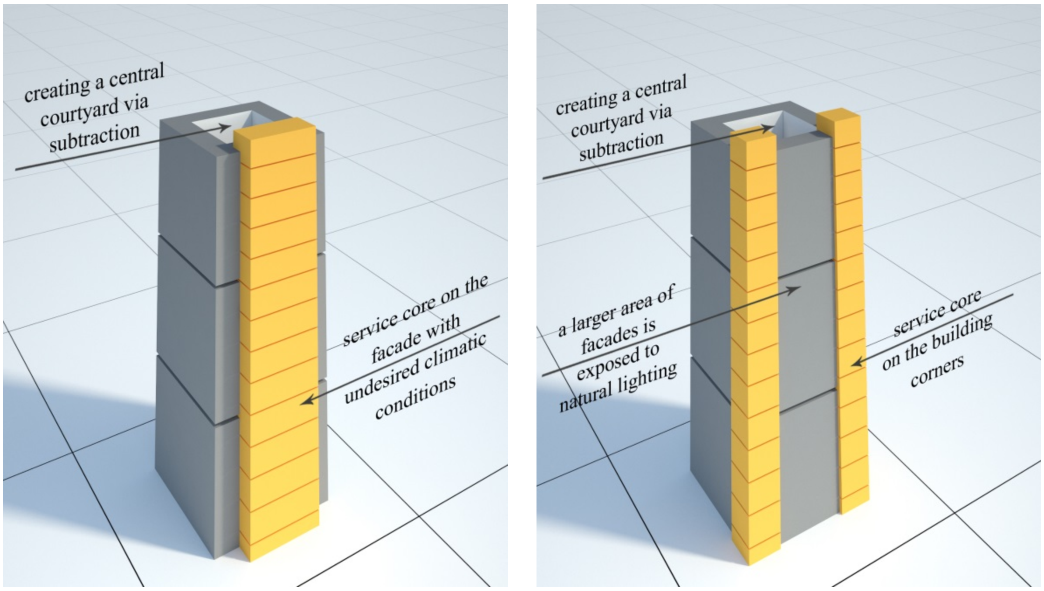
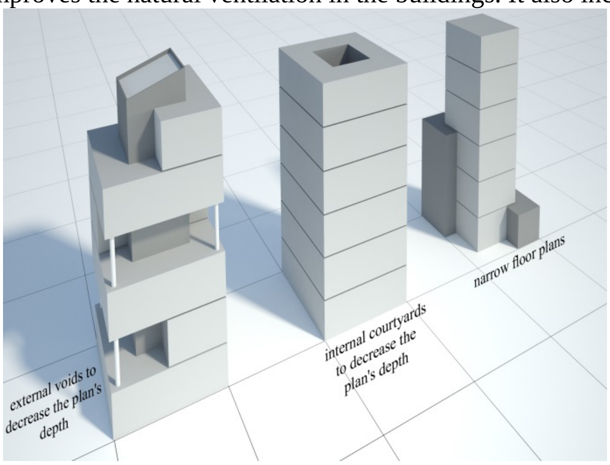


Fig. 5 Proposed services core location

3.1.2 Conceptual development

- *Building Shape, form and geometry*

The level of compactness, the ratio between the building surface areas to the volume, has a great impact on the energy consumption. The larger the level of compactness the more energy efficient the can be achieved. This will decrease the depth of the internal spaces and increase the natural ventilation and daylight. This can be achieved via narrow plans and/or courtyards external or internal to reduce the floor depth (Figure 6). The use of aerodynamic shapes reduces the wind turbulences and waves around the buildings which will lead to a decrease in the embodied energy for the building structure and the envelope's material. It also creates a pressure around the building that improves the natural ventilation in the buildings. It also increases the efficiency of wind energy systems (Figure 7).



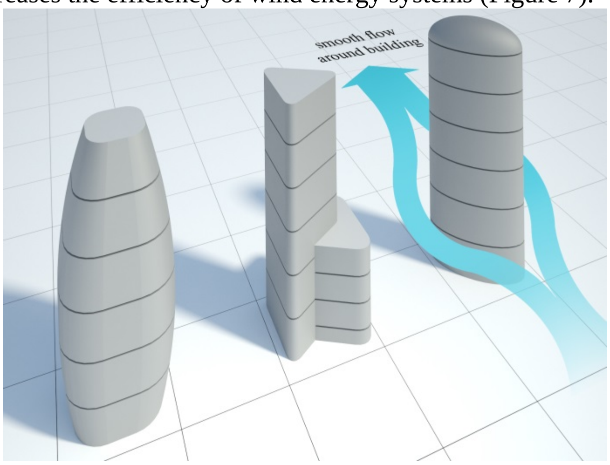


Fig. 6 Increase the external surface area to volume ratio

Fig. 7 Aerodynamic shapes for tall buildings

In hot climate the contrast between the building shape and the surface pattern reduce the energy consumption in buildings that have a fixed extruded shape from the building plan as it helps in controlling wind directions and decrease the effect of solar radiation on the building's facades via providing more shading (Figure 8).

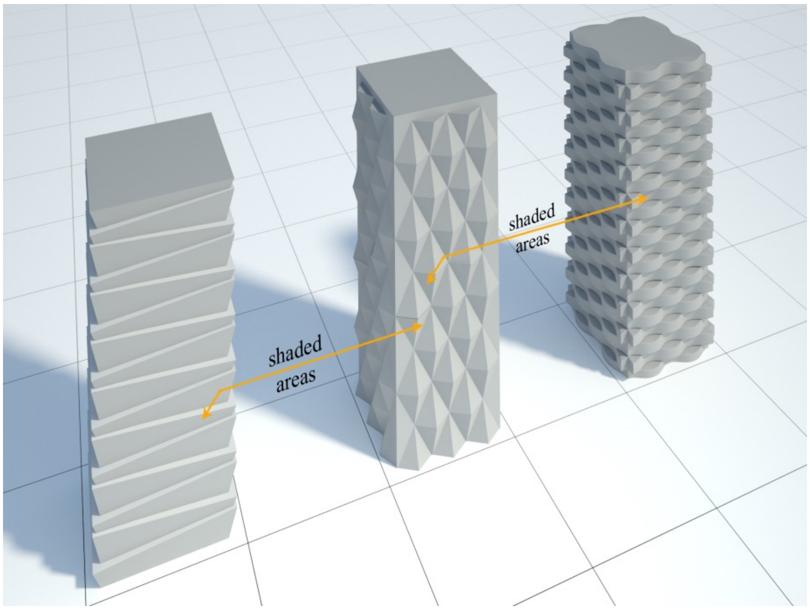


Fig. 8 Contrast in façades surface pattern

In hot humid climate buildings with circular plan of ratio 1:1 followed by the square shape have the lowest exposure to solar radiation. Compact Building plans that support natural ventilation such as linear plan, central courtyard plans and one-side open courtyard (Figure 9). Another technique is subtracting parts from the building on the facades that are highly exposed to solar radiation in hot climates to create voids. These voids created allow the natural daylight to enter the internal spaces, increasing shading rations and decrease the solar gain and glare on those facades (Figure 10).

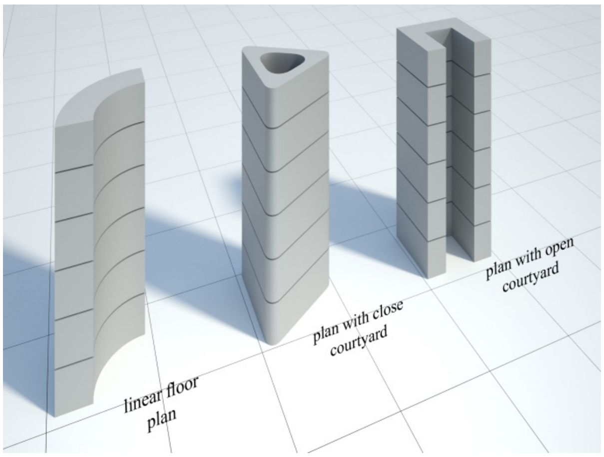


Fig. 9 Building floor plans that support natural ventilation

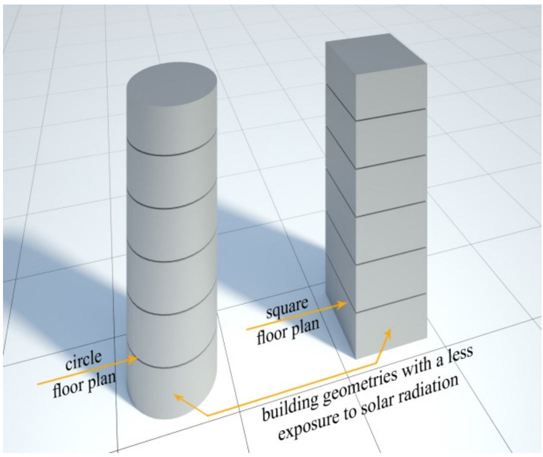


Fig. 10 Design with low exposure of solar radiation in hot humid climates

- *Natural ventilation*

The use of external opening along with the courtyards improves the natural ventilation via the stack effect. The location of these openings should be on the lower levels and on the façade facing the desired wind direction. The natural ventilation inside the building improves with a larger vertical distance between the air entering and leaving openings. Having the openings distributed on opposite facades increases the natural ventilation in the courtyard when the wind directions changes (Figure11)

Solar chimneys also provide an extra dimension in improving the natural ventilation inside the building and the stack effect (Figure12). These opening should be operable and controllable to allow the use of complete mechanical ventilation in extreme cold and hot weather condition where the natural ventilation cannot be achieved. Single or multi-level double skin façade is considered one of the important strategies that assist in improving the air circulation inside the building. In cold climates they can be used for heating via passive solar gain. The use of double skin on the entire building façade acts as courtyard that allows the hot air escaping from the buildings to leave through top openings (figure 13).

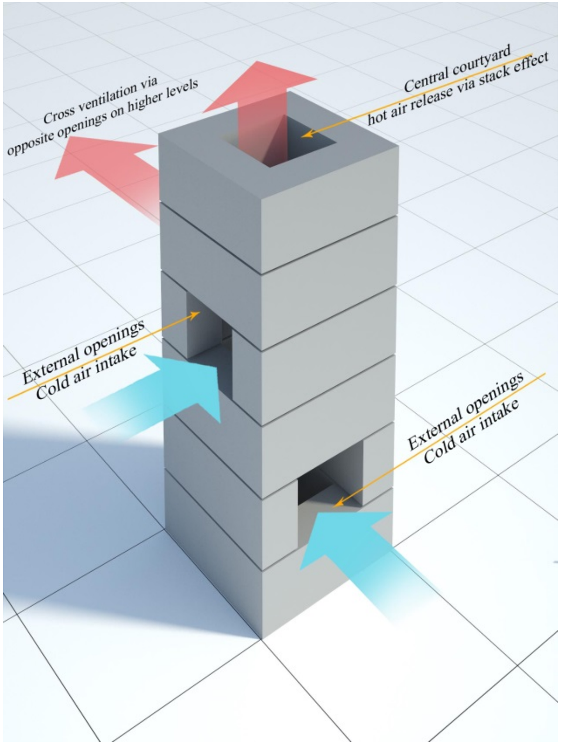


Fig. 11 Natural ventilation via double skin facades

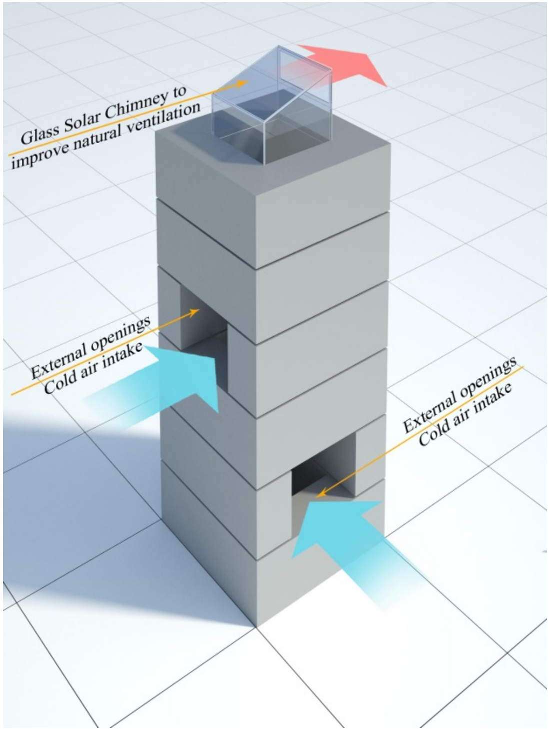


Fig. 12 Natural ventilation via central courtyard and external openings with the support of solar chimney

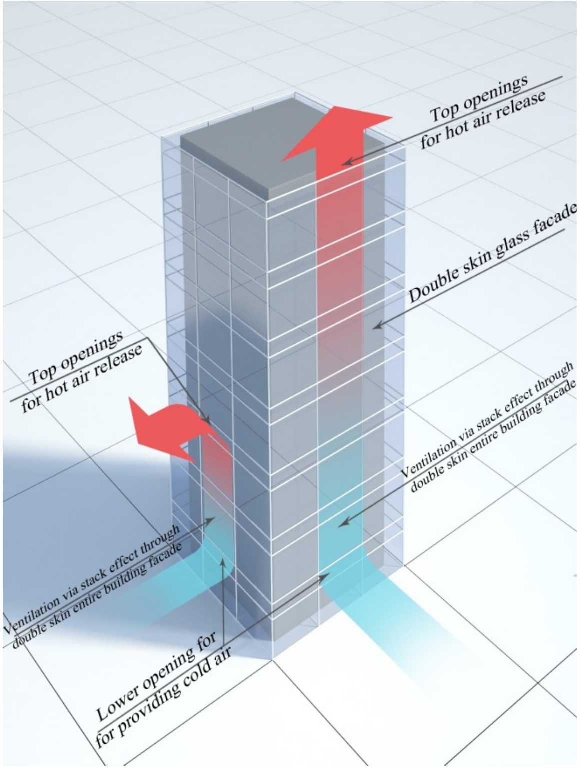


Fig. 13 Natural ventilation via central courtyard and external openings

4. **Conclusions**

The design guide presents an integrated approach to achieve energy efficiency in tall buildings. A 3D visualization approach has been used to illustrate the environmental design principles adopted in various phases. The design strategies has been divided into four phases namely Design programme, conceptualisation, documentation and operational phases. It should be taken into considerations that these strategies are not applicable to all tall buildings. The designer should select the appropriate strategies based on the climatic conditions, the exact building height and the environmental and urban circumstances. The number of floors in the 3D sketches is merely for illustration purpose and does not represent the number of floors in a real tall building. It presents an example for the concepts to be applied on the high, intermediate and lower levels and their best location on the building.

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References

[1] Elotefy H. A., Abdelmagid K. S., Morghany, E. Design Guidance to Improve the Energy efficiency of Tall buildings, M.Sc. thesis, Department of Architectural Engineering, Assiut University, Assiut, 2015.

[2] Reffat R. M., Abdou A. A., and Hamid S. M. Towards a Low-Energy Architecture using Design-based Strategies for Energy-Efficient Building Envelope in Hot Humid Climate, in The Conference Proceedings "Energy Solutions for a Sustainable World", Third International Conference on Applied Energy, University of Perugia, Perugia, Italy, 2011, pp. 1413-1420.

[3] Clair P. The Climate of Tall Buildings: An Investigation of Building Height in Bio-climatic Design. 2010. Available at: http:www.peterstclair.com

[4] Ling C. S., Ahmad M. H., Ossen R. D. The Effect of Geometric Shape and Building Orientation on minimising solar Insolation on High-Rise Buildings in Hot Humid. Journal of Construction in Developing Countries, 2007, Vol. 12, No. 1, Denmark, pp. 27

[5] Kleiven T., Natural Ventilation in Buildings: Architectural concepts, consequences and possibilities, PhD thesis, Faculty of Architecture and Fine Art, Norweigian University of Science and Technology, 2003, pp. 225

[6] Haase M., Amato A., Sustainable Façade Design for Zero Energy Building in the Tropics: Conference proceedings, The 23th International Conference on Passive and Low Energy Architecture (PLEA), Geneva, 2006.

[7] Yeang K., Ecoskyscrapers and Ecomimesis: New tall building typologies, Conference proceedings, CTBUH 8th World Congress, Dubai, 2008.

[8] Rovers, R., How Tall is a Sustainable Building?, Paper based on a presentation at XXIII UIA, World Congress of Architecture, Torino, 2008.

[9] Ellis PG, Torcellini PA. Simulating Tall Buildings Using EnergyPlus, Conference proceedings, Ninth International Building Performance Simulation Association IBPSA Conference, Montreal, 2005, pp. 1.

[10] Oke, T.R., Review of Urban Climatology 1968-1973, World Meteorological Association, Geneva, 1974, pp. 18.

[11] Lowry W. Atmospheric Ecology for Designers and Planners", Thomas Nelson Australia, South Melbourne, 1991, pp. 135.