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Net-Zero Energy Mixed-Use High Rise Design:

Principles and Proposals for Two Environmental Contexts

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs

unter der Leitung von

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Abstract

Net-Zero Energy Mixed-Use High Rise Design:
Principles and Proposals for Two Environmental Contexts

I will design two net-zero energy mixed-use high rises, in two contrasting climates, that supply 100 % of their energy needs through the power of sun, wind, water, and earth. My research and designs will help address growing and valid concerns about rising energy prices, energy dependence, and the impact of climate change. Buildings are the primary energy consumers in the United States and most developed countries. Furthermore, the demand for mixed-use high rises continues to grow as the world population increases and urbanizes. The creation of net-zero energy mixed-use high rises by the building sector is therefore key to decreasing the developed world's energy consumption. To date, there are no net-zero energy mixed-use high rises.

In order to achieve my design and research goals, I will first conduct an extensive literature search drawing upon scholarly resources from the Technical University of Vienna in Austria and the University of Maryland in the United States, as well as suitable internet resources. Identified resources will be categorized and used to define net-zero energy building specifications and relevant terminology. Second, I will conduct case studies, analyzing the development of exceptional sustainable high rises over time. The case studies will provide useful principles, guidelines, and technologies for my final designs. I will then identify two varying and distinct environmental climates to serve as sites for the design of mixed-use high rise buildings projected to achieve net-zero energy. The two contrasting climates will determine the parameters for the testing of my design concepts, resulting in unique designs for each climate. Next, through the process of trial and error I will use analytic software to test and record the relevant net-zero variables for each of my design concepts. After sufficient testing I will be able to refine the set of principles to allow me to achieve my final design goals. Lastly, I will use these principles to refine the design of the two net-zero energy mixed-use high rises, one design for each contrasting climate, that supply 100 % of their energy needs through the power of sun, wind, water, and earth.

My thesis research will result in a set of practical principles and cutting-edge technologies for application in net-zero energy high rise designs in two distinct climates. I will collaborate with my professors in the United States and Austria to write an article for submission to a journal in the field documenting my research and analysis.

Table of Contents

1. Net Zero Energy Building

1.1 Introduction

With the increasing number of Net Zero Energy Building (NZEB) projects in the world, the need for a calculation methodology and the significance of how the zero balance is calculated has become more and more important. Some developed countries are embracing the NZEB in their building codes, however, no standardized calculation procedure has been made yet and the internationally agreed NZEB definition is still lacking.

I surveyed the literature defining Net Zero Energy and discovered that the balance between feed-in and delivered energy over a period of time is the common denominator for the different definitions. In 2006, to improve clarity, the National Renewable Energy Laboratory created four ways of defining and measuring net zero energy for buildings.[1] These are Net Zero Site Energy, Net Zero Source Energy, Net Zero Energy Cost and Net Zero Energy Emissions. The NREL paper, published by Paul Torcellini et al. *Zero Energy Buildings: A Critical Look at the Definition* introduced these standardized definitions.[2]

This conference paper points out that the unit applied in the NZEB definition can be impacted by the energy cost, the investor's intention, the project objectives and the concerns about the green house emissions and climate. Hence, the four different definitions were proposed. Most authors base their definitions on this paper. Therefore, for the purpose of this thesis, I am adapting these definitions of Net Zero Site, Source, Cost and Emissions Energy. Furthermore, I am adapting their NZEB Classifications of NZEB A, B, C and D, which I introduce on the next page.[3]

1.2 Net Zero Energy Definitions

1.2.1 Net Zero Site Energy

When accounted for at the site, the site NZEB produces at least as much energy as it uses over the course of a year. Generaly, NZEB refers to this type of building.

1.2.2 Net Zero Source Energy

When accounted for at the source, the source NZEB produces at least as much energy as it uses over the course of a year. Source energy assigns the primary energy used to extract, process, generate and deliver the energy to the site impacting the energy that might be wasted or lost in

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[1] Marszal, Anna Joanna; Heiselberg, Per Kvols, *A Literature Review of Zero Energy Buildings (ZEB) Definitions*, 2009, 1.
[2] P. Torcellini, S. Pless, M. Deru, *Zero Energy Buildings: A Critical Look at the Definition*, 2006, 4.
[3] Shanti Pless, Paul Torcellini, *Net Zero Energy - A Classification System Based on Renewable Energy Supply Options*, 2010, 9.

the process. Exported and imported energy must be multiplied by the appropriate site-to-source conversion multipliers to compute the building's entire source energy.

1.2.3 Net Zero Energy Cost

It is probably the simplest definition to use and means that the building's energy utility bill is zero, when accounted for a year. Thus the amount of money the building's owner pays the utility for the energy services for this period of time is at least the same as the utility pays the owner for the exported energy.

1.2.4 Net Zero Energy Emission

The Energy Emission NZEB produces at least enough emission-free renewable energy to offset emissions from all energy used in the building.

1.2.5 Conclusion from the Definitions

There are more options on how to achieve an NZEB within these four definitions however they are not equitable and they can be hard to compare. For instance, how is a building which generates and harnesses energy by on-site systems only comparable with the one which uses renewable energy generated off-site or by purchasing Renewable Energy Certificates (RECs)?[4] For this reason, four years after publishing the NZEB definitions the National Renewable Energy Laboratory proposed a technical report introducing a classification system for NZEB. *The Net-Zero Energy Buildings: Classification System Based on Renewable Energy Supply Option* by Shanti Pless and Paul Torcellini came out in 2010.[5] The classification system is explained below.

1.3 Classifications

The classifications NZEB A, B, C and D were created to deal with the renewable energy type and location with respect to the building. This classification system introduced the concept that, depending on the locally available renewable energy possibilities and the site constraints, there are many possible renewable energy supply options.

1.3.1 NZEB A

This type of NZEB uses a combination of energy efficiency and renewable energy gathered within the footprint to generate and harness energy.

1.3.2 NZEB B

This type of NZEB uses a combination of energy efficiency and renewable energy gathered within the footprint and within the site boundary to generate and harness energy.

[4] U.S. Environmental Protection Agency, *Renewable Energy Certificates*, 2008, 1.

[5] Shanti Pless, Paul Torcellini, *Net Zero Energy - A Classification System Based on Renewable Energy Supply Options*, 2010, 8.

ZEB Classification	ZEB Supply-Side Options	ZEB Definitions
On-Site Supply Options		
A	Use renewable energy sources available within the building's footprint and directly connected to the building's electrical or hot/chilled water distribution system. (Examples: Photovoltaic, solar hot water, and wind located on the building.)	YES: Site, Source, Emissions Difficult: Cost If the source and emissions multipliers for a ZEB:A are high during times of utility energy use but low during times the ZEB is exporting to the grid, reaching a source or emissions ZEB position may be difficult. Qualifying as a cost ZEB may be difficult depending on the net-metering policies in the area.
B	Use renewable energy sources as described in ZEB:A and Use renewable energy sources available at the building site and directly connected to the building's electrical or hot/chilled water distribution system. (Examples: Photovoltaic, solar hot water, low-impact hydroelectric, and wind located on parking lots, adjacent open space, but not physically mounted on the building.)	YES: Site, Source, Cost, Emissions Difficult: Cost If the source and emissions multipliers for a ZEB:B are high during times of utility energy use but low during times the ZEB is exporting to the grid, reaching a source or emissions ZEB position may be difficult. Qualifying as a cost ZEB may be difficult depending on the net-metering policies in the area.
Off-Site Supply Options		
C	Use renewable energy sources as described in ZEB:A; ZEB:B, and ZEB:C and Use renewable energy sources available off site to generate energy on site and directly connected to the building's electrical or hot/chilled water distribution system. (Examples: Biomass, wood pellets, ethanol, or biodiesel that can be imported from off-site, or collected from waste streams from on-site processes that can be used on-site to generate electricity and heat.)	YES: Site, Difficult: Source, Cost, Emissions A ZEB:C source and emission position may be difficult if carbon-neutral renewables such as wood chips are used or if ZEB has an unfavorable source and carbon multipliers. This can occur if a ZEB exports energy during times that the utility has low source and carbon impacts, but imports energy when the utility has high source and carbon impacts. ZEB:C buildings typically do not reach a cost ZEB position because renewable materials are purchased to bring on-site—it would be very difficult to recoup these expenses by any compensation received from the utility for renewable energy generation.
D	Use renewable energy sources as described in ZEB:A, ZEB:B, and ZEB:C and Purchase recently added off-site renewable energy sources, as certified from Green-E (2009) or other equivalent renewable-energy certification programs. Continue to purchase the generation from this new resource to maintain ZEB status. (Examples: Utility-based wind, photovoltaic, emissions credits, or other "green" purchasing options. All off-site purchases must be certified as recently added renewable energy (Green-E 2009). A building could also negotiate with its power provider to install dedicated wind turbines or PV panels at a site with good solar or wind resources off-site. In this approach, the building might own the hardware and receive credits for the power. The power company or a contractor would maintain the hardware.)	YES: Source, Emissions NO: Site, Cost ZEB:D buildings may qualify as source and emissions if they purchase enough renewable energy and have favorable source and emissions factors. They will not qualify as site and cost.

Fig. 1. The NZEB Classification System is Shown Depending on the Renewable Energy Supply Option the Building Uses. It also Sums up how these Classifications Apply to the NZEB Definitions.

1.3.3 NZEB C

This type of NZEB can use not only the energy supply options of NZEB B but it can also harness energy through off-site renewable energy sources which are brought on site.

1.3.4 NZEB D

This type of NZEB can use not only the energy supply options of NZEB C but it can also harness energy through purchasing REC.

1.4 Nearly NZEB

It is not so easy to meet the net zero energy objectives. Even though the building was planned to achieve at least one of the NZEB definitions it may not be able to obtain a net zero energy position every single year and produce the required amount of energy for that. Due to the weather, such as below-average wind and solar resources, or the inappropriate condition of the building, it can happen to any NZEB that the building gets into the so called near NZEB category in a certain year. The status of an NZEB should be assessed and tracked with utility bills and submetering year by year. Even though a building fails to achieve the NZEB status every year, it can still be acknowledged as an exceptional energy performer.[6]

1.5 Off-Site Renewable Energy Supply

Not only on-site renewable energy resources, for example sun or wind, could be used to accomplish an NZEB, but also resources coming from outside the boundary of the building, such as biomass, biogas, biodiesel, wood pellets etc. This approach might attain net zero energy consumption, however, it is not the same as an NZEB that generates the energy on-site only.[7] See the four different NZEB Classifications above.

It should be mentioned that there is some vagueness if the combustible off-site renewable energy supply such as biodiesel or biogas etc., could be seen as off-site (i.e., considering the energy source’s origin) or on-site renewable supply (i.e., considering the location of the energy generation). It is also possible to purchase another type of off-site renewable energy source, namely the REC, to make up a gap between the building’s energy production and energy use.[8]

1.6 Energy Grid Connection

NZEBs are either connected to one or more energy infrastructures, for example a district heating and cooling system, biomass and biofuel distribution network, gas pipe network or the electricity

[6] Drury Crawley, *Getting to Net Zero*, 2009, 7.
[7] Marszal, Heiselberg, Bourrelle, Musall, Voss, Sartori, Napolitano, *Zero Energy Building - A review of definitions & calculation methodologies*, 2010, 4.
[8] A. J. Marszal, P. Heiselberg, R. L. Jensen, J. Nørgaard, *On-site or off-site renewable energy supply options*, 2012, 1.

grid, or they are not connected to any energy grid. The term Net, in Net Zero Energy points out that there is a balance between energy given to and taken from the energy grid over the course of a year.[9]

1.6.1 On-Grid

The NZEB is usually connected to the electricity grid to be able to cope with fluctuations in demand. The on-grid NZEB is also known as ”grid integrated” or ”grid connected”. The building draws electricity from the grid if it is needed and exports it back when there is a surplus. Other buildings may be entirely autonomous and off the grid.[10]

1.6.2 Off-Grid

This kind of NZEB also has the name ”stand alone”, ”self-sufficient” or ”autonomous” in the literature. Off-grid buildings stand alone and are not attached to any energy utility facility, thus they require distributed energy generation and energy storage capability for when there is no sun, wind etc. With the limited energy storage technologies of today, aiming an NZEB without the grid is quite a challenge.[11] Necessary energy needs could be gathered from off-site renewable sources. A stand alone NZEB without using any fossil fuels could be called a pure Zero Energy Building.[12]

1.7 Certifying NZEBs

NZEB is a sought-after goal for buildings all over the globe to achieve. Some present energy-related building labels and certification programs such as the Building Energy Quotient from the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), the Department of Energy (DOE) Building Energy Asset Score,[13] the Green Star Certification by the Green Building Council of Australia, the more and more widespread American LEED environmental impact-rating system, the BREEAM of Great Britain measuring the sustainability of commercial buildings or the Energy Performance of Buildings Directive of the European Union.[14] These entities assess a building's energy efficiency, however, they are not global and were not specifically created to certify NZEBs. Although, the NZEB Certification program of the International Living Future Institute, which has been operating since 2011, allows green pioneers from all over the globe to obtain this recognition.[15] The performance metrics and guiding principles can apply no matter where the project is located, as the certification is performance based.

[9] Patxi Hernandez, Paul Kenny, *From net energy to zero energy buildings: Defining life cycle zero energy buildings*, 2009, 817.
[10] H. Lund, A. Marszal, P. Heiselberg, *Zero energy buildings and mismatch compensation factors*, 2011, 1.
[11] Tom Hootman, *Net Zero Energy Building*, 2012, 12.
[12] Shanti Pless and Paul Torcellini, *Net Zero Energy -A Classification System Based on Renewable Energy Supply Options*, 2010. 11
[13] http://energy.gov/eere/buildings/building-energy-asset-score Accessed August 2016
[14] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 172.
[15] Tom Hootman, *Net Zero Energy Building*, 2012, 24

Fig. 2. Building Energy Quotient from ASHRAE

1.7.1 NZEB Certification by the International Living Future Institute

The NZEB Certification by the International Living Future Institute uses the structure of the Living Building Challenge, which is the most forward-looking and rigorous green building program to date and first-of-its-kind NZEB certification program. This program defines and promotes the highest level of sustainibility. The certification is cost effective, very simple, critical for integrity and the only program in the world verifying NZEB performance.[16]

1.7.2 Living Building Challenge Requirements

The Living Building Challenge is based on required strategies called imperatives. In order to achieve the NZEB Certification these four criteria of three imperatives must be fullfilled:

- Energy Imperative, Net Positive Energy. This is the main focus of the certification and it requires the NZEB cover 100 percent of its annual energy needs by on-site renewable energy. No on-site combustion or purchase of RECs is allowed. Submetering and energy bills are assessed to confirm the performance of the NZEB.[17]

- Site Imperative, Limits to Growth. The building sites are restricted to brownfields and greyfields. There are no chemicals and pesticides allowed for the treatment of the on-site landscape.[18]

[16] http://living-future.org/netzero Accessed August 2016
[17] International Living Future Institute, *Living Building Challenge 3.0*, 2014, 37.
[18] International Living Future Institute, *Living Building Challenge 3.0*, 2014, 27.

- Beauty Imperative, Beauty and Spirit: The NZEB must incorporate design features that are intended entirely for human delight and for the celebation of spirit, culture and place appropriate to its function. Furthermore, it needs to integrate public art.[19]

- Beauty Imperative, Inspiration and Education. In order to motivate others and to share succesful solutions to the public, the project needs to provide educational materials about the building's operation and performance.[20]

1.8 Future Prospects

The primary objective of sustainable architecture is to diminish the building's negative effects on the environment as well as the more efficient use of resources. Buildings are serious contributors to greenhouse gases and they consume about 40 percent of the entire fossil fuel energy.[21] The building sector's energy use grows continuously, mainly for the reason that new buildings are built quicker than the old ones become unused.

1.8.1 NZEB's Significance

NZEBs are considered to support lowering dependence on fossil fuels and carbon emission. The Energy Performance of Buildings of the EU Directive defines that all newly constructed buildings should be nearly Zero Energy Buildings by the end of 2020 and all new public buildings must fulfill this requirement by 2018.[22] Similar to this in the United States, the Building Technologies Program of the DOE set the aim to accomplish commercial zero energy buildings by 2025 and marketable zero energy homes by 2020.[23]

While currently there are only a small number of NZEBs, their creation is becoming more feasible as a result of advances in renewable energy systems, construction technologies and academic research. While the investment costs of an NZEB are more than for a regular building, due to reduced energy use, the operation costs are lower, thus the overall costs should favour the NZEB in the future.

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[19] International Living Future Institute, *Living Building Challenge 3.0*, 2014, 63.
[20] International Living Future Institute, *Living Building Challenge 3.0*, 2014, 64.
[21] P. Torcellini, S. Pless, and M. Deru, *Zero Energy Buildings: A Critical Look at the Definition*, 2006, 1.
[22] I. Sartori, A. Napolitano, A. J. Marszal, S. Pless, P. Torcellini, K. Voss, *Criteria for Definition of Net Zero Energy Buildings*, 2012, 1.
[23] Igor Sartori, Assunta Napolitano, Karsten Voss, *Net zero energy buildings: A consistent definition framework*, 2012, 1.

2. High Rise Building

2.1 High Rise Building Definition

There is no one single internationally agreed upon definition on what constitutes a high rise building, but there are many different approaches. At the end of the 19th century, the term high rise or skyscraper was used to describe a multi-story office building type which was prevalent in the American cities of Chicago and New York City.[24]

The number of stories might not be a good indicator to define a high rise since each floor height may be different in each building. The different floor usage (e.g., hotel, office) may also influence the height. Some sources consider a tall building as a high rise from above 7-10 floors,[25] [26] while others from 12-14 floors.[27] [28] [29] [30]

A specific height limit given in meters or feet could be a more accurate approach to define a high rise. However, the information varies, as most sources mention as a rule a multi-story structure is from 23 or from 30 meters (from 75 or from 100 feet) and above.[31] [32] [33] The Life Safety Code, which is generally accepted by fire services across the USA, stipulates a high rise is taller than 23 meters (75 feet) and the International Building Code uses the same measurement. [34] Thus 23 meters (75 feet) seems to be the most widely adopted height limit for a high rise building.[4] Although Emporis, which is a real estate data mining company with headquarters in Germany and is frequently cited by numerous media sources as an authority on building data, distinguishes between a high rise 35-100 meters (115-328 feet) and a skyscraper which has an architectural height of at least 100 meters (328 feet).[35]

The Council on Tall Buildings and Urban Habitat goes even further and defines a tall building as one with an average height of 50 to 300 meters (164 to 984 feet) which constitutes about 90 percent of the total tall buildings on the globe. It claims that "supertall buildings" have an average height between 300 and 600 meters (984 and 1,968 feet) and these buildings represent roughly 10 percent of the world's tall buildings. Structures with a height of more than 600 meters (1,968

[24] Ken Yeang, *The skyscraper bioclimatically considered*, 1996, 11.
[25] David M. McGrail, *Firefighting operations in high-rise and standpipe-equipped buildings*, 2007, 18.
[26] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 250.
[27] Kheir Al-Kodmany, *New Sururbanism Sustainable: Tall Building Development*, 2016, 41.
[28] Fred Steiner, Kent Butler, *Planning and Urban Design Standards*, 2006, 14.
[29] CTBUH, *Criteria for the Defining and Measuring of Tall Buildings*, 1.
[30] https://www.emporis.com/building/standard/3/high-rise-building Accessed August 2016
[31] National Fire Service, *Model Procedures guide for high-rise fire fighting*, 1996, A1.
[32] Barbara Nadel, *Building Security Handbook for Architectural Planning and Design*, 2004, 5.1.
[33] http://booksite.elsevier.com/samplechapters/9781856175555/02~Chapter_1.pdf Accessed August 2016
[34] David M. McGrail, *Firefighting operations in high-rise and standpipe-equipped buildings*, 2007, 18.
[35] https://www.emporis.com/building/standard/3/high-rise-building Accessed August 2016

feet), called “megatall” buildings, make up only a tiny amount, around 0.05 percent, of the total tall buildings on the earth today.[36]

Another approach of defining a high rise relates to the reach of the fire-fighting equipment, especially the firetruck’s ladders. Considering that, buildings where at least one occupied floor lies above the reach of the standard fire-engine ladder are called as high rises.[37] [38] [39] [40]

Some sources consider load collection, load transfer and stabilization against lateral sway as important.[41] [42] [43] [44] [45] They recognize structures which are homogeneous systems with unique problems and solutions rather than a sequence of single-story, stacked up systems as high rises. Others see this in buildings that are tall enough to necessitate the employment of mechanical vertical transportation such as elevators[46] [47] or where the height can have a serious impact on the building evacuation.[48]

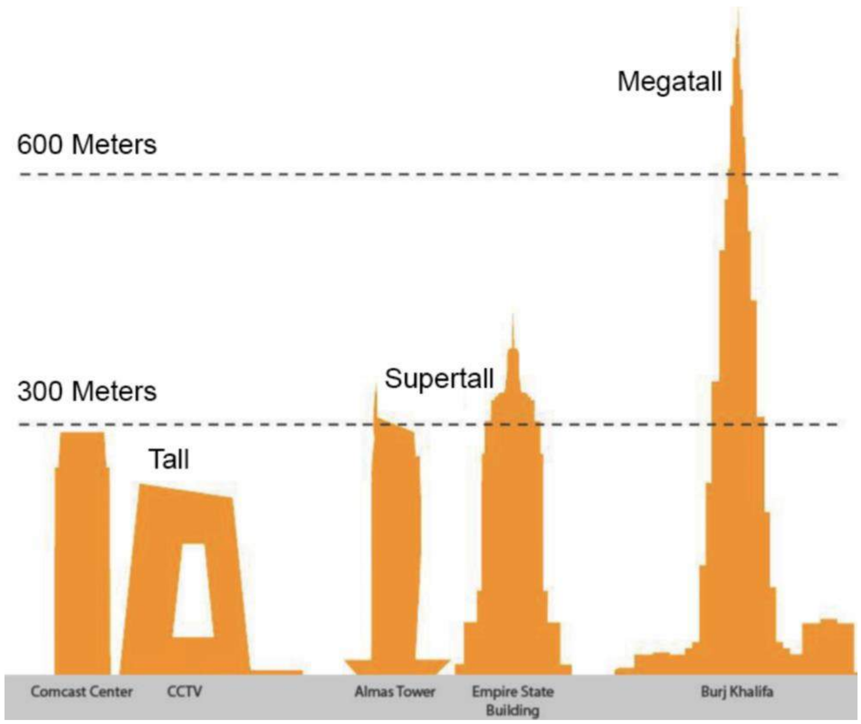

Fig. 3. Tall Buildings, Megatall Buildings and Supertall Buildings according to CTBUH

[36] CTBUH, *Criteria for the Defining and Measuring of Tall Buildings*, 1.
[37] David M. McGrail, *Firefighting operations in high-rise and standpipe-equipped buildings*, 2007, 19.
[38] Ken Yeang, *The skyscraper bioclimatically considered*, 1996, 13.
[39] Barbara Nadel, *Building Security Handbook for Architectural Planning and Design*, 2004, 5.1.
[40] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 250.
[41] M. Y. L. Chew, *Construction technology for tall buildings*, 1999, 1.
[42] Ali Mohammad Sami Kashkooli, *Considering Re-usability in Design of High-rise Buildings*, 2010, 4.
[43] Bungale S. Taranath, *Structural Analysis and Design of tall buildings*, 1988, 8.
[44] R. M. Kowalczyk, M. B. Kilmister, *Structural systems for tall buildings*, 1995, 5.
[45] Francis Brannigan, *Building Construction for the fire service*, 1992, 451.
[46] Ken Yeang, *The Green Skyscraper*, 1999, 24.
[47] CTBUH, *Criteria for the Defining and Measuring of Tall Buildings*, 1.
[48] David M. McGrail, *Firefighting operations in high-rise and standpipe-equipped buildings*, 2007, 18.

A different definition comes from the *Handbook Fundamentals* of ASHRAE which classifies a high rise as one in which height is more than three times its cross-wind width.[49] Another interesting approach for the definition is a building with a small footprint and roof area though with tall facades.

According to a more physical approach, special engineering systems needed by greater height differentiate a high rise from a low rise building. These systems include mechanical and electrical service systems, vertical transportation and movement systems, special fire-protection devices, water supply system etc. [50]

As a conclusion, one could say that "high" is a relative term. What is high for one person might be too low or maybe on the contrary even too high for another one. It can be based on one's own interpretation and it also widely depends on the surroundings. Neither a 5 nor a 20 story building would be considered tall in cities like Chicago or Hong Kong. The large number of structures above 20 or more floors means that these heights don't represent a distinguishing feature in these environments. In contrast with that, in a middle-sized European city a 20 story building would be most likely called "tall". Furthermore, people in a small village may point to their 5-story building as a "high rise". Therefore, a high rise or skyscraper is not only about height or other features but also the context in which it exists.[51]

Fig. 4. Middlie-Sized European City and New York City

2.2 High Rise Building History

In history, it has always been a desire of humanity to build higher in order to create taller and taller buildings. Thousands of years ago, people erected ancient structures such as the Tower of Babel, pyramids in Egypt or temples in Mexico by the Mayans. These buildings were monumental and symbolized power.

[49] ASHRAE, *Handbook Fundamentals*, 2005, 16.4.

[50] Ken Yeang, *The Green Skyscraper*, 1999, 24.

[51] Bungale S. Taranath, *Structural Analysis and Design of tall buildings*, 1988, 8.

Later, humans in other eras constructed tall buildings not only to express power but also wealth and military strength. Well known towers in Italian towns such as Bologna or San Gimignano represented power and wealth of families which used them to serve as bastions in times of conflict.[52]

The first real high rises in the modern world occurred in New York City and Chicago which did not have military functions anymore though still wanted to express wealth and power. They were erected either for reasons of space scarcity or simply to get dominant in the city's image. Chicago, which is also called the cradle of the skyscraper, was only a remote and tiny town in the 1820s. Though, in a spectrum of 40 years, it became the commerce center of the United States.[53]

There was a big turn in the city's life in October 1871 when a cow allegedly kicked over a lamp which caused a disaster, the Great Chicago Fire.[54] In just 48 hours, the flames destroyed nearly 18,000 buildings on 2,000 acres which made up one third of the city, including the central business district.[55] Houses with wooden balloon frames burned down quickly and the exposed cast iron of commercial and government buildings melted easily. These unprotected cast iron frames were thought to be fireproof, however, the molten iron led to an even bigger fire.

This inferno turned out to be the catalyst of proper planning regulations. The newly developed electric safety elevator by Otis, used new construction methods and materials such as fireproof iron and steel construction. These and the increasing land prices during Chicago's rebuilding, led to the birth of the modern era high rise.

The first so called high rises of the modern word had 10-20 stories and were heavy masonry buildings, having extremely heavy load bearing exterior walls usually built of stone or brick. These walls had to be really thick to be able to carry the total load of the building. A good example of this kind of structure is the Monadnock Building in Chicago, completed in 1891. It is considered the highest load-bearing building on the globe.[56] For these buildings, a twelve-inch-thick wall was needed to support the first floor and four additional inches were added to every extra floor. Indeed, this put a limit on the maximum building height which was around 10 stories. The Monadnock Building is an exception from this rule with its height of 16 stories.

[52] H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 9.
[53] David Bennett, *Skyscrapers form and function*, 1995, 38.
[54] David Bennett, *Skyscrapers form and function*, 1995, 38.
[55] Tatjana Anholts, *Rethink the skyscraper*, 2012, 15.
[56] David M. McGrail, *Firefighting operations in high-rise and standpipe-equipped buildings*, 2007, 24.


Fig. 5.
Great Chicago Fire


Fig. 6.
Monadnock Building

The 10-story Home Insurance Building in Chicago is considered to be the first building having a lightweight, curtain-wall facade supported by an internal frame from fireproof iron and steel. The Reliance Building was a very advanced structure for its time and erected amazingly quickly at that time. Its frame was made entirely of steel which was unprecedented. This meant that its exterior could be built from non-loadbearing, lightweight materials like glass. Thus the facade could be configured with large windows framed by slender piers and terracotta panels. This 15-story building was a landmark of the so called Functional Period in high rise history, lasting from about 1890 to 1900. The Functional Period meant a revolution in high rise technology, leading from heavy masonry edifices to light, steel skeleton buildings offering new possibilities.[57]


Fig. 7.
Home Insurance Building

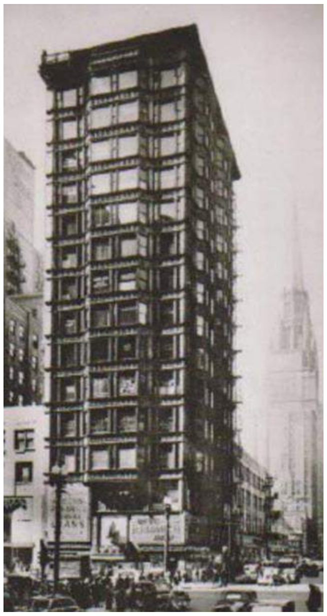
Fig. 8.
Reliance Building

[57] David Bennett, *Skyscrapers form and function*, 1995, 40.

In the first decades of the new century, decoration and building design became important. Energetic Renaissance and Gothic motifs imported from Europe appeared on buildings. This era is named as the Eclectic Period and lasted for about two decades, 1900-1920. The Flatiron Building and Woolworth Building in New York City are both perfect examples of this dynamic, exciting style.[58] The Flatiron Building (1903) is one of the biggest symbols of the city and its sheer triangular shape is instantly recognizable for everyone.[59] The steel frame dominated skyscraper construction by this time and allowed this building a wider range of flexibility for external decoration. It is clad by limestone blocks which are decorated in the French Renaissance style, showing a clear structural expression which at that time was a rarity.

Fig. 9.
Flatiron Building

Fig. 10.
Woolworth Building

The Art Deco period (1920-40) was an extension of the Eclectic style including more color, imagery and flamboyance. This period is characterized by a mixture of different styles and cultures such as Aztec, Mayan, past European fashion and Chinese architecture, influenced by Futurism, Cubism and Expressionism. Great examples of these styles are the Chrysler Building and the Empire State Building in Manhattan which belong to the most famous high rises of all time.[60]

The Chrysler Building's spire of stainless-steel arches is inspired by the automobile motif of the client. William Von Alan's high rise is described as the "Cathedral of Capitalism" and its fantastic spire was copied and worn by William at the 1931 Beaux-Arts Ball, for the scene called New York skyline where architects dressed up as their own creations. For a little more than a year (1930-31), the Chrysler Building was the tallest building in the world surpassed by the great Empire State Building.[61]

[58] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 14.
[59] David Bennett, *Skyscrapers form and function*, 1995, 47.
[60] David Bennett, *Skyscrapers form and function*, 1995, 57.
[61] David Bennett, *Skyscrapers form and function*, 1995, 56.

Fig. 11. The Spire of Chrysler Building

Fig. 12. William Van Alen is Admired by his Wife in his Costume at the Beaux-Arts Ball in 1931

The 102-story Empire State Building was the tallest and largest building on the earth for almost four decades. Starting with the construction on 17 March 1930, and raising four and a half stories every week, the building was completed in just 410 days which was a record. It is one of those very few high rises (if not the only one) which was built for less than its originally planned $50 million budget. Plenty of lights around the building top change their color to mark national holidays such as red, white and blue for the 4th of July, green on Saint Patrick's day and red and green at Christmas. However it is also lit up during other major events for example it has the colors of the organizing country during the Olympic Games every four years.[62]

Fig. 13. Empire State Building

Fig. 14. Empire State Building's Top is Lit Up during Christmas

[62] David Bennett, *Skyscrapers form and function*, 1995, 59.

Meanwhile, there were a few advances in tall building technology over the decades. Thus high rises having 100 stories became a reality. Different types of structures such as the framed-tube were developed. Fewer elevator shafts were needed in the buildings through new elevator designs thus not requiring so much usable floor space and resulting in more economic efficiency. Moreover, the building's comfort level was further improved by fluorescent lighting, forced ventilation or pressurized hot water systems.[63]

The International Style (1950-70) was developed in Europe in the first decades of the 20th century spreading to the USA through refugees fleeing from World War II. This style is generally attributed to Mies Van der Rohe, who moved to Chicago from Germany. Buildings of this era were in most cases box-shaped, made of concrete, steel and glass. They had to be functional, economical and lacked any decoration.[64]

Mies's Seagram Building was an icon of this period and is considered as the fulfillment of the architect's philosophy. The Lever House by Skidmore, Owings and Merrill (SOM), almost in front of the Seagram Building in Manhattan is another key example of the International Style. These minimalist, glass-boxes with steel construction (clearly expressed behind the glass facade) and flat roofs meant a significant change compared to the former Art Deco and Eclectic styles. The glass curtain wall offered great benefits since it was cheaper than stone and provided significantly greater light penetration into the building. These features, along with the fluorescent lighting and air conditioning development, permitted the design of larger blocks with larger, continuous open space within the tower. Indeed, this resulted in greater flexibility for the users with more space to rent for the owners. As proof of how admired and high ranked these two buildings were, New York City and Chicago changed their zoning laws at that time in order to encourage the building of similar structures.[65]


Fig. 15. Seagram Building


Fig. 16. Lever House

[63] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 16.
[64] David Bennett, *Skyscrapers form and function*, 1995, 60.
[65] David Bennett, *Skyscrapers form and function*, 1995, 60.

The Supertall Period (1965-75) can be described as the high rise image re-appearance in the form of might and economic prowess. Most likely, this can be attributed to the tedious and growing dissatisfaction with the uniform glass-box look from the former period. New construction and connection types, along with the high grade steel development all provided large weight saving potential thus reducing construction time and costs. The leading architect of these new designs was Fazlur Khan working for SOM in Chicago. His two world-famous, unique high rises, the John Hancock Center and the Sears Tower (today also known as the Willis Tower) in Chicago deserved to challenge and surpass the height record of the world's tallest building at that time. First, the Hancock Center earned this title with 10 meters (130 feet) over the Empire State Building's top, in 1969.[66] Although the record was broken quite quick by the World Trade Center in Manhattan three years later. In 1974, the Sears Tower won this title back for Chicago with its 442 meters (1,451 feet).[67]

The 100-story John Hancock Center nicknamed "Big John" dominates Chicago's skyline. The high rise steel structure is outside of the building's so called exterior-braced frame tube, acting as a wind brace and giving the building extreme rigidity. Around $15 million was saved just by using these huge cross braces. Another new construction type by Khan, the bundled tube, was used for the Sears Tower, where the perimeter columns of the tubes brace the building perfectly against strong winds. The nine tubes terminate at various heights, providing a stepped appearance to the high rise.[68]

Fig. 17. Sears Tower

Fig. 18. Hancock Center

During the height record battle between New York City and Chicago, other parts of the world were just starting to erect tall buildings. Torre de Madrid with its 37 stories was one of the first high rises in Europe, completed in 1957. Tall buildings between 30 and 40 stories were built also on other continents such as Africa, Australia and the Middle-East, by the mid-1960s.[69]

66 David Bennett, *Skyscrapers form and function*, 1995, 63.
67 Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 17.
68 David Bennett, *Skyscrapers form and function*, 1995, 62.
69 Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 16.

From the 1970s, high rises could no longer be considered as isolated towers only, cut off from the street and community, but they needed to include a human face and work on a personal scale. These are the characteristics of the Social Style (1970-80). Although, the John Hancock Center was a very successful mixed-use structure it never really had an interaction with its environment. The first real social high rise was the Citicorp Center in New York City.[70]

The Citicorp Center, built in 1977, comprises the best ideas behind the social high rise and it determined the direction of tall building design for this period. This complex is meant for public use on the street level, including department stores and restaurants, around an atrium. There is a plaza around the building's giant supporting columns which includes a sunken terrace garden and Saint Peter's Lutheran Church. The top of the building has a large, tuned mass damper that is a 400-ton concrete block, moving on a thin oil layer in order to limit the high rise's sway during strong wings.[71]

Fig. 19. Citicorp Center

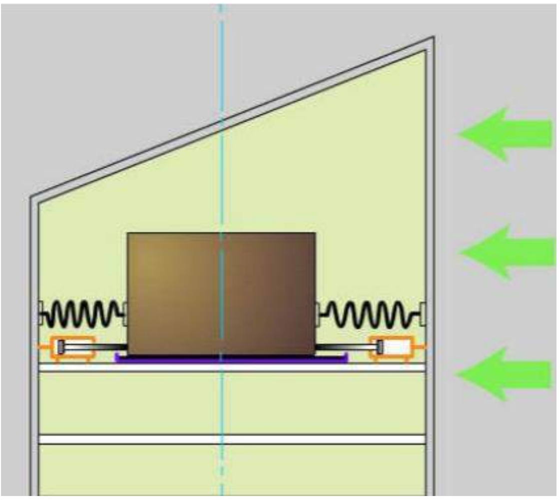

Fig. 20. Tuned Mass Damper

The Postmodern (1980-1990) period is characterized by the clients who were aware of the high rise power and romance that wanted the kind of buildings which represent them. Postmodern was a reaction to the International style. It incorporated color, sculptured form, and decoration. An example from this period is the 52-story Trump Tower (1983) in New York City which is clad in dark reflective mirrored glass on the outside and embellished by dazzling chandeliers, polished pink-marble hallways and bronze handrails inside. The sculptured form has a series of setbacks planted with shrubs and trees, creating a cascading garden. The high rise sawtooth faceting gives two different views to the rooms.[72]

From the early 1970s, the oil crises and the following recession put a hold on the race for height. For about 20 years, no really tall high rises were planned anywhere in the world and when the market started to revive in the 1990s, USA was no longer at the center of this phenomenon. Asia

[70] David Bennett, *Skyscrapers form and function*, 1995, 72.
[71] David Bennett, *Skyscrapers form and function*, 1995, 72.
[72] David Bennett, *Skyscrapers form and function*, 1995, 74.

and the Middle East became the locations of the new super tall high rises. These towers are not only office buildings, anymore, but most of them are mixed-use developments.[73]

Fig. 21. Trump Tower

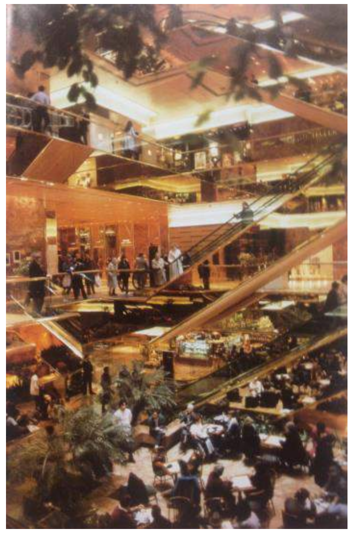

Fig. 22. Trump Tower Interior

This geographic change of high rises was very quick. Whereas about 85 percent of the world's structures above 150 meters (500 feet) were located in North America in 1980, not even 30 years later this number decreased to under 30 percent. Also, in 1980 49 of the 100 tallest buildings in the world were either in Chicago or New York City (including 9 of the top 10), this number was reduced to 18 by 2010 and stands at 17 as of 2016. The shift from office use only was also remarkable. In 1985, 85 percent of all high rises were pure office buildings. By 2008, this number declined to under 50 percent since residential and mixed-use towers became more and more popular.[74]

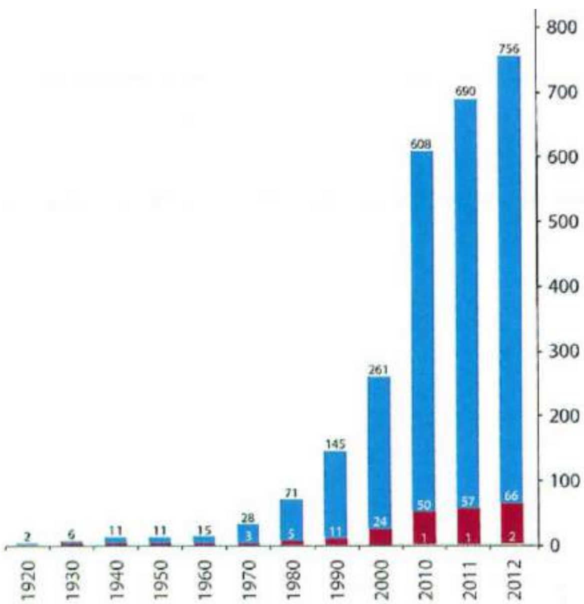

Fig. 23. Total Number of Tall Buildings over 200 m and 300 m between 1920 and 2012

[73] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 17.
[74] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 18.

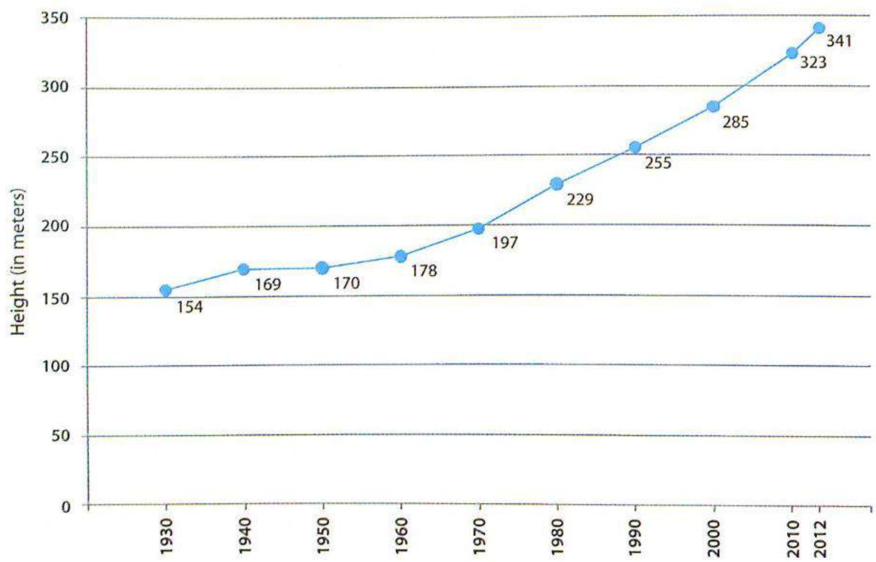

Fig. 24. Average Height of the 100 Tallest Buildings between 1930 and 2012 (in meters)

These super tall new high rises were significantly higher than the ones in the earlier decades. They often rose above 305 meters (1,000 feet) which was of course also thanks to new technologies such as the outrigger construction, that had a lot of benefits (see: Outrigger System). The Petronas Twin Towers claimed the title of the world's tallest building from the Sears Tower in 1998. This high rise, located in Kuala Lumpur, Malaysia reached 452 meters (1,483 feet) in height. This record was surpassed six years later by the Taipei 101 in Taiwan with 101 stories and 509 meters (1,670 feet). Though it held the title only for five years once the Burj Khalifa in Dubai opened in 2010 with its absolute height record to date of 160 stories and 818 meters (2,684 feet).[75]

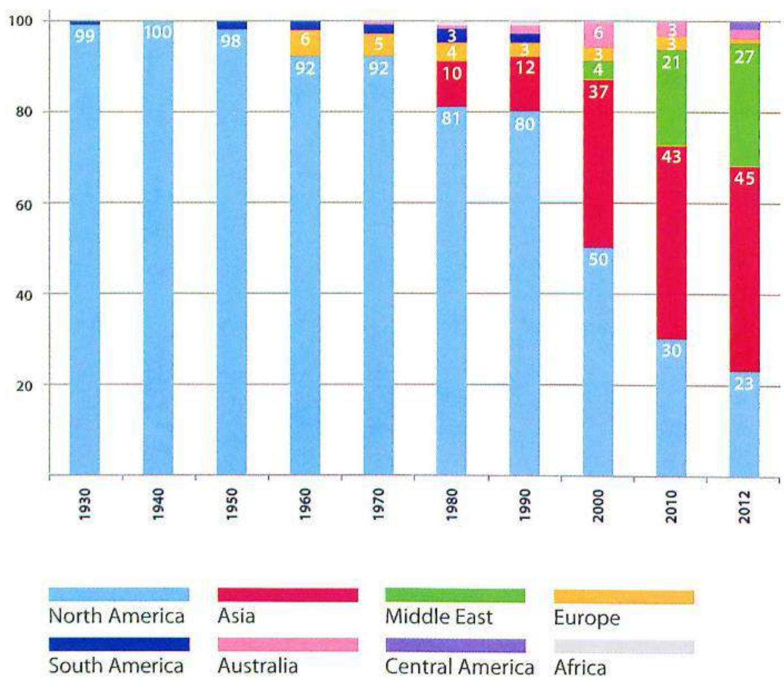

Fig. 25. 100 Tallest Buildings of the World by Location between 1930 and 2012

75 Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 18.

Although the new high rises in Asia could not claim the title of the world's tallest so far, they are still remarkably high. To give some examples: the Jin Mao Tower in Shanghai's Pudong district has 88 stories; whereas the Shanghai World Financial Center built in 2008 has 101 stories; and the Shanghai Tower completed in 2015 rises to 128 stories. Many of these new high rises are not simply geometric shaped but they represent endless possibilities of forms. Several cultural references are incorporated into their design such as the form of pagodas for the Jin Mao or ancient Chinese symbols for the Shanghai World Financial Center. The Middle East towers are characterized by patterns typical of Islamic architecture as their cultural references.[76]

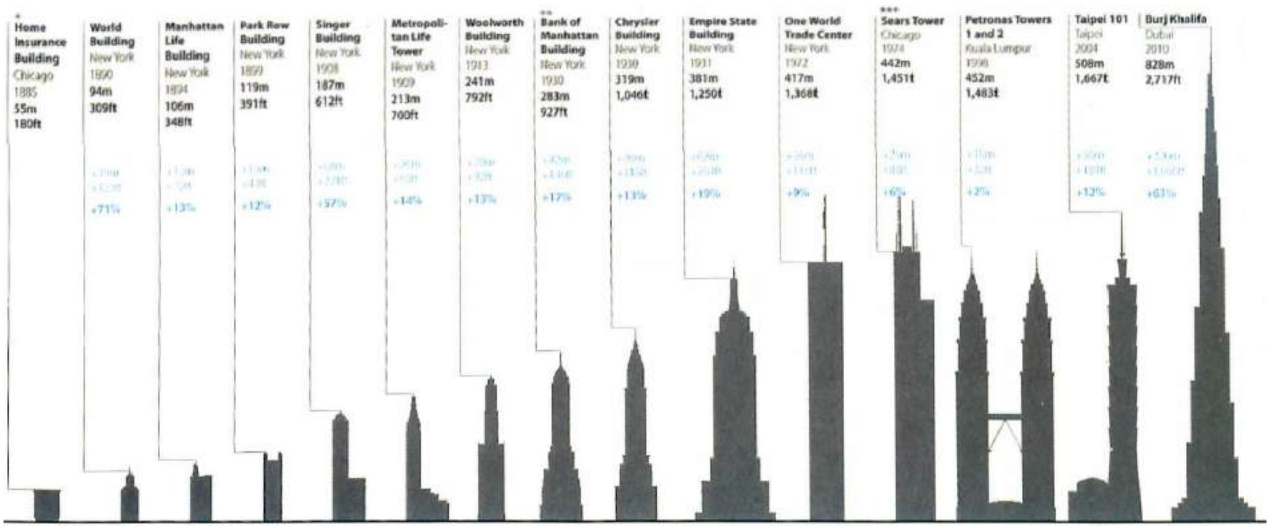

Fig. 26. History of the Tallest Building of the World

Today, the enormous height is not the only feature of tall buildings. Besides the race for height there is another field which became important in the past few decades. Sustainable planning and energy efficiency is turning into a more and more significant factor for high rises all around the world, thus raising the overall building's value. The Commerzbank in Frankfurt (1997) or the 30 St Mary Axe (2004) are perfect examples of this kind of energy efficient high rises.[77]

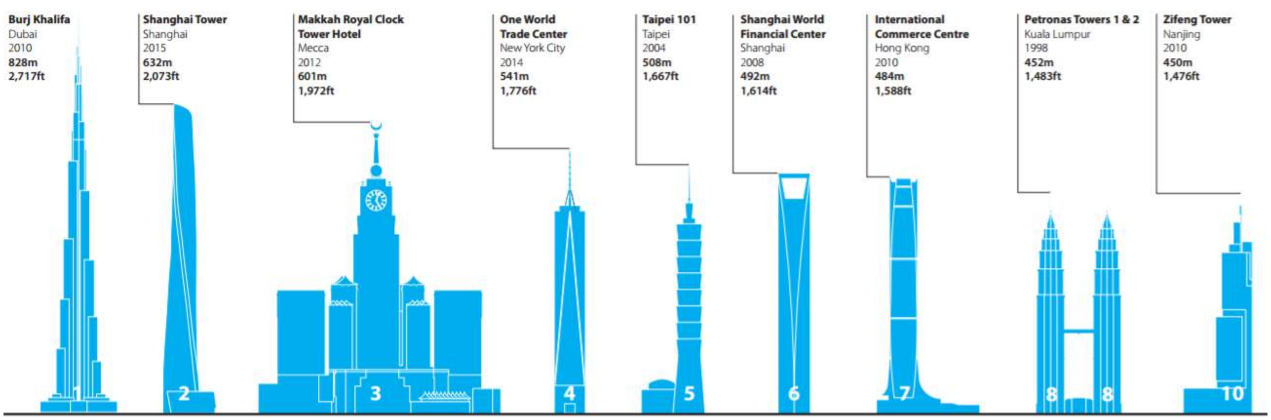

Fig. 27. World's ten tallest buildings according to Height to Architectural Top

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[76] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 18.

[77] Antony Wood, *Sustainability A new high-rise vernacular*, 2007, 405.

2.3 High Rise Building Buildup

2.3.1 Structure

2.3.1.1 Structural Systems

2.3.1.1.1 Rigid Frame

The Rigid Frame system was the primary and predominant structural system for tall buildings until the 1960s. In general, the rigid frame system is built up by vertical columns and a rectangular grid of horizontal beams connected by a rigid joist. The strength of the individual columns and beams very much influences the frame's load capacity. Indeed, this capacity declines with building height and with the increase of column spacing.

This system was not only a steel phenomenon, though. At the beginning, concrete was used to frame these structures; however, they rarely reached higher than 15 stories as a result of their bulkiness. High rises with steel frames were able to reach three or four times higher, although at this height their stability started to be jeopardized by wind loads. Towers higher than this first became possible with the development of new systems.[78]

2.3.1.1.2 Tubular System

Fazlur Khan, who is considered to be the father of modern high rise structures and designs, came up with a new framing system, called the Tubular System, for tall buildings in the mid-1960s. He recognized that the rigid frame system was not necessarily the best solution for the tallest buildings. He also realized that between the simple rigid frame and the tubular system there is a range of structural systems depending on the different building heights.[79]

He described different structural concepts, each suitable for various high rise heights, whereas he later separated concrete and steel systems, too. However, these hierarchy systems should be treated more like guidelines for tall building design rather than rules. They were based on research and computer simulations that he was a big supporter of. Today, these charts are not really in use anymore besides for preliminary design stages in some cases, since the benefits of using computer programs and modern modeling techniques have replaced them.

[78] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 50.
[79] Mir M. Ali, *Art of the Skyscraper: The Genius of Fazlur Khan*, 2001, 6.

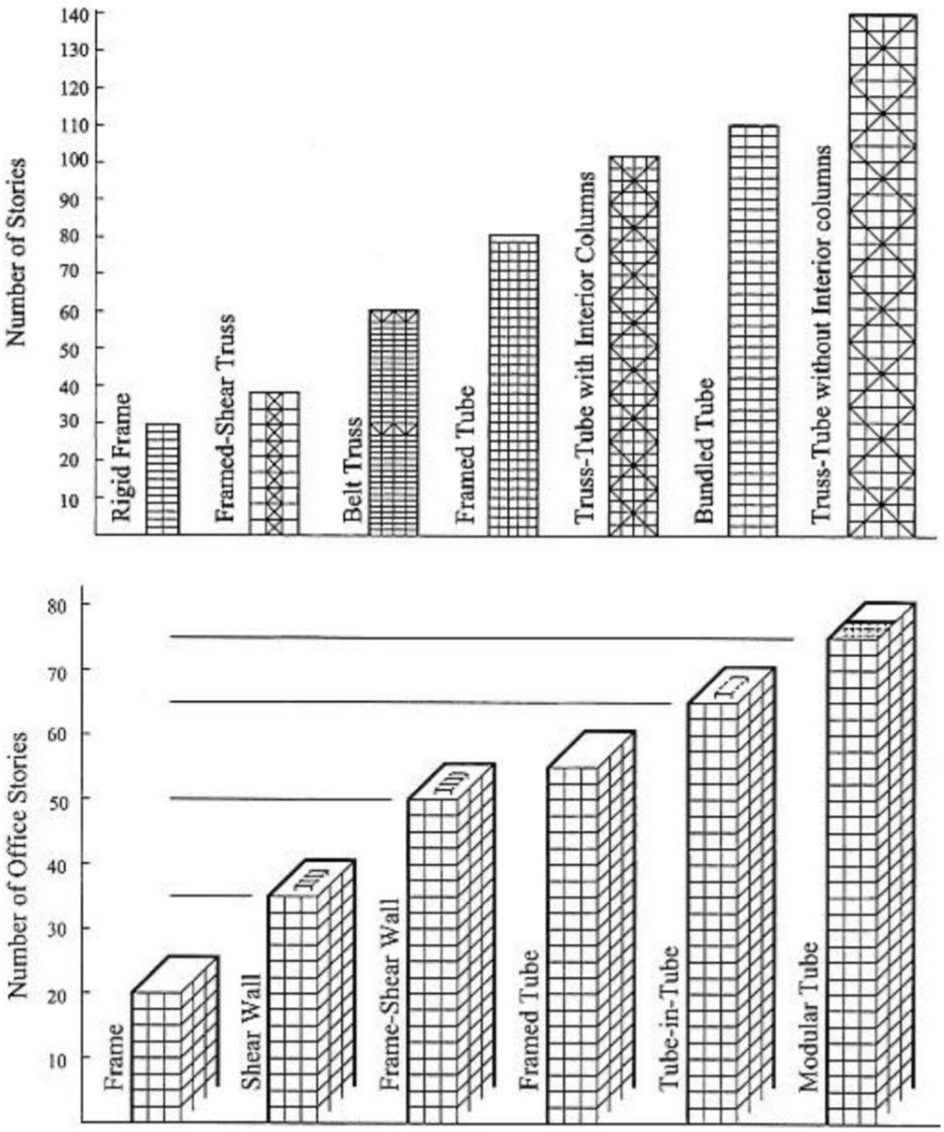

Fig. 28. Classification of Tall Building Structural Systems by Fazlur Khan

The Tubular system developed by Khan, relied on the building perimeter tubes, which are responsible for both carrying the building gravity loads and for the resistance of the lateral loads. The tube system with perimeter columns was constructed by closely spaced exterior columns that formed a spatial skeleton for the high rise, freeing buildings from the more common rectilinear shape since tubes could be arranged in any form. Thus, the building interior opened up, as a lot fewer internal columns were necessary than before, if there were any at all. With this new system, buildings could rise higher because they were able to resist heavier loads and had a great stability. The tallest buildings in the 1970s were tube-based structures. They had in common that they all had lateral load-resisting tubes at their perimeters even though they had different bracing systems.[80]

[80] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 50.

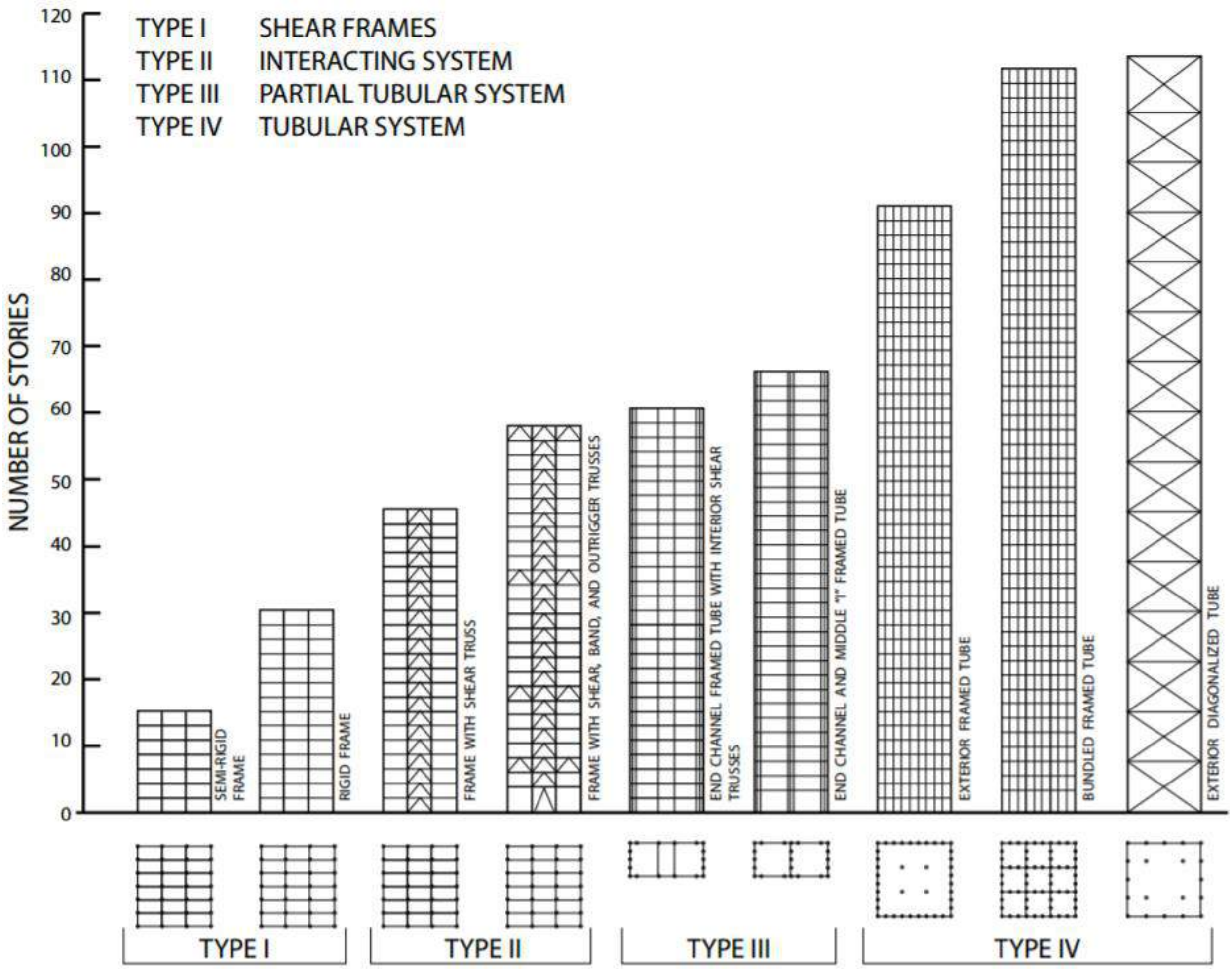

Fig. 29. Comparison of Structural Systems

2.3.1.1.2.1 Framed Tube

The Framed Tube system is the basic tubular system where the closely spaced perimeter columns are rigidly connected to deep spandrel beams. These exterior columns resist lateral loads; thus, there is no need for interior shear walls or diagonals. Interior columns do not contribute to the building stiffness since they are only carrying gravity loads.[81]

The 43-story DeWitt-Chestnut Building in Chicago (1965) was the first building where Khan used the tubular principle. This apartment high rise has a no core structure and is built from reinforced concrete employing the framed tube concept. This idea by Khan, incorporated in the Chestnut building, revolutionized the high rise design.[82]

[81] B. S. Smith, A. Coull, *Tall building structures - Analyses and design*, 1991, 45.

[82] Wolfgang Schueller, *High-rise building structures*, 1977, 103.

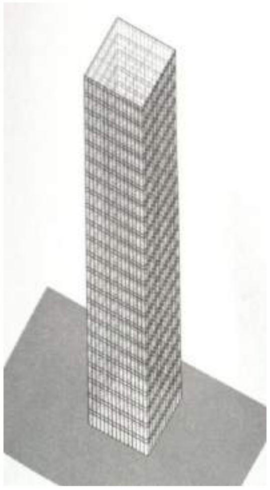

Fig. 30. Framed Tube

Fig. 31. DeWitt-Chestnut Building

Some of the most famous examples for a framed tube high rise were the former World Trade Center Towers in New York City.[83]

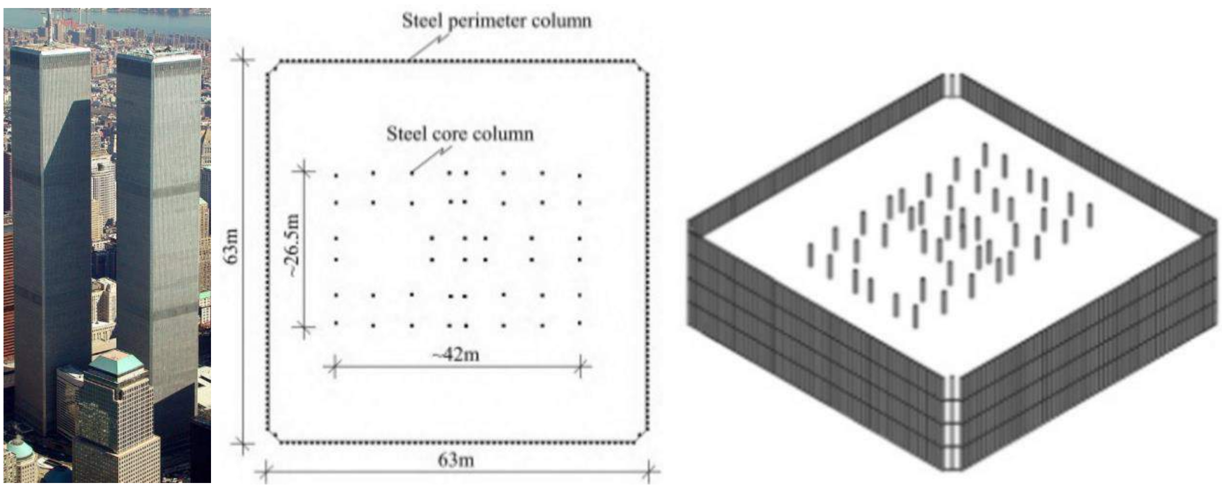

Fig. 32. The World Trade Center Twin Towers' Columns were 0.65 meters (2.1 feet) apart

2.3.1.1.2.2 Tube in Tube

In order to further stiffen the framed tube, a structural core can be introduced to the interior. As the exterior and interior tubes are connected by the floor diaphragms, they will resist lateral and gravity loads as a unit.

One of the first precedents for a tube-in-tube concept was the Brunswick Building in Chicago and the One Shell Plaza Building in Houston with a story number of 38 and 52, respectively. An interesting example for this system provides a 60-story office building in Tokyo that uses a triple core system to resist earthquake loads.[84]

[83] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 50.
[84] Wolfgang Schueller, *High-rise building structures*, 1977, 107.

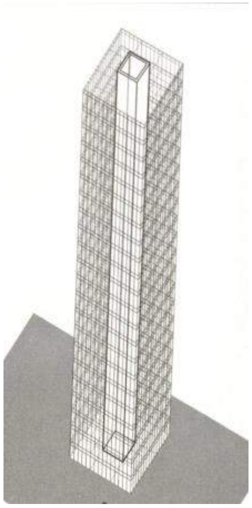
Fig. 33. Tube in Tube


Fig. 34. Brunswick Building

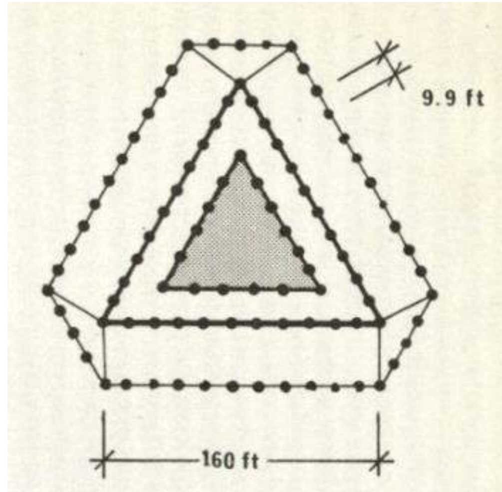

Fig. 35. Triple Core System of an Office Building in Tokyo

2.3.1.1.2.3 Trussed Tube

Adding diagonal bracing to the framed tube structure further increases its stability and allows wider spacing between perimeter columns. It also reduces the need for interior columns, thus resulting in more floor space. This type of structure was first introduced in the 100-story Hancock Center, Chicago (1969) by Khan, which was the highest building in the world at that time outside of New York City and has one of the most remarkable structures in the high rise history.[85]

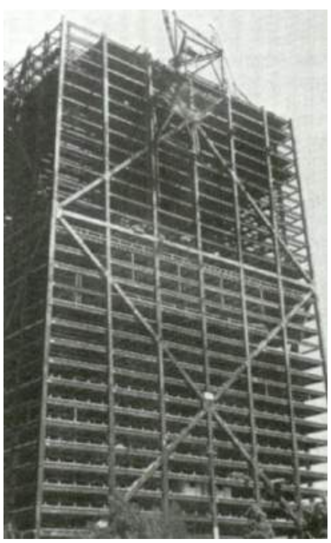
Fig. 36. Hancock Center's Construction

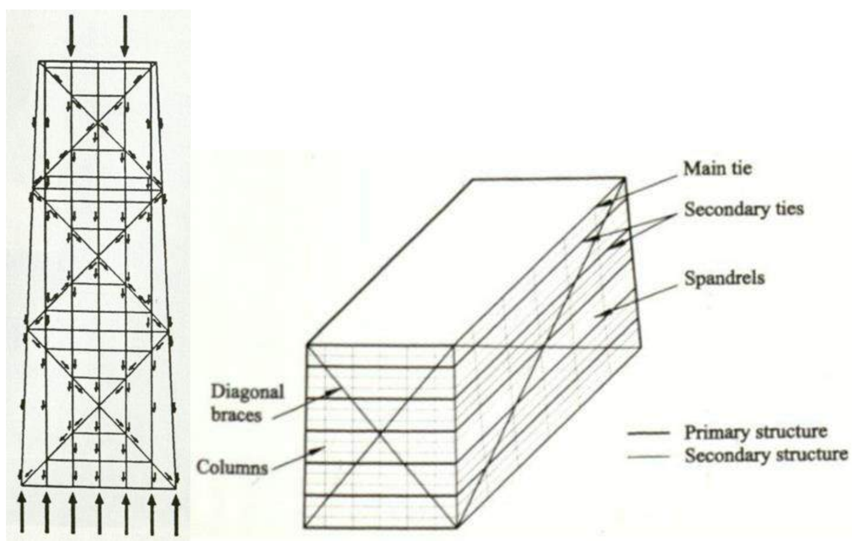

Fig. 37. Load Redistribution and Structure of the Hancock Center

This structure does not work with steel only but also with concrete. The 50-story 780 Third Avenue is a concrete frame office building in Manhattan using concrete shear walls for bracing its trussed tube structure.[86]

[85] M. Y. L. Chew, *Construction technology for tall buildings*, 1999, 38.
[86] B. S. Smith, A. Coull, *Tall building structures - Analyses and design*, 1991, 46.

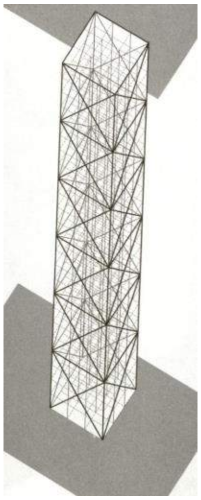

Fig. 38. Trussed Tube

Fig. 39. 780 Third Avenue

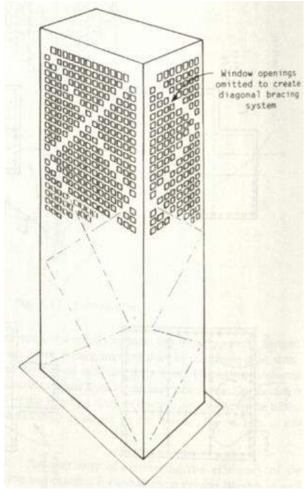

Fig. 40. Window Openings Omitted of the 780 Third Avenue to Create Diagonal Bracing System

2.3.1.1.2.4 Bundled Tube

The Bundled Tube concept consisted of several tubes tied together that thereby have a great lateral force resistance. These structures have columns only at the tubes' perimeter that provides large open spaces to the building. From this point on, tall buildings did not have to be box-like anymore since the tubes could take on any kind of form. The service core here does not serve any structural function.[87]

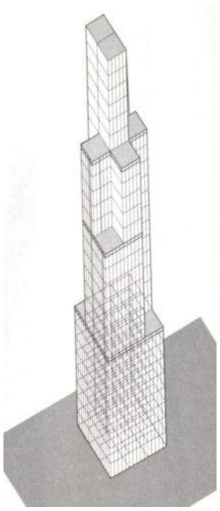

Fig. 41. Bundled Tube

Fig. 42. Sears Tower

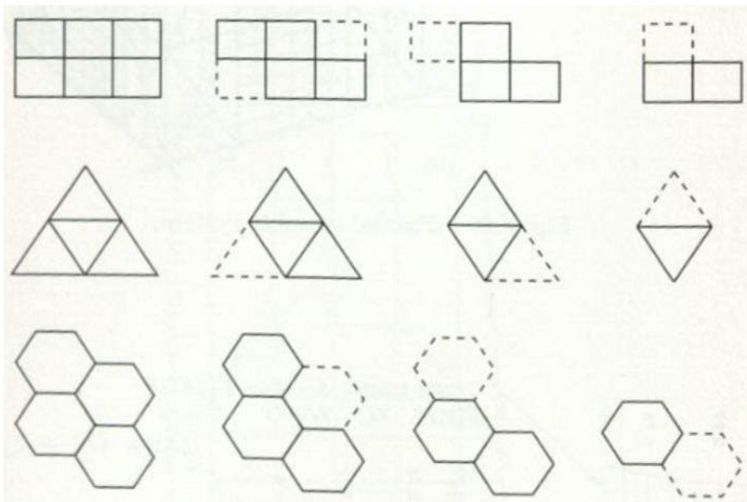

Fig. 43. Modular Tubes

Consisting of nine tubular modules, the Sears Tower (1974) or Willis Tower was the first Bundled Tube structure, ascending to 442 meters (1,454 feet) and thus it became the tallest building in the world for almost 25 years. Its nine tubes terminate at different levels that create various floor configurations and a step back system. According to Khan's estimation, around $10 million was saved by the use of this kind of structure for the tower.[88]

[87] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 267.
[88] Mir M. Ali, *Art of the Skyscraper: The Genius of Fazlur Khan*, 2001, 124.

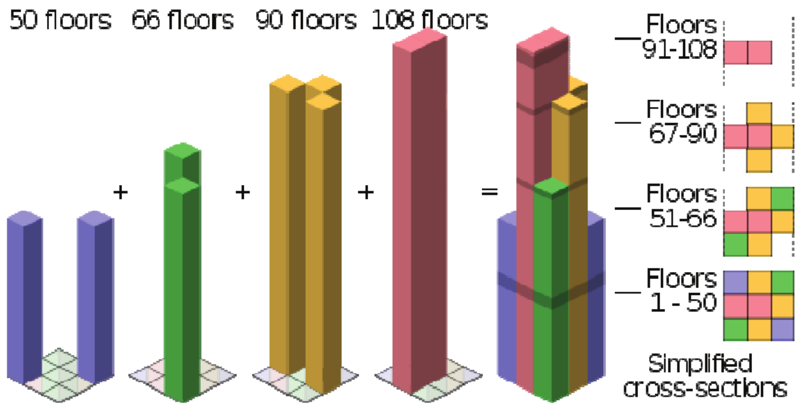

Fig. 44. Axonometric Drawings of the Sears Tower's Bundled Tube System

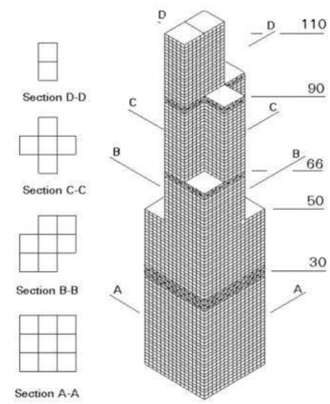

Fig. 45. Sears Tower's Floor Configuration

2.3.1.1.3 Occurrence of New Structures

The flaw of the tubular system was that the great perimeter tubes blocked views from the building interior, meaning also that, for example, the half of the World Trade Center's facade was made from steel and one third of the Sears Tower's facade was dedicated to the tubular structure. Improving upon the tube idea, new structural systems were developing from the 1980s and -90s.

2.3.1.1.3.1 Space Truss

The Space Truss is basically a modified trussed tube structure. In this system, mainly triangulated prisms are stacked on each other containing diagonals that connect the interior with the exterior frame, resisting vertical as well as lateral loads. These diagonals are prominent and well noticeable parts of the building's facade and usually of the interior space, as well.[89]

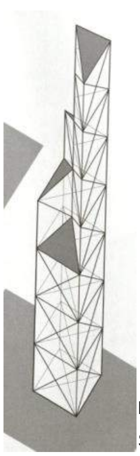

Fig. 46. Space Truss

Fig. 47. Shanghai Bank

Fig. 48. Century Tower

Fig. 49. Bank of China

The Century Tower in Tokyo, the Bank of China and the Shanghai Bank in Hong Kong all have very conspicuous structural systems that not only affect the facade but also have a large impact on the interior design.[90] [91]

[89] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 267.
[90] B. S. Smith, A. Coull, *Tall building structures - Analyses and design*, 1991, 53.
[91] K. Al-Kodmany, *Eco-Towers Sustainable Cities in the Sky*, 2015, 27.

Fig. 50. Shanghai Bank's Interior Design

Fig. 51. Century Tower's Interior Design

Fig. 52. Diagonal Structural Components as a part of the Interior Design in Shanghai Bank

2.3.1.1.3.2 Megaframe

With the increased building height, the Megaframe or also known as Superframe structure comes into picture whereever mega columns are located at the building corners that are attached by multi-story trusses at about every 15-20 story levels. These levels would usually be the locations of mechanical floors as well as sky lobbies. With the linkage of these huge space trusses to the mega columns is a rigid megaframe created that can be filled in with a lighter secondary frame. This sort of structure can be applied for super high buildings and will probably be a more often used solution for buildings in the near future.[92]

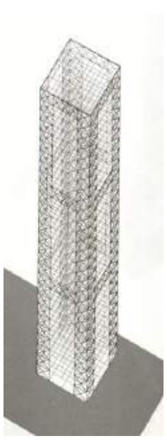

Fig. 53. Mega Frame

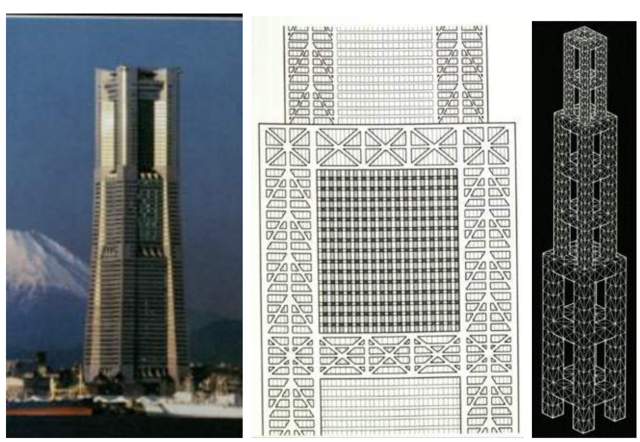

Fig. 54. Landmark Tower in Yokohama with Mega Frame Structure

[92] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 269.

2.3.1.1.3.3 Diagrid

Practically, any form is possible with the Diagrid design; thus, it is very often used in the case of an aerodynamic building. This system is built up by closely spaced diagonal braces and it does not need any large corner columns or vertical components on the building's perimeter. The facade is integrated with the structure and it provides a high degree of resistance against vertical and lateral loads.[93]

Fig. 55. Hearst Tower in New York City with Diagrid Structure

2.3.1.1.3.4 Exoskeleton

The exoskeleton structure is quite a new system and it also has green design principles such as reducing wind pressure, giving shade for the building's interior or providing natural stack effect ventilation. This system is usually made of concrete and it can have various forms such as a lattice work form or a diversely punctuated wall. As this structure is very stable, there is no need for interior columns thereby creating large open spaces.[94]

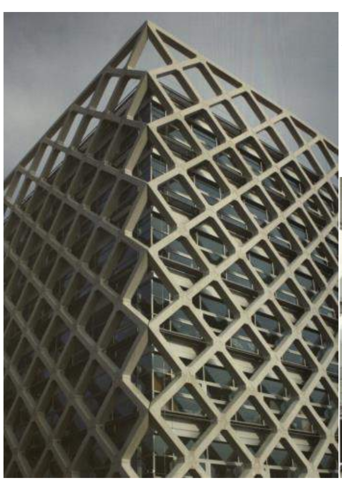

Fig. 56. Exoskeleton Structure of the Atlas Building, Wageningen, Netherlands

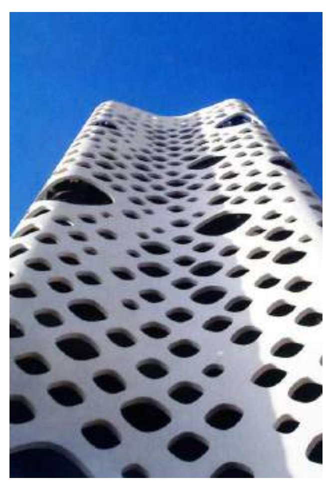

Fig. 57. Exoskeleton Structure of the O-14 Tower, Dubai

[93] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 269.

[94] Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 23.

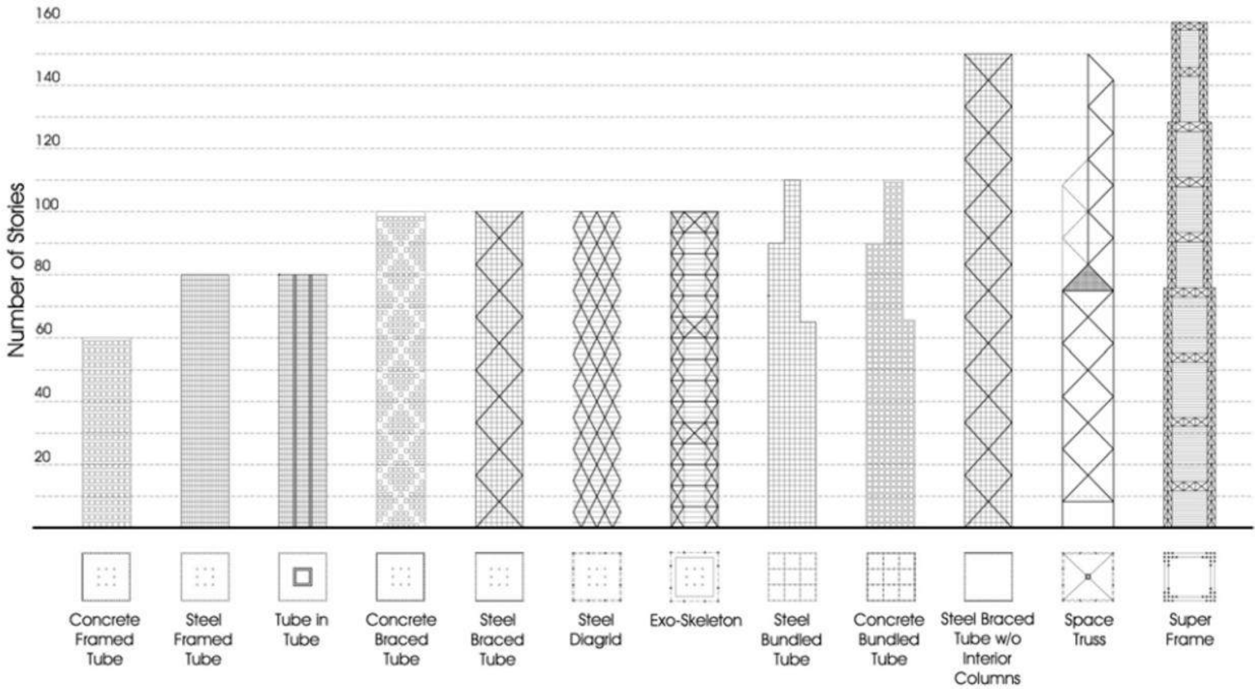

Fig. 58. Exterior High Rise Structures

2.3.1.1.3.5 Outrigger System

In the past years, the major part of high rises has been designed with an outrigger structural system. It is a combination of structural efficiency and architectural flexibility and has the huge advantage over other systems (e.g., tubular system, diagrid system) because there is no view obstruction from the building's interior through the exterior structure and the facade design is free. Furthermore, it provides the building with a great resistance against lateral forces. This system also allows discontinuities in the exterior design such as setbacks or notches.[95]

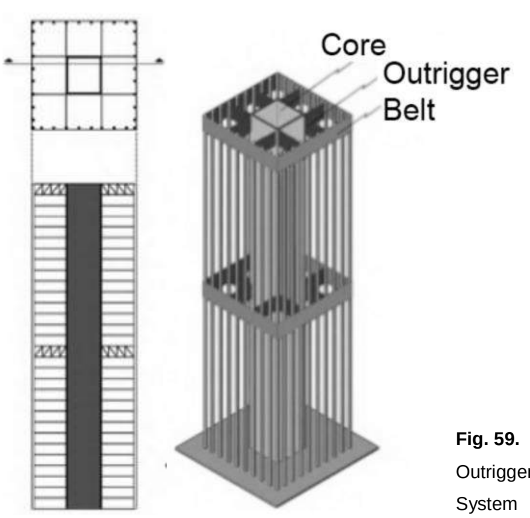

Fig. 59. Outrigger System

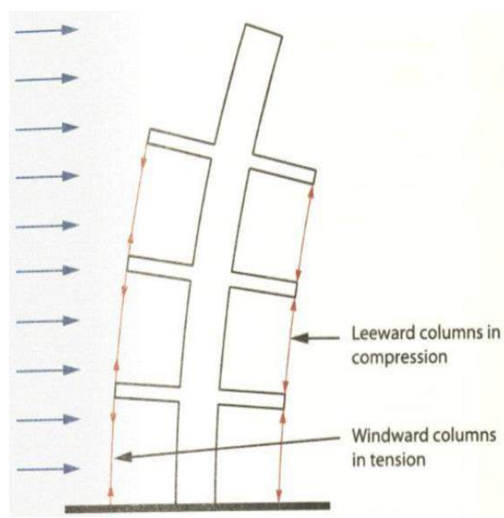

Fig. 60. Interaction of Core and Outriggers

95 H. S. Choi, G. Ho, L. Joseph, N. Mathias, *Outrigger Design for High-Rise Buildings*, 2014, 22.

The outrigger system usually consists of a shear wall core and columns on the building perimeter that are connected by stiff outrigger trusses (or in some cases by walls). In order to further improve the building stability, belt trusses can be applied that encircle the tower perimeter, thereby allowing the perimeter column sizes to be reduced. Typically, steel is used for outrigger trusses, perimeter columns and belt trusses, whereas reinforced concrete is used for the shear wall core.[96]

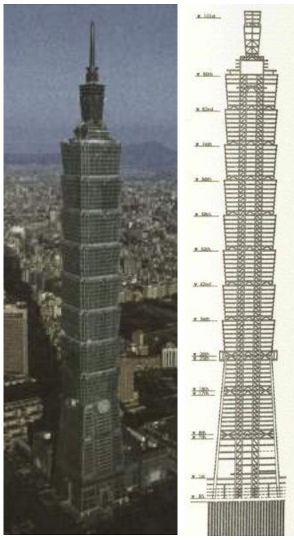

Fig. 61. Structure of Taipei 101 in Taiwan

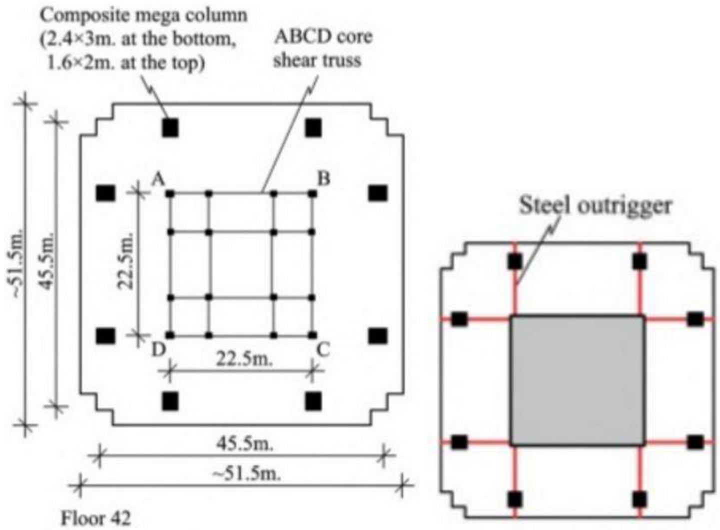

Fig. 62. Outrigger System of Taipei 101

Outriggers usually occupy double floors that in most cases correspond with the mechanical floors' height and location; thus, the outriggers are usually located on the mechanical levels. For really tall towers, the building's stability and stiffness can be further increased by introducing perimeter mega columns, linked to the belt truss and thus to the outriggers. The application of these mega columns can mean up to 60 percent in core overturning reduction.[97]

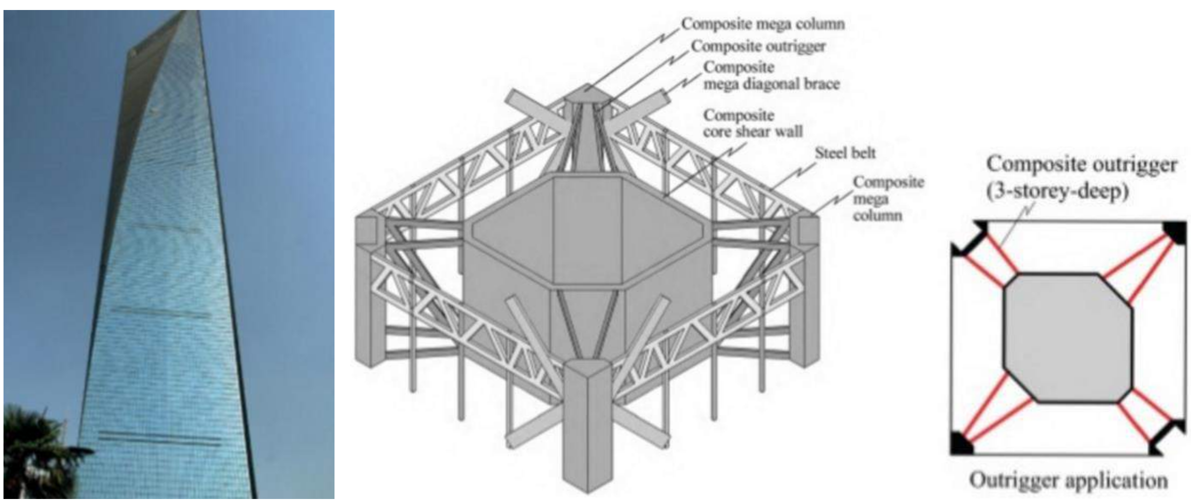

Fig. 63. Outrigger System of the Shanghai World Financial Center

[96] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 208

[97] H. S. Choi, G. Ho, L. Joseph, N. Mathias, *Outrigger Design for High-Rise Buildings*, 2014, 15.

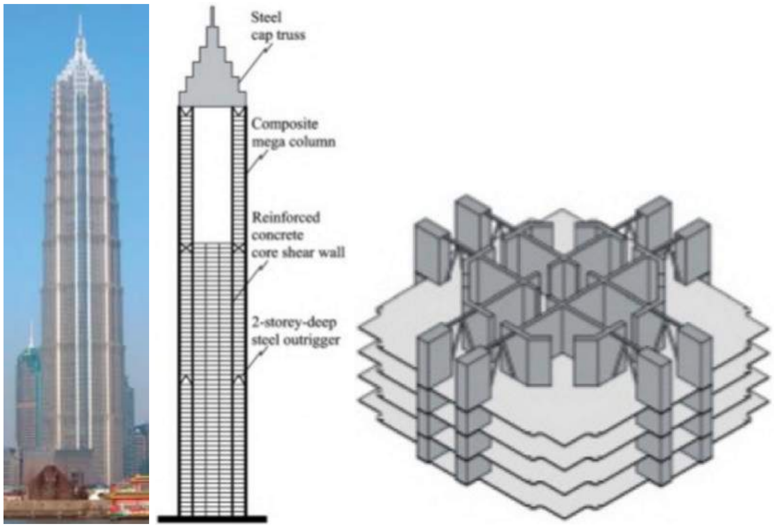

Fig. 64. Outrigger System of the Jin Mao Building, Shanghai

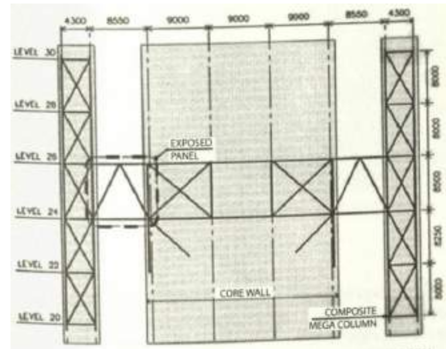

Fig. 65. Outrigger Truss Elevation of Jin Mao

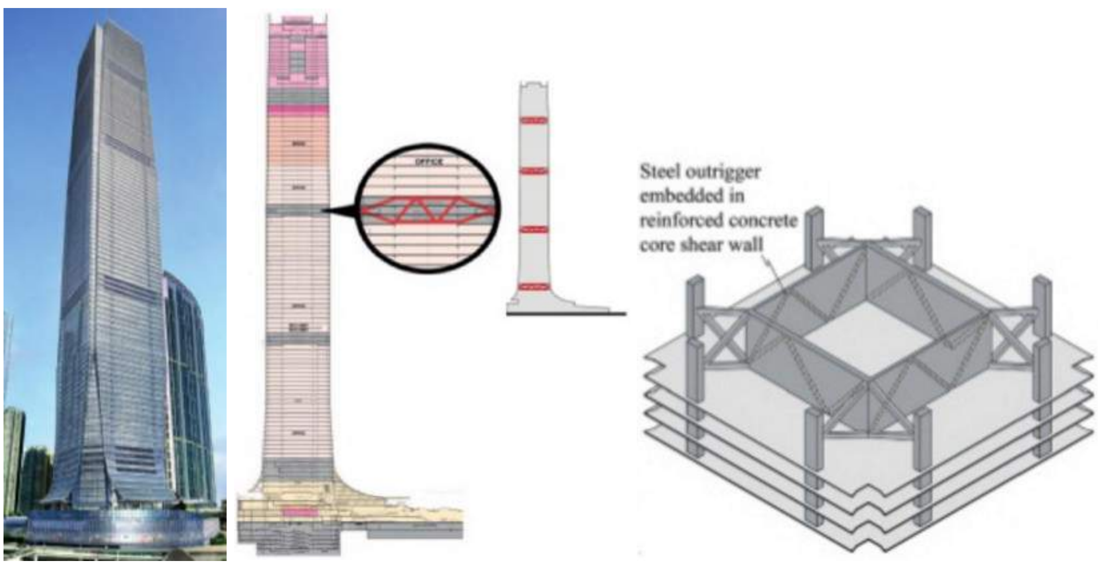

Fig. 66. Outrigger System of the International Commerce Center, Hong Kong

2.3.1.2 Perimeter Columns Opening

The provision of a wide entrance or any opening on the ground level for a tall building using a perimeter structure might be not easy. The designer needs to find an appropriate solution for transferring the load from the upper level to the ground when opening up the perimeter structure. Different high rise buildings use different ways to solve this problem.

The World Trade Center Towers had only 0.65 meters (2.1 feet) distance between their perimeter columns. In order to provide proper entrances on the ground level, these columns had to merge into greater columns having more distance between them.[98]

[98] H. Y. Sutjiadi, A. W. Charleson, Structural–Architectural Integration of Double-Layer Space Structures in Tall Buildings, 2013, 223

One can see a different solution in the Fleet Place House in London, where the columns deviate from their original, vertical positions and form diagonal components to allow a wide building entrance.[99]

Fig. 67. The World Trade Center's Columns on the Lower Foors Merged to Provide Enough Area for the Entrance

Another example from London is the entrance of the 30 St Mary Axe, which provides a unique entrance for its tenants, as well. This issue, however, can be also solved with the help of a transfer beam that is a trusslike structure deflecting and carrying the gravity load from the upper columns to the ones below or to the ground.[100]

Fig. 68. 30 St Mary Axe, London

Fig. 69. Entrance of the Fleet Place House, London

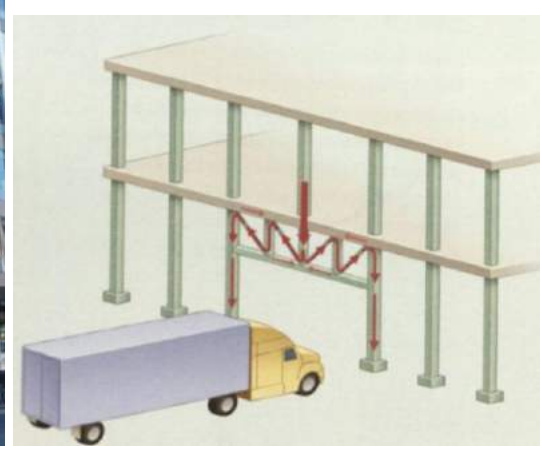

Fig. 70. Transfer Beam

[99] H. Y. Sutjiadi, A. W. Charleson, Structural–Architectural Integration of Double-Layer Space Structures in Tall Buildings, 2013, 223.
[100] H. Y. Sutjiadi, A. W. Charleson, Structural–Architectural Integration of Double-Layer Space Structures in Tall Buildings, 2013, 223.

2.3.2 Service Core

The service core is a key factor for an efficient, successful high rise design. In general, the service core cost is estimated to be around 40 percent of the total structural cost and about 4-5 percent of the total development cost. Furthermore, the service core is responsible for a large amount of the building's energy consumption. A well organized and thought-through service core design is crucial for an efficient and sustainable high rise. The service core area has a capitalized value and even a small reduction in the concrete wall thickness of the core such as 5 cm (about 2 inches) results in cost savings as much as 30-40 percent of the service core's total structural costs.[101]

The high rise floor plate depth from the service core to the building envelope depends on the user and on the function of the space. In general, occupants prefer to have 8-10 meter (26.2-32.8 foot) distance from the floor perimeter to the service core wall in order to have access to daylight, ventilation and views.[102] Contemporary studies suggest that the furthest distance of a work desk from natural daylight should not be more than 2.5 times the height of the external window surface.[103]

Service core can contribute to the principal structure of the high rise for both the lateral load resisting and the gravity load-resisting system. The lateral-load resisting system becomes more and more important with the rise of the building height and it gives the stiffness to the high rise restricting deflections and movements to decent levels at the top floors. The service core can be not only responsible for the building's stability but it is also in charge of the connection of vertical networks that go through the entire building from the ground to the top. Consequently, the service core could be described as the building element that involves the spaces which are necessary to provide physical, visual and functional vertical relations that work efficiently to allot different services throughout the high rise.[104]

2.3.2.1 Service Core Functions

The high rise floor area can be separated into two different sections. The effective space which is used for what it has been built for (e.g., apartment rooms for residential use) and the spaces with servant roles serving the former areas (e.g., elevators enabling vertical transport for occupants). The occupant pays for the effective area and it is called the Net Rentable Area (NRA). GFA stands for the total Gross Floor Area whereas SC is the area of the service core. As a consequence, SC is equal with GFA - NRA.[105]

The high rise service core includes the servant functions which are necessary for the building's existence. We can organize the service core functions in three groups:

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101 Ken Yeang, *Service Cores*, 2000, 21.
102 Ken Yeang, *Service Cores*, 2000, 34.
103 Ken Yeang, *Service Cores*, 2000, 38.
104 Ken Yeang, *Service Cores*, 2000, 13.
105 D. Trabucco, *An analysis of the relationsip between service cores and the embodied, running energy of tall buildings*, 2008, 942.

- Services: these are the fundamental servant facilities of the high rise which are indispensable to its operation and existence such as elevators, elevator lobbies, egress stairs, secure spaces, toilets, ancillary rooms (e.g., pantry or storage room for cleaning materials), M&E mechanical and electrical services plant rooms.

- Subservices: vertical risers, pipes, chutes, ducts which contribute to the appropriate operation of the main services. Usually they occupy the places which are left free after the design of the main facilities.

- Core: depending on the type of the high rise structure a structural shell might encircle the services which provides stiffness to the building against mainly horizontal forces. In case of an external structure (e.g., diagrid structure), the service core is freed from load-bearing and static functions, therefore it can be omitted and a wider diversity of floor plate design is possible, included with the elimination of interior columns. However, it should be clear that the exterior structures are obtrusive and they block out views through windows of the building.[106]

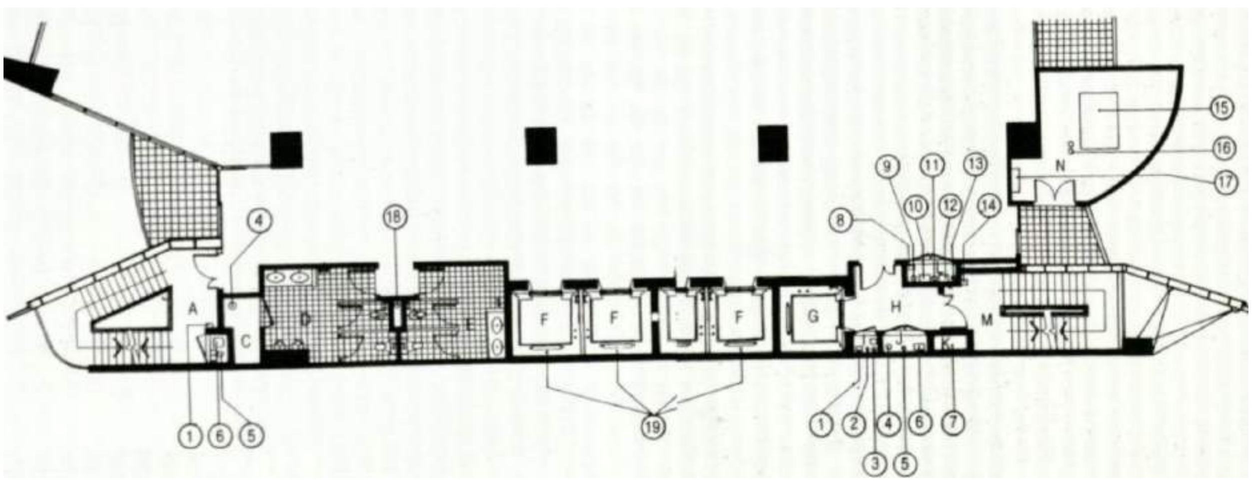


Fig. 71. Service Core of Menara UMNO, Malaysia

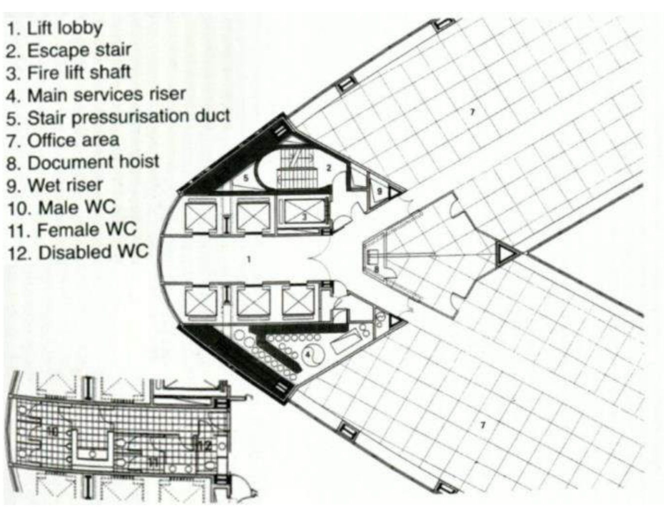


Fig. 72. One of the Three Service Cores of the Commerzbank, Frankfurt

[106] D. Trabucco, *An analysis of the relationsip between service cores and the embodied, running energy of tall buildings*, 2008, 942.

2.3.2.2 Service Core Types and Placements

The design team should consider the implications of all possible core placement options at the concept stage since it affects several aspects of the building such as the overall structural stability, the space functionality, building typology, costs, etc. Choosing the correct criteria for the core design helps to come up with the best solution meeting the objectives of the building. For example, a high rise aiming for sustainability and low energy consumption requires split core design (see: Core Position). The service core placement stems from the following generic types:[107]

A, the Central Core
B, the Split Core
C, the End Core
D, the Atrium Core

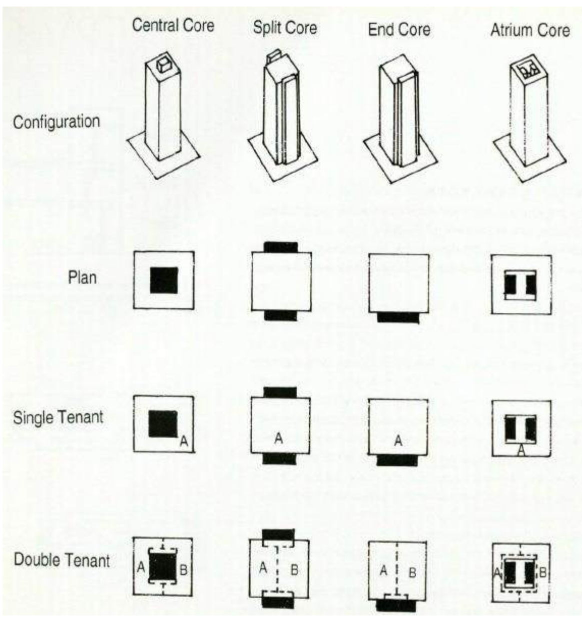


Fig. 73. The Generic Four Service Core Arrangements

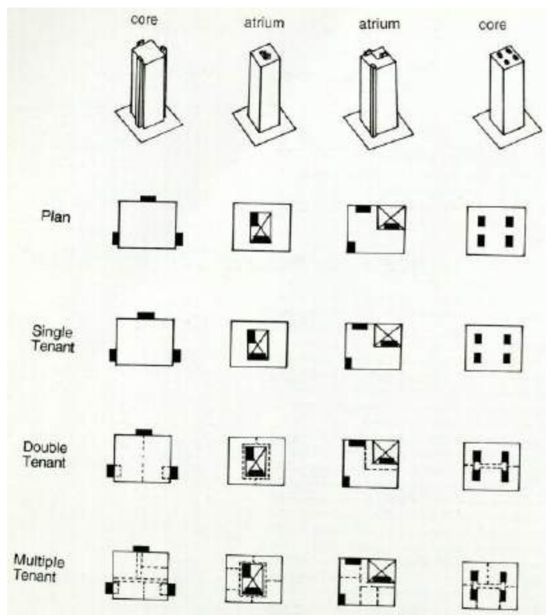


Fig. 74. The Hybrid Service Core Arrangements

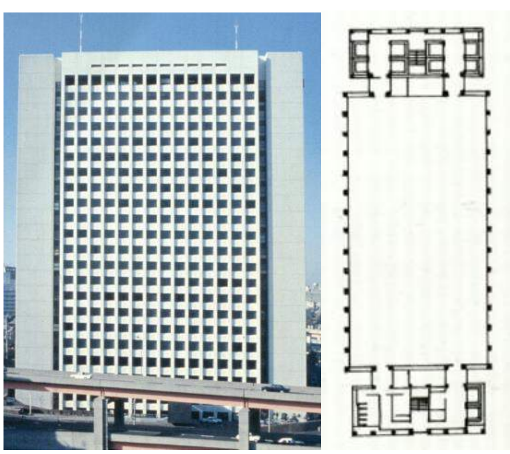
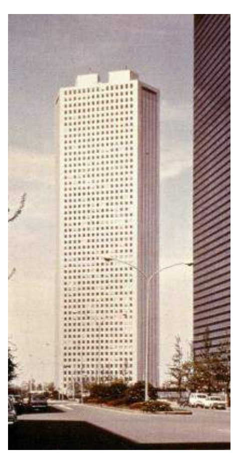


Fig. 75. Split Core of the IBM Headquarters Building, Tokyo



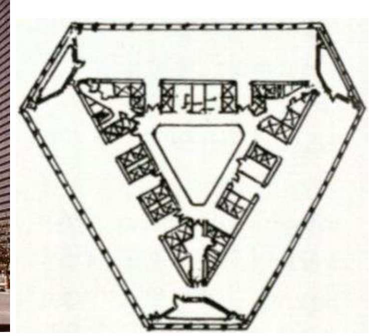


Fig. 76. Atrium Core of the Shinjuku Sumitomo Building, Tokyo

[107] Ken Yeang, *Service Cores*, 2000, 15.

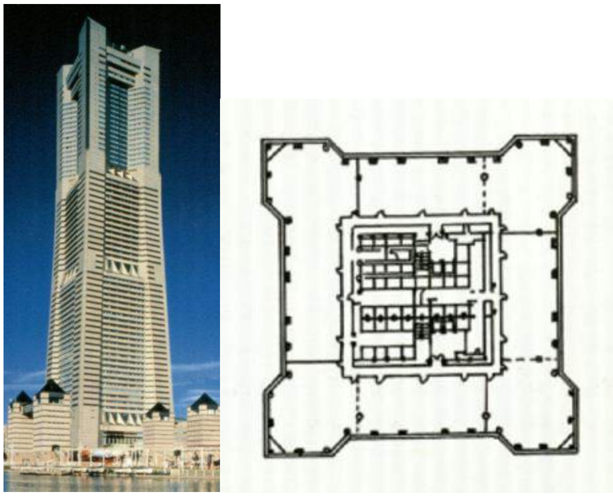


Fig. 77. Central Core of the Landmark Tower, Yokohama

Fig. 78. End Core of the Menara TA1, Kuala Lumpur

2.3.2.3 Service Core Services

2.3.2.3.1 Elevator

Elevators in high rise buildings provide vertical transportation. A few design strategies and technical solutions make their function more time and energy efficient thereby reducing the building's overall energy consumption. It should be clear that the energy consumption is also related to the type of the high rise use(s) (office, hotel etc.), since the use and occupation pattern specify the frequency with which the occupants go in and out of the high rise, how often they use the elevators and how high they travel on them.

2.3.2.3.1.1 Elevator User Segregation

2.3.2.3.1.1.1 Segregation by User Type

Elevators are used most often by office workers whereas tenants from the building's residential section take the elevator the least often.[108] Also, the elevator handling capacity expectations and the average wait times for the elevator varies by user group. Careful attention should by paid to the stacking design of different building functions. For instance, functions belonging to a hotel should be planned as close to each other as possible and exclude the need for more elevators than necessary. If the hotel sky lobby is located on the 40th floor though the pool is on the 10th floor, then the hotel might apply local elevators for pool users all the way down to the 10th floor so that they do not disturb the arriving guests while in their wet bathing suits. Of course, this would require more core space, uses more energy and makes the project more inefficient.

Today, elevator technology allows a fine segregation between building users. For instance, the Destination Based Dispatching (DBD) system together with an access control system (e.g.,

[108] Lerch Bates, *Vertical Transportation and Logistics in Mixed-Use High-Rise Towers*, 2012, 2.

different type of cards, fobs or keypad PIN entry) allows private ride access to VIP users or provides security against unauthorized travel to certain levels.[109]

2.3.2.3.1.1.1.1 Destination Based Dispatching

The DBD helps to minimize wait times, stops' number and prevents from overcrowding. In a typical situation, the rider calls for the elevator and takes the next available one. So this system does not make any difference between an elevator car that stops at every level and the one which provides a direct transport for the user. The DBD system minimizes the total transport time by directing users to a particular elevator riding to their destination instead of loading every single waiting person in one car, disregarding the riders' final destination. So with the help of a traffic management algorithm, the system optimizes drop-offs and pick-ups by grouping passengers to their selected floor. This leads to less crowded elevator cars which make fewer stops and at the end get the rider to their destination floor sooner.[110]

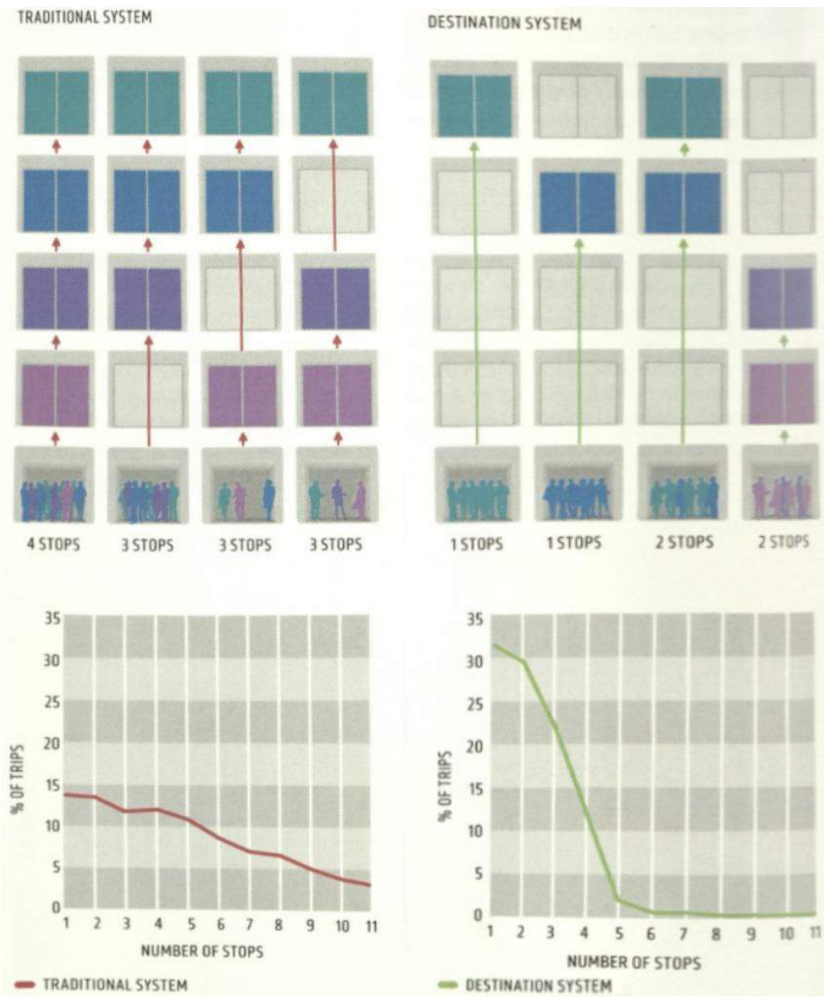


Fig. 79. Traditional Elevator System Compared to the DBD System

Fig. 80. Control Panel of a DBD System

109 Lerch Bates, *Vertical Transportation and Logistics in Mixed-Use High-Rise Towers*, 2012, 3.
110 Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 14.

2.3.2.3.1.1.2 Segregation by People vs. Material

It is important to keep Back of House (BOH) staff and transportation of materials separated from building occupants. It is also necessary to separate BOH user types since, for example, the needs of hospitality BOH are very distinct from the office or residential BOH use. Most building codes require at least two elevators serving BOH vertical transportation for every level of the high rise.[111]

2.3.2.3.1.2 Efficient Elevator Sytems

The biggest problem with elevators is providing enough elevator capacity. The most obvious solution seems to be the application of lots of elevators however as the high rise gets taller, more and more floor plate area will need to be planned for elevator shafts in order to keep up with the same level of service needs. There are some modern solutions to resolve this problem.

2.3.2.3.1.2.1 Double-Deck Elevator

Indeed, direct elevators provide the best comfort level for the vertical transfer however high rises can suffer large space inefficiencies from this. The space-use efficiency is significantly improved by double-deck elevators, especially if used with the DBD system. In this type of elevator, two elevator cars are attached on top of each other so that users of two consecutive floors can be served at the same time. Basically, they work the same way and have the same advantages as double-deck trains or buses thus doubling the space for only a small amount of more energy. The lower deck stops at all evenly numbered levels as the upper one at the uneven floors. Obviously, this requires less space in the core than the single-deck versions and offers much larger handling capacity during emptying and filling of the high rise.[112]

Fig. 81. Double-Deck Elevator

[111] Lerch Bates, *Vertical Transportation and Logistics in Mixed-Use High-Rise Towers*, 2012, 2.
[112] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 99.

2.3.2.3.1.2.2 Shared-Shaft Elevator

As the building height grows, the elevator shaft becomes taller too. In order to make this more efficient, there is a technique to use multiple elevators in the same shaft. Therefore, individual elevator cars are located above each other and use different sections of the shaft making it more energy efficient and serving the occupants quicker at different parts of the building for example the lowest elevator cab in the shaft serves the first 30 stories of the building as the cabs in the middle and top are responsible for the floors between 30-60 and 60-90, respectively.[113]

2.3.2.3.1.2.3 Odyssey

Although it is not operational yet, the Odyssey elevator system by Otis might introduce the next generation of high rise elevators. This system enables multiple cabs to travel not only vertically but also horizontally through a series of shafts in the building.[114]

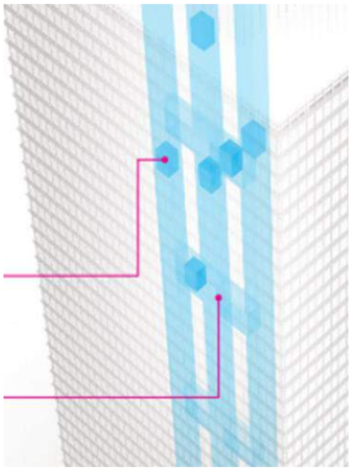


Fig. 82. Odyssey Elevator System by Otis

2.3.2.3.1.3 Elevator Bank Position

In mixed-use high rises, it is important to provide different lobbies for each elevator group, identified as such. This is even more significant on the ground floor where clear signage is necessary.

The elevator lobby where cabs face towards each other is considered less efficient than outward facing elevators in terms of Net Usable Area (NUA) compared to Gross Floor Area. For this system, both ends of the lobby should be kept open. Generally, it can be said that the elevator lobby should be planned twice as wide as the depth of the elevator cab itself.

Outward facing elevators are the ones in which doors face directly into the NUA. This positioning is more efficient than the former one since the elevator lobby of this system can be counted as part of the NUA.[115]

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[113] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 99.
[114] Willie D. Jones, *How to build a mile high skyscraper*, 2007, 52.
[115] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 45.

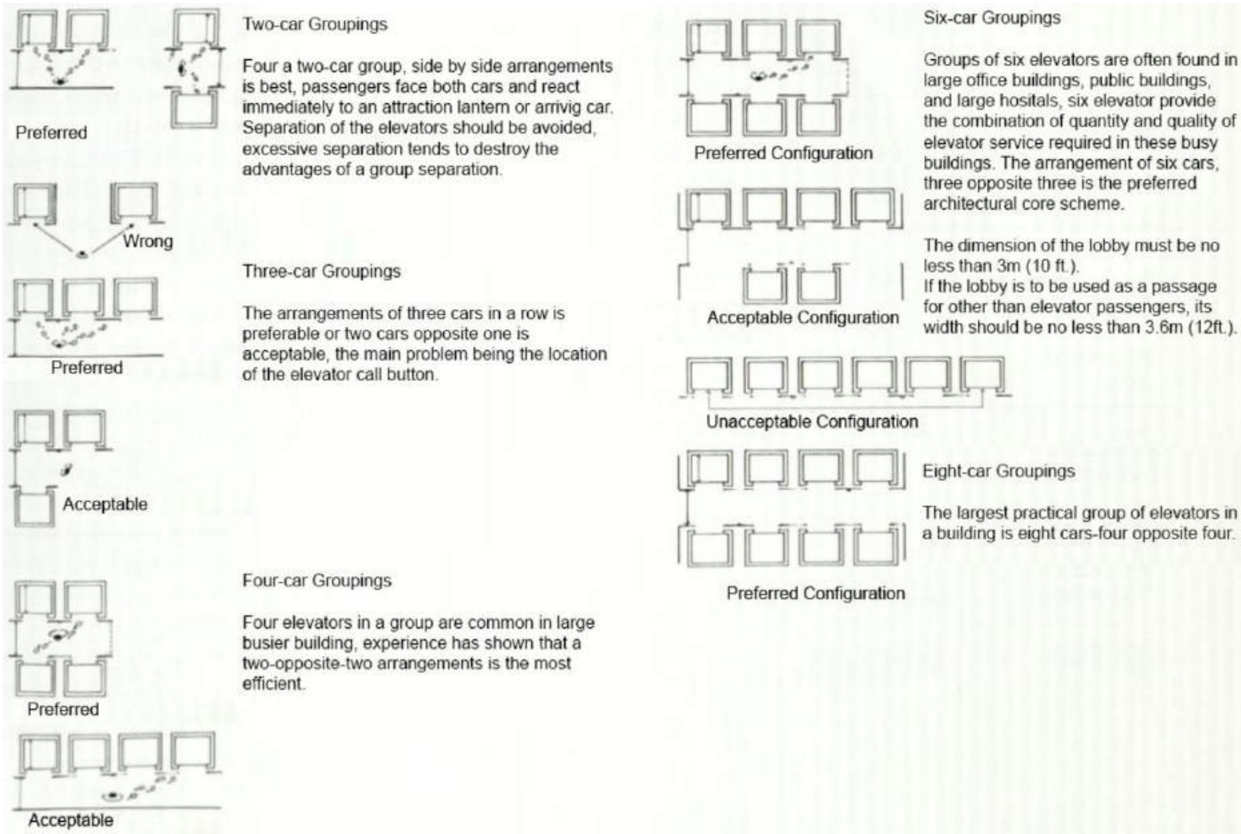

Fig. 83. Elevator Car Configuration Options

2.3.2.3.1.4 Elevator Zone Configuration

High rises under about 25 floors are in general served by only one elevator group. That means that every floor can be reached with a single travel without transferring to another elevator. In case, more than six elevator cars are necessary in the building, then the elevators will most likely be divided into two separate groups.[116]

For high rises well over 25 stories it is suggested to apply an elevator zoning concept. This means that each segment of the building is served by different elevator groups with separate entrances and these segments end in the form of transfer floors or sky-lobbies.

For tall buildings possessing between around 20-35 floors, the separation into short and long-distance elevator groups is reasonable. This results in fewer numbers of stops for each elevator, reduces waiting times and enhances handling capacity. Therefore, the number of riders in the cabs decreases so the cabs can even designed to be smaller. The higher stories will also be reached faster and need less intervening stops.[117]

[116] Johann Eisele, *High-rise Manual: Typology and Design, Construction and Technology*, 2002, 209.
[117] Johann Eisele, *High-rise Manual: Typology and Design, Construction and Technology*, 2002, 210.

It makes sense to include short, medium and long-distance elevators for high rises having up to 45 floors. Buildings up to approximately 60 stories can have an extra group of elevators, which mean four in total. As a result, it is possible to ride from the ground floor to any floor without changing cabs.[118]

For buildings above 200 meters (656 feet) the application of stacked elevators might come into the picture. This means literally stacking elevator shafts above each other which reduces the total shaft volumes and the required space in the main lobby compared to the non-stacked elevator shafts. This solution can be observed, for example, in Frankfurt, Westend Strasse 1 or in Kuala Lumpur, Petronas Towers. The Millennium Tower in Frankfurt possesses two different sky-lobbies and they are both connected by separate express elevators with the main lobby. The building is broken up into three equal zones which all have short and long-distance elevator groups.[119]

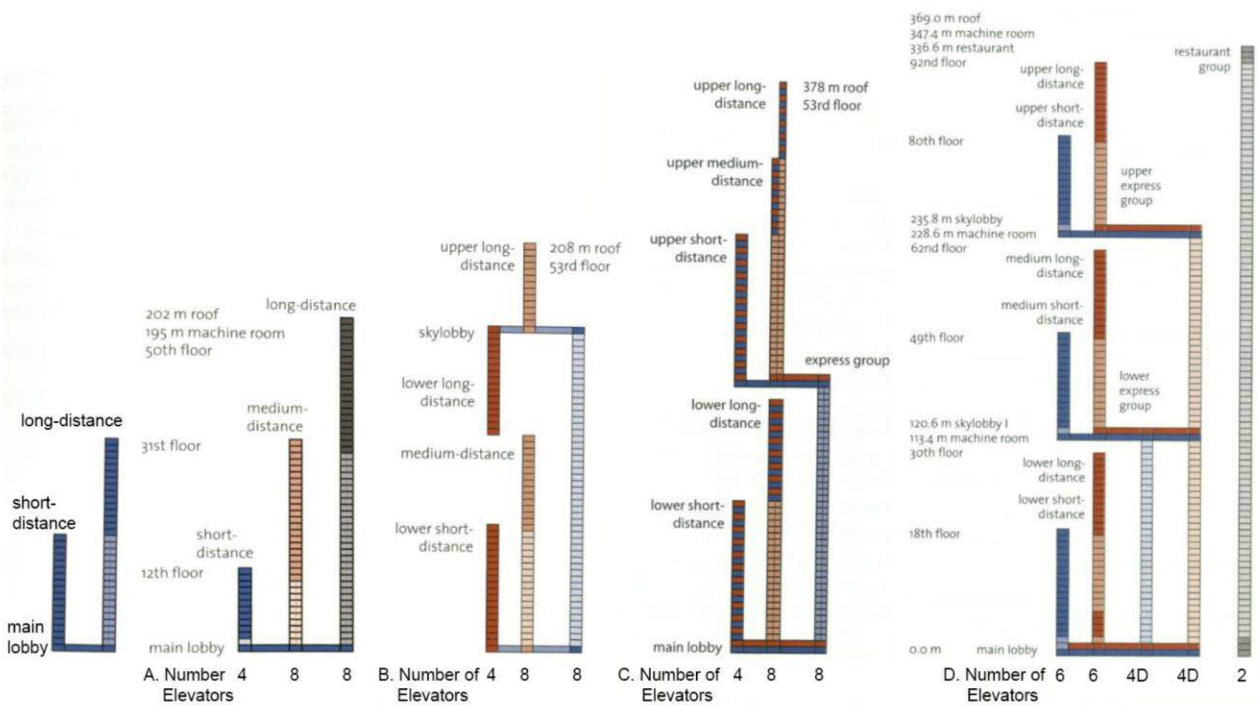

Fig. 84. High Rise Elevator Zone Configurations: A. UEC, Frankfurt; B. Westend St. 1, Frankfurt; C. Petronas T., K. Lumpur, D. Millenium T., Frankfurt

2.3.2.3.1.5 Energy Generation

A regular elevator cab uses energy even when it descends, in order to control the descent speed and brake the cab when the chosen floor is achieved. While breaking, energy is dissipated in the form of heat, as well, which has an impact on the building's cooling load, too. On the contrary, the Elevator Regenerative Braking System generates electric power when the cab travels down with a heavy load, when it descends and even when it travels up with a light load. This generated electricity is then returned back to the building's energy system. In comparison with elevators with

[118] Johann Eisele, *High-rise Manual: Typology and Design, Construction and Technology*, 2002, 210.
[119] Johann Eisele, *High-rise Manual: Typology and Design, Construction and Technology*, 2002, 210.

non-regenerative travels, this system is able to reduce the overall energy usage of the elevator by up to 70 percent. This is an investment for the building that is highly energy efficient and has a great return.[120]

2.3.2.3.2 Mechanical and Electrical Systems

Mechanical and Electrical systems (M&E) bring the high rise to life while the occupants depend on these systems to provide them comfort conditions. These conditions are crucial for a high-performing high rise. The M&E are the biggest energy consumers of the building, however, a smart design and the right equipment selection can provide great long-term savings in energy expenditures. Poor design or installation may affect the occupant productivity and might even cause health problems. On the contrary, proper design and mechanical performance increases the worker productivity and improves their health. The service core position within the floor plate can have a large impact on the M&E systems' distribution routes such as on the vertical circulation system and on the building use efficiency, as well. M&E systems include among others ventilation system, air conditioning, heating, power distribution, elevators, lighting, plumbing, waste disposal system, communications systems, fire alarm and protection.[121]

2.3.2.3.2.1 Mechanical Floor

The mechanical floor is not only the heart of the mechanical and electrical systems but also of the entire building. It contains the building's mechanical equipment and its associated electrical equipment, therefore, it is not intended for human occupancy. Air, water, light and electric power all dissipate from here. Lower buildings usually possess only one mechanical floor which is most likely located in the basement, however, tall buildings in general have multiple mechanical floors.

Fig. 85. 11 Mechanical Floors of the Taipei 101

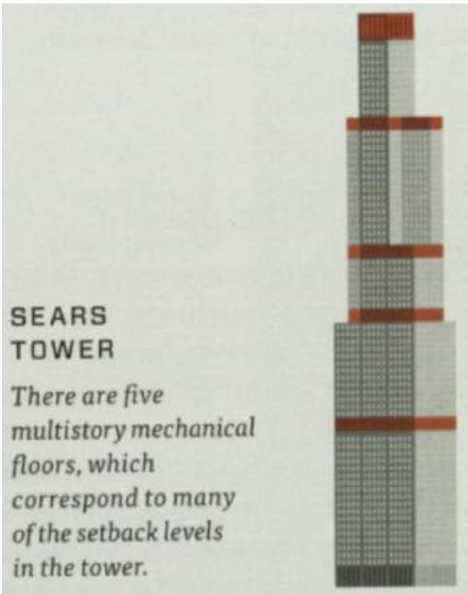

Fig. 86. 5 Mechanical Floors of the Sears Tower

[120] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 159.
[121] Wolfgang Schueller, *High-rise building structures*, 1977, 57.

Mechanical floors are most likely distributed evenly throughout the building, but can be also clustered in groups or concentrated at the building top. In many cases, the top level is used as a mechanical floor anyway, containing the tallest elevators' mechanical room, telecommunications equipment and also the window-washing equipment. When the mechanical floors are spread out at different floors, one for up to every 30 floors, they can serve the levels above and below more efficiently and manage the building's water pressure more effectively. Usually, the mechanical floor positions coincide with the structural needs of the high rise. This means that the level of the often applied outrigger system (see: Outrigger System) can perfectly house the M&E equipment.[122]

2.3.2.3.2.1.1 Building Management System

High-efficient high rises use automatic control systems in order to achieve comfort and efficient building operations. These systems are usually called the Building Management System (BMS). They control multiple pieces of mechanical equipment and also other systems which might be integrated using computerized systems. BMS control system hardware is usually installed on the mechanical floor and can be remotely accessed from elsewhere. BMS manages building's functions such as heating, air conditioning, ventilation, elevators, lighting, communications and life safety equipment.[123]

BMS works with smart solutions to efficiently manage and lessen the high rise energy consumption. Dimming systems located in building spaces automatically adjust levels of electric light depending on the natural light available in that area, whereas, motion detector systems switch off lights when the user leaves the room. This makes even more sense in under-used areas such as hallways, lavatories or storage rooms.[124] The building automation system is also able to be programmed to turn on and off lights in advance at set times thereby saving plenty of energy during hours when the building is not occupied (e.g., at night). These systems can lead to 30-50 percent energy savings.[125]

More efficient delivery of desired indoor temperature is provided by a new type of air-handling controls that reduce air conditioning costs, too. Refined, modern motors are able to vary the water speed being pumped up to higher levels as well as to adjust the circulation rate.[126] Today, tenants even have the option to access real-time information about the amount of their energy usage through analyzing and submetering technologies. Not only is this possible through the internet but users can also have control over building systems remotely.[127]

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[122] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 106.
[123] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 164.
[124] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 88.
[125] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 164.
[126] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 164.
[127] C. Eika, E. Alslund-Lanthén, *Sustainia 100*, 2013, 22.

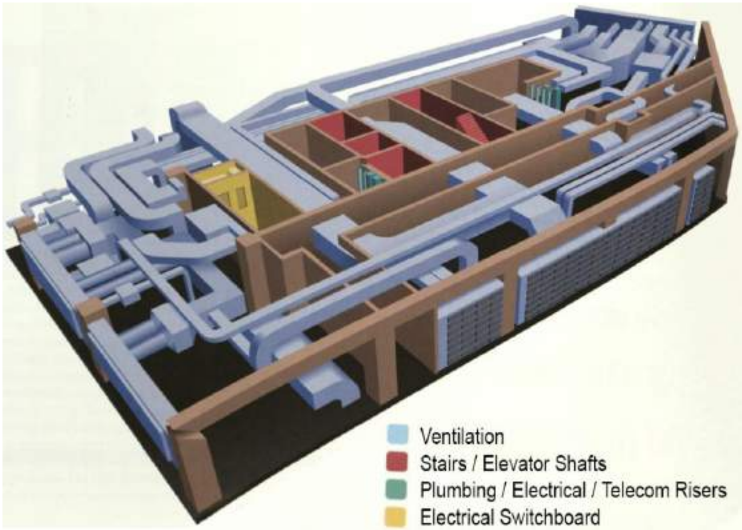

Fig. 87. Mechanical Floor Shown here Contains a Large Amount of Ventilation Equipment

Fig. 88. Control over Room Temperature through Phone Application

2.3.2.3.2.2 Riser Ducts and Chases for M&E Services

Riser ducts and vertical chases for M&E services are usually located wherever there is some spare space within the core to deliver service where it is needed in the high rise. However, it must be carefully planned, otherwise it can lead to weaving piping, wiring and ductwork in and around the structure of the building thus making acces for future alterations or maintenance complicated and decreasing the systems' efficiency. Often mechanical chases are grouped with other shafts together such as those encasing elevators, plumbing risers or exit stairways. This leads to bundling of shafts to one or more cores which extend vertically through the entire high rise. Additional fireprotection is required for these shafts since they run through many levels. Therefore, they can be built as shear walls and help to assist carrying the gravity loads as well as to resist against lateral loads.[128]

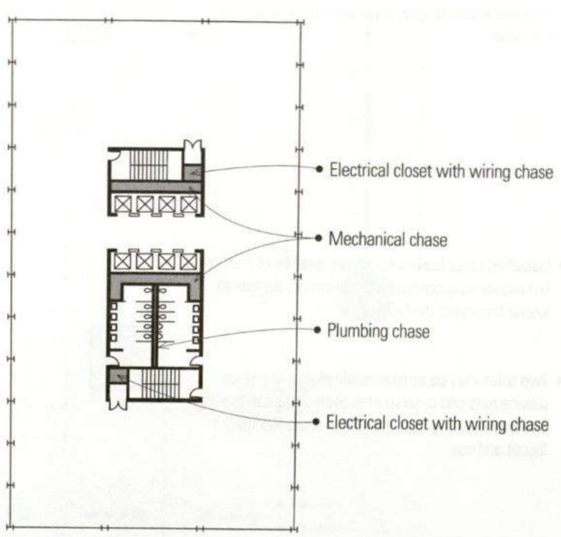

Fig. 89. Grouping of Different Types of Chases into Efficient Cores

[128] F. D. K. Ching, N. Onouye, D. Zuberbuhler, *Buildings Structures Illustrated*, 2013, 285.

Risers with wet services, telecommunication risers and those carrying electrical power should all be physically separated from one another. Data and voice communication should each have a separate riser. Moreover, a communication room (at least 2x1 meters / 3.3x 6.6 feet) should be provided for every 500-1,000 m2 (5,382-10,764 ft2) of floor space and these rooms should be positioned so that the length of their cables do not exceed 90 meters (295 feet). Usually, pipework risers are adjacent to the toilet areas. In taller buildings, or where the water service pressure is simply low, the water is pumped up and stored in a tank at the building top for gravity downfeed and it can also be used as a reserve for fire-protection systems.[129]

About 1.5-2 percent of the Gross External Area (GEA) on a typical floor is made up of the M&E service risers and there should be at least two different riser locations in order to secure resilience in case there is fire in the building or any other major problem.[130]

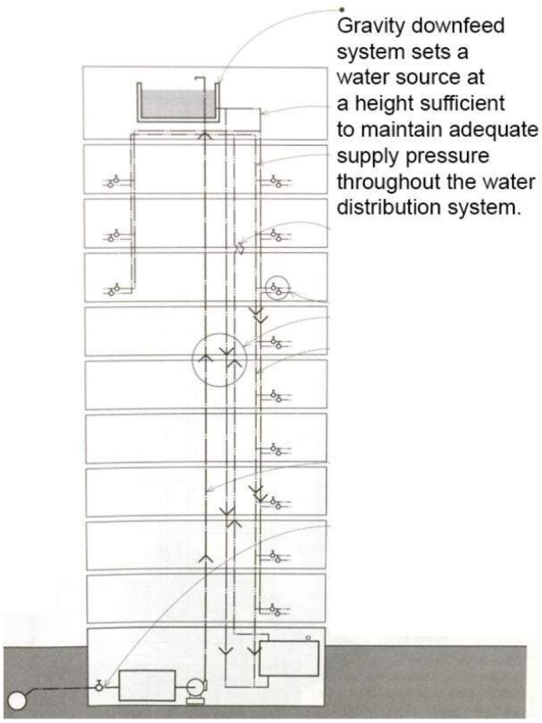

Fig. 90. Water Stored in a Tank at the Building Top

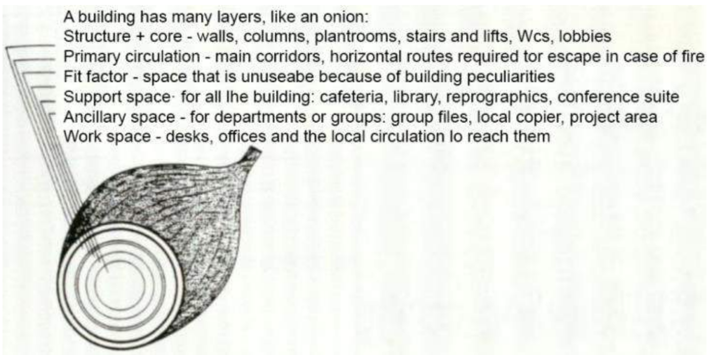

Fig. 91. Building Layers

2.4 Material

Steel used to play a main role in the history of tall building's structure. It allowed partial prefabrication, longer floor spans, reduced site work, provided a rapid building erection and had a high strength-to weight ratio, too, although it needs fire protection, rust protection and requires diagonal bracing.

[129] Ken Yeang, *Service Cores*, 2000, 52.
[130] Ken Yeang, *Service Cores*, 2000, 52.

Later on, the combination of different materials was able to achieve the same or better results, however with increased economy. High rise cores started to be constructed of reinforced concrete walls rather than stiffening them by a steel structure. This led to a self-supporting, stiff and stable core to which the building's outer frame is attached, which might be concrete or steel.[131]

Further innovations and refinements of new forms along with the development of high-strength, and furthermore very high-strength concrete with steel fiber reinforcements, resulted in a width decrease of building structure elements such as skinnier columns or cores. Thus, the building construction also became faster and this was further supported by technologies that allowed concrete to be pumped higher and higher. Whereas in 1960, a building with 20 stories was considered to be the tallest concrete structure, a couple of decades later, concrete was the material of some of the tallest buildings in the world. After its completion in 2009, the Trump Tower in Chicago became the high rise with the highest residence in the word, which record was overtaken by the Burj Khalifa in 2010. Both buildings were constructed by concrete and the Burj Khalifa in Dubai is the tallest building of the world today.[132]

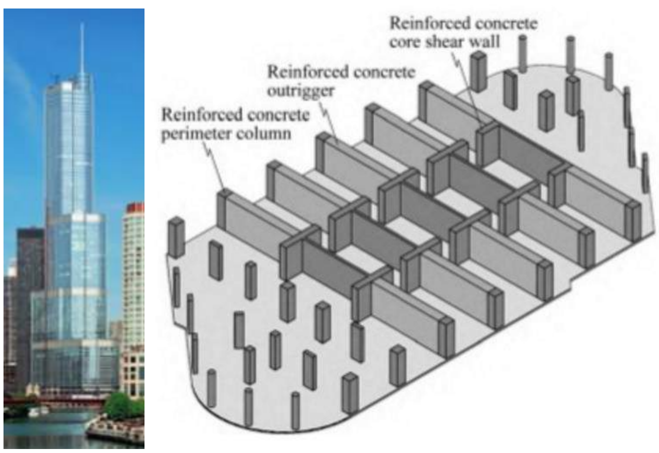

Fig. 92. Concrete Structure of the Trump Tower, Chicago

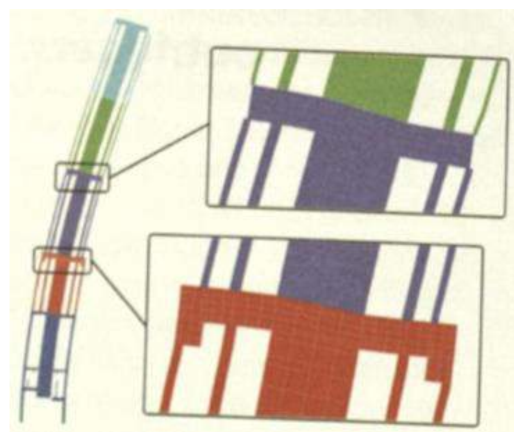

Fig. 93. Core-Outrigger Diagram of the Trump Tower

In the contemporary high rise architecture, composite systems, also known as mixed mode systems, from reinforced concrete and steel, are used as the most common structural materials of tall buildings. In this system, steel and concrete are implemented in ways that use each material to its advantage.

Structures are often divided into two subsystems as horizontal and vertical framing. Vertical elements can be both steel and concrete. Concrete is very economical in compression and vertical elements are usually dominated by vertical compression. Vertical elements of concrete such as columns are larger and heavier than the same elements from steel, thus reducing the useful floor area. However, concrete is only 1/5 to 1/8 the cost of steel when used for carrying compressive loads. Therefore, the loss of floor area is sometimes offset by the financial compensation. [133]

[131] Ken Yeang, *Service Cores*, 2000, 23.
[132] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 55.
[133] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 220.

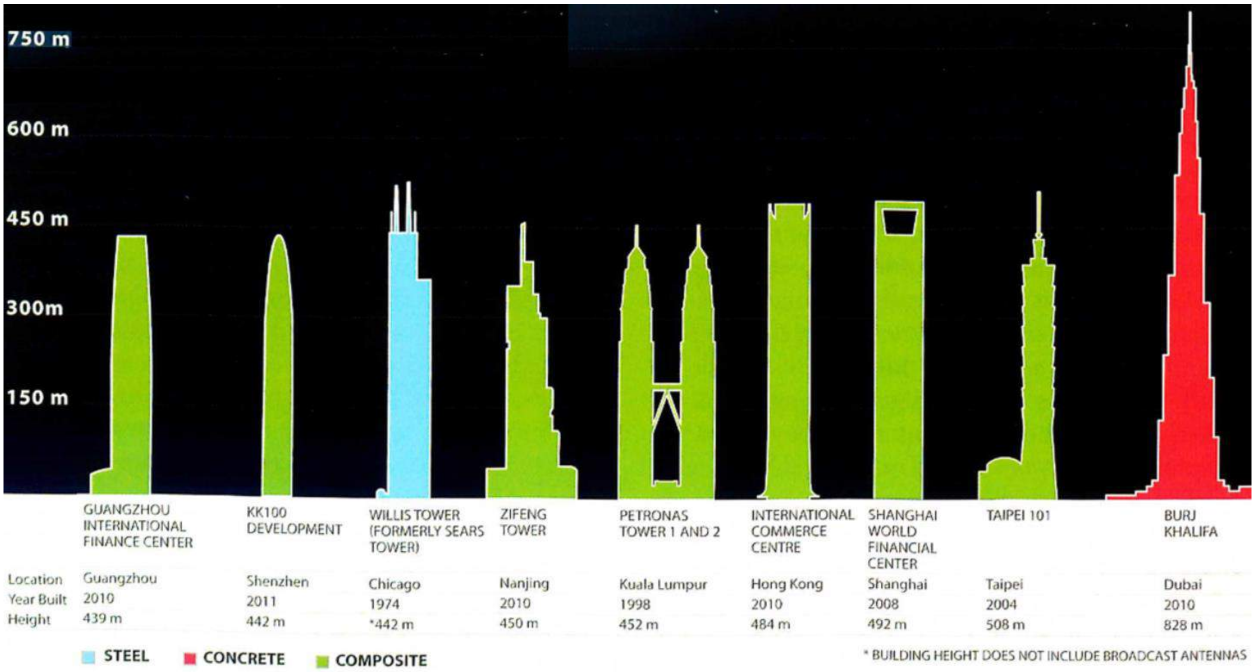

Fig. 94. Structural Materials of the World’s Tallest Buildings

There are different ways how concrete and steel systems are integrated; however, the usual system is based on a reinforced concrete core. The core is then encompassed by structural steel floor framing where concrete or steel columns are placed on the building’s perimeter. For enhanced stability or with the increment of slenderness, outriggers and belt trusses are added to connect the core to the perimeter columns and in some cases to composite mega columns.[134]

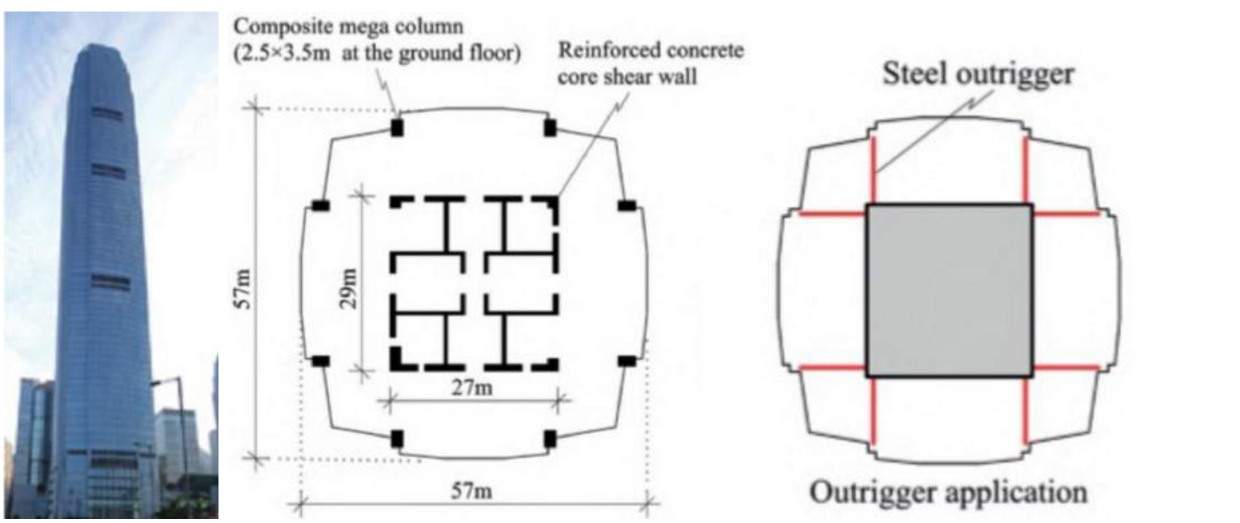

Fig. 95. Steel and Reinforced Concrete Construction of the Two International Finance Center, Hong Kong

[134] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 219.

2.5 Evacuation

2.5.1 Staircase

According to the International Building Code (IBC), a multiple story building with an occupant load of 500 people or less for each story, needs to provide at least two exits for every story. Furthermore, if the building height exceeds 61 meters (420 feet) then a third staircase is needed. In case the building has an occupant evacuation elevator then the additional staircase is not required.[135]

There is also a remote requirement stating that the interior exit stairways should be separated by a distance not fewer than 9 meters (30 feet) or by a quarter of the building's overall diagonal. That distance is applied to whichever is shorter. If the high rise possesses three or more staircases, then at least two of them should correspond with the remoteness requirement. In case, interlocking stairs are located in the building, these will be counted as a single staircase.[136]

2.5.2 Informative Fire-Warning System

Standard fire-alarm systems are not able to give more information to the occupants than that there is a fire somewhere in the building. However, the succesful evacuation of occupants depends on early fire detection and the communication to the people about the exact fire location, its size and possible spread characteristics. These requirements are met by the computer-based Informative Fire-Warning systems (IFW). IFW provides the occupants different messages, including the location, severity, if there is a need for evacuation or not and the exit route suggested to be used.[137]

2.5.3 Egress Elevator

In general, people are taught to not use elevators but to use the stairs during a fire. However as high rises get taller and taller, total building evacuation by using only staircases, might be very difficult. Long stairs may be challenging for mobility occupants, elderly people or small children. Using elevators can make the evacuation significantly more efficient. In 2001, about 3,000 people exited safely from the WTC2 using the elevators what was much faster than the WTC1's evacuation in which elevators were damaged and inoperable. Today there is an option to apply egress elevators in a tall building which are able to operate during fire in some portion of the building.[138] As mentioned above, IBC allows the use of occupant evacuation elevators instead of an additional exit stairway above a building height of 61 meters (420 feet).[139]

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[135] http://specsandcodes.typepad.com/the_code_corner/2013/02/high-rise-buildings.html Accessed August 2016

[136] http://specsandcodes.typepad.com/the_code_corner/2013/02/high-rise-buildings.html Accessed August 2016

[137] D. Sfintesco, *Fire Safety in Tall Buildings*, 1992, 82.

[138] E. M. Camiel, *Occupant Evacuation Operation of Elevators*, 2015, 8.

[139] http://specsandcodes.typepad.com/the_code_corner/2013/02/high-rise-buildings.html Accessed August 2016

Fig. 96. Signs Prohibiting the Elevator Use in Case of Fire

This type of elevator has all the necessary components to resist fire such as water-tolerant parts, pressurized shafts, extra power supply, refined ways to communicate with riders and special smoke-protection mechanisms. Egress elevators automatically stop slightly higher than the floor level avoiding water entrance to the cab from the sprinkler system. These kinds of elevators are used more and more in different parts of the world including the Middle East, Asia or the United States (e.g., Stratosphere Tower in Las Vegas).[140]

A study, using Pathfinder which is an evacuation simulator based on the technology of gaming and computer graphics industries, focuses on tall building evacuation utilizing a combination of stairs and egress elevators. According to the study, both the rise of the elevator speed and the number of elevators significantly reduce the evacuation times. However, this reduction is not as much of a speed enhancement as it is an effect of an increase in the elevator number. The research also points out that the selection of a proper percentage of occupants (e.g., by the IFW) evacuated by elevators is crucial to reach minimum evacuation times. If elderly people, who are not as fast as younger people, are evacuated by stairs then congestion might develop in the staircase. The elevator’s utilization rate is improved when children are evacuated with them. Thereby, the selection of children and elderly people for egress elevators can speed up the evacuation process and reduce stair congestion. Further results show that the evacuation with an order going from lower floors to upper ones can significantly decrease congestion caused by aged people and means a faster evacuation rate.[141]

As a conclusion, it should be noted that the high rise full evacuation is most effective in the case of considering different occupant ages, and with both the staircases and emergency elevators being used.

[140] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 136.

[141] Y. Ding, L. Yang, F. Weng, Z. Fu, P. Rau, Natural ventilation and temperature conditions in some high-rise building flats in Bandung and Jakarta in perspective of adaptiv, 2015, 72.

2.5.4 Rescue Area

Some countries require rescue areas or refuge floors within the high rise. They are usually located on the mechanical floors and are equipped with different safety systems such as providing a steady stream of fresh air and maintaining emergency lighting for at least two hours. These protective zones give occupants enough time to transfer to another set of stairs or to rest and wait for rescue personnel. These safety zones can be provided with egress elevators, too. However, in order for proper use of these rescue areas and for a successful evacuation strategy, occupants must have relevant training and evacuation exercises.[142]

2.5.5 Evacuation from Outside

Although Collapsible Escape Pods seem like an exotic solution, it is an existing and operable system for occupants to be rescued from outside the building. Escape is possible through a set of external elevator units stored on the rooftop. In case of an emergency, five collapsible escape pods swing out over the roof edge, go down to the ground level and expand. Each of these pods is able to carry 30 people at the same time. After the evacuees safely arrive on the ground, the pods ascend to the top again in order to pick up more people. Theoretically, such an up-down cycle can be repeated about every 8 minutes.[143]

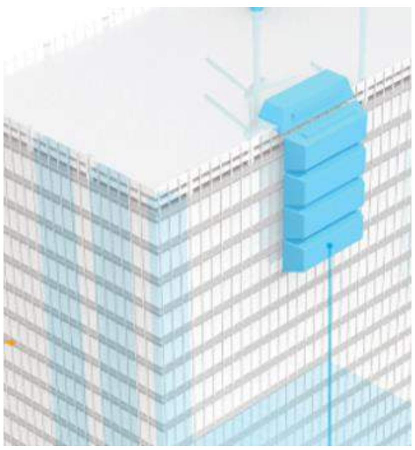

Fig. 97. Collapsible Escape Pods at the Building's Top

Fig. 98. Collapsible Escape Pods Descending Down

2.6 Logistics

Building logistics is not negligible in high rise design and should be taken care of in the Back of the House. The logistics include the proper design of loading docks for truck deliveries and waste disposal, which are usually located within the building's boundary (e.g., on the ground floor or in the basement) or at an adjacent building location. The use of signage systems is available to alert truck drivers when open truck docks are accessible to warn of traffic congestion that can be avoided at the loading bays. The location of these spaces is important as a large amount of a

[142] Johann Eisele, *High-rise Manual: Typology and Design, Construction and Technology*, 2002, 209.
[143] Willie D. Jones, *How to build a mile high skyscraper*, 2007, 53.

building's waste should be transported away outside the public's view on a regular basis. Loading docks need to be accessible for building tenants, since move in and out activities happen here as well.[144]

Fig 99. Signage System for Truck Drivers

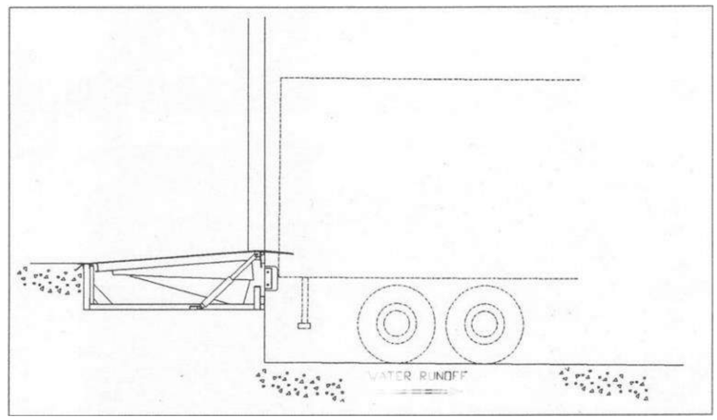

Fig. 100. Truck Loading Dock

2.7 Occupant's Comfort

An occupant's physical comfort in an indoor environment is quite complex and depends primarily on thermal, visual influences but also on their knowledge about surrounding building systems, as well as, on social, cultural habits.

2.7.1 Thermal Comfort

Thermal comfort is used to give information about a person's thermal state within a thermal environment. It indicates whether this individual feels too cold, too hot or is satisfied in the given environment. Thermal comfort is influenced by humidity, air velocity, air temperature and mean radiant temperature. However, non-environmental factors have impacts on them such as gender, age, clothing and metabolic activity. It is important to note that comfort is not an absolute state but a set of these conditions that the majority of people interpret as acceptable (e.g., the ASHRAE's comfort standard which is called "Standard 55" aims to satisfy 80 percent of the occupants). Conventional tall buildings are usually mechanically controlled and provide thermal comfort to only 80 percent of the occupants, thus the rest will probably feel uncomfortable at some point during the day.[145]

The human body has the ability to regulate its own temperature in the range between 36.6 and 37.8 °C (98 and 100 °F). The following describes environmental conditions in which the human body remains in a comfort state: if the air velocity ranges between 0.1 and 0.3 meter per second (20 and 60 foot per minute), the air temperature is between 20 and 25 °C (68 and 78 °F) and the relative humidity ranges from 20 to 60 percent in the summer, and from 20 to 80 percent in

[144] Lerch Bates, *Vertical Transportation and Logistics in Mixed-Use High-Rise Towers*, 2012, 4.
[145] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 97.

wintertime. Previous activity or exposure can seriously affect thermal comfort perception for an estimated 1 hour, hence temporary visitors of the environment are not addressed by thermal comfort requirements. This applies also to sleeping or bed rest.[146]

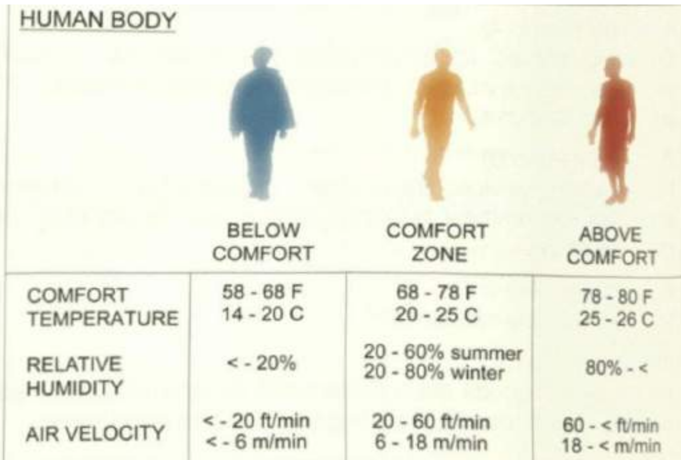

Fig. 101. Average Temperature Regulaton of the Human Body

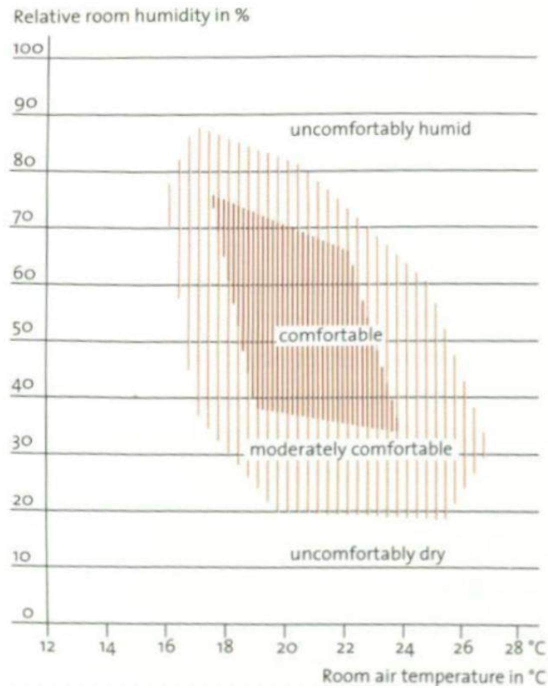

Fig. 102. Comfort Zone in Relation to Room Air Temperature and Relative Humidity in Room

2.7.1.1 Thermal Comfort Models

2.7.1.1.1 PMV-PPD Model

Today, there are a few thermal comfort models available, however, Fanger's comfort model is probably the most used and prevalent one. It is called the PMV-PPD Model using the concept of PMV, developed in the 1970s by Povl Ole Fanger who was an expert in the field of perception of indoor environment and thermal comfort, as well. This model predicts the mean thermal response of a large group of people and the respective percentage of this group's dissatisfaction with the thermal environment. This is expressed via the indices Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), according to the ASHRAE thermal sensation scale, representing very hot (+3), hot (+2), warm (+1), neutral (0), cool (-1), cold (-2) and very cold (-3). The PMV is calculated through the abovementioned six variables (i.e., air temperature, humidity etc.). After this, the PPD value can also be estimated whereas a PPD of 10 percent is in accordance with the PMV range of ±0.5. The PMV-PPD model is generally acknowledged and very often used for design and field assessment of comfort conditions in mechanically conditioned environments, thus for most of the office buildings.[147]

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[146] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 97.
[147] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 151.

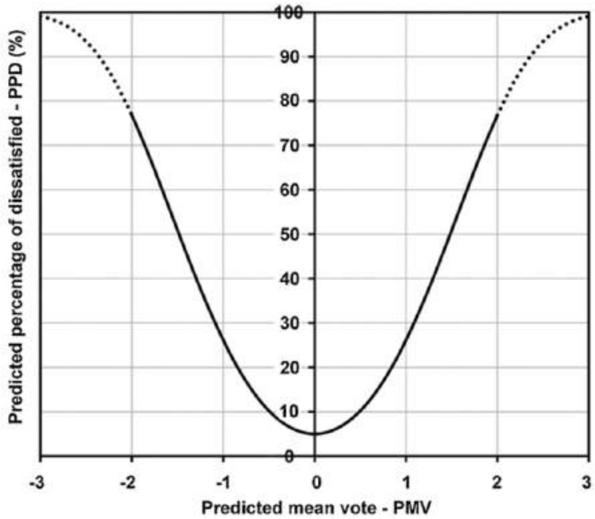

Fig. 103. Predicted Percentage of Dissatisfied (PPD) as a Non-Linear Function of Predicted Mean Vote (PMV)

2.7.1.1.2 Adaptive Model

The other meaningful thermal comfort model is the Adaptive Model which basically considers the user having an active role instead of a passive one. This means that if a change occurs in the environment which produces discomfort, people are going to try to restore their comfort.[148] This model is based on field studies of naturally ventilated buildings and is a clear shift in comparison with Fanger's method. These studies show that, even if occupants experience higher or lower temperatures, the occupants in naturally ventilated building tolerate their thermal environment far more than those in mechanically ventilated environments. It turns out that the type of conditioning system (e.g., natural-ventilation NV, air-conditioning AC) influences the users expectations with respect to their quality satisfaction of the environment. [149]

Several researchers have shown that people in NV environment are satisfied for a much wider range of thermal conditions than their peers in an environment with AC.[150] They have a different psychological perception and adaptation quality so that they are simply willing to adapt to the surrounding environment suiting their expectations, such as changing metabolic rate (i.e., drink cold or warm drink, enhance or lower their activity level), lose or gain heat (i.e., wear appropriate clothing, use of ceiling fans, doors, windows, blinds etc).[151]

Air Velocity	Probable Impact
Up to 50 ft/minute	Unnoticed.
50 to 100 ft/minute	Pleasant.
100 to 200 ft/minute	Generally pleasant, but causes a constant awareness of air movement.
200 to 300 ft/minute	From slightly drafty to annoyingly drafty.
Above 300 ft/minute	Requires corrective measures if work and health are to be kept in high efficiency.

Fig. 104. Effect of Air Movement on Occupants

148 R. F. Rupp, N. G. Vasquez, R. Lamberts, *A review of human thermal comfort in the built environment*, 2015, 2.
149 S. Attia, S. Carlucci, *Impact of different thermal comfort models on zero energy residential buildings in hot climate*, 2015, 119.
150 R. F. Rupp, N. G. Vasquez, R. Lamberts, *A review of human thermal comfort in the built environment*, 2015, 2.
151 S. Attia, S. Carlucci, *Impact of different thermal comfort models on zero energy residential buildings in hot climate*, 2015, 119.

A study in Singapore indicates that the neutral temperature for a NV building was found to be 28.5°C (83.3°F) while an AC building in the same environment was 24.2°C (75.6°F). According to another study, the upper temperature bound in a Thai NV office building should be 31°C (87.8°F) instead of 28.5 °C (83.3°F) which would indicate those using AC.[152] It seems obvious that dissatisfaction of people with certain climatic conditions mainly results from their negative view of the mechanical equipment usage and the lack of or limited personal control.

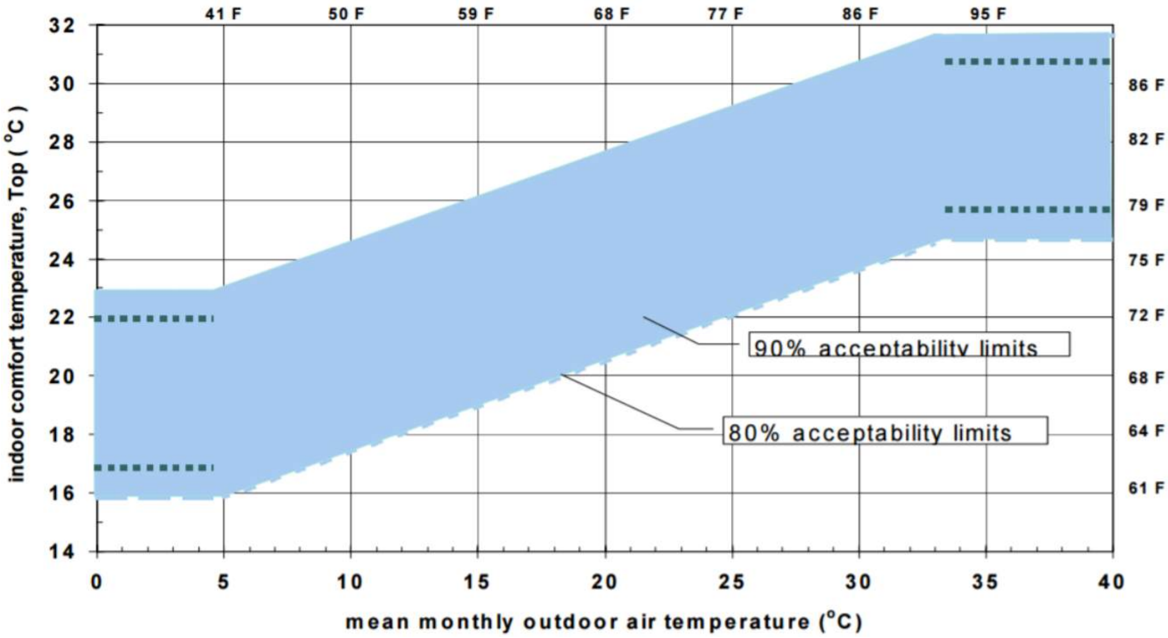

Fig. 105. Adaptive Model for Thermal Comfort

2.7.2 Occupant's Control

Studies have shown that people are much less satisfied if they have no control of their environment. As soon as they have access to control, though, they feel more satisfied. However, in order for this to work they need to understand specific strategies, corresponding behaviors of how to interact with the building systems in a way that it supports not only their personal comfort but also the building's energy efficiency. Hence, occupants need guidance and additional training since a lack of knowledge surrounding building systems might mean a barrier to understanding these things. [153]

Data were collected from about 56 buildings in North America and Europe assessing occupants' satisfaction with their environment.[154] There were two groups of people. The first group (G1) received training on the building system control (i.e., thermal control, natural ventilation, etc.), whereas the second group (G2) did not receive any training. This research showed that there is a much higher chance for dissatisfaction by those people participating in G2. Thus people with

152 A. Mahdavi, S. Kumar, *Implications of indoor climate control for comfort, energy and environment*, 1996, 174.
153 J. K. Day, D. E. Gunderson, *Understanding high performance buildings*, 2014, 116.
154 J. K. Day, D. E. Gunderson, *Understanding high performance buildings*, 2014, 118.

knowledge about their building system were widely more satisfied since they were able to manipulate their environment to adjust thermal and visual comfort.

In a lot of cases, high performance buildings are also equipped with signaling systems that notify the occupants when conditions are appropriate for human intervention (e.g., opening windows manually).[155] Clearly in this situation active occupant engagement is required hence it is essential that the person is trained on these systems and possesses the proper knowledge for using them.

2.7.3. Social Influence

In case one's actions are influenced by the actions of someone else, we can talk about social influence which can have an impact on the occupant's comfort. As reported by an assessment, a worker in an office building remained uncomfortable in the mornings by sun glare since he or she did not want to disturb the coworkers with changing the blinds. It seems that the culture in this environment did not encourage social interactions, whereas, in another building it was normal for coworkers to discuss with the others when they were feeling uncomfortable in the room and before intending to open a window, closing the blinds or turning down the AC. In this case there is an interactive office culture that tries to maintain comfort for all of its occupants. [156]

After a survey of numerous field studies considering experiences over the past decades it was found that the neutral temperature preferred by most people ranges between 17 and 30°C (62.6 and 88 °F). According to different research conducted in three countries with similar household incomes and energy prices, the indoor temperature preferences were given to be from 21°C (57.2°F) in Sweden, 17°C (62.6°F) in Norway and only 14°C (69.8°F) in Japan. In another study, the preferred air temperature in a NV building in Bangladesh was found to be 28.9°C (84.02°F). In conclusion, one can see that there is a clear influence on the occupant's indoor comfort perception through the culture and social influences.[157]

2.7.4. Visual Comfort

Daylight is very important for high performance buildings though it is variable by nature and changes very often, depending on the sun's angle and weather conditions. Therefore, it is crucial that people are able to control the blinds, shades or similar coverings of their windows. A lot of office buildings use daylight as a passive design strategy since studies show that natural light not only enhances occupants' satisfaction and productivity but also improves health conditions. Many studies point out that occupants simply perform better in environments with daylight compared to those who only have electric lights. Access to views and natural light are strongly connected with stress reducing and improved mood. It also decreases headaches, fatigue and improves overall well-being. On the other hand, if there is too much of it or the blinds are not used appropriately, it might lead to glare issues, which can have consequences such as eye-strain or migraine headaches.[158]

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[155] J. K. Day, D. E. Gunderson, *Understanding high performance buildings*, 2014, 116.
[156] J. K. Day, D. E. Gunderson, *Understanding high performance buildings*, 2014, 122.
[157] A. Mahdavi, S. Kumar, *Implications of indoor climate control for comfort, energy and environment*, 1996, 174.
[158] J. K. Day, D. E. Gunderson, *Understanding high performance buildings*, 2014, 116.

3. Mixed-Use High Rise Building

3.1 Definition

In case a tall building's total floor area is dedicated to a single use only (e.g., office space), according to the Council on Tall Buildings and Urban Habitat (CTBUH), it is called a single-function tall building, whereas a mixed-use tall building comprises at least two uses/functions such as hotel rooms, apartments, office spaces etc. Each of these functions have to comprise a minimum of 15 percent of the building's total space. This is not entirely the case for "supertall" towers though where a 20 story residential use of a 150-story high rise doesn't coincide with the abovementioned rule, however, where this building would still live up to be called a mixed-use high rise.[159] Other sources mention at least 2, 3 or more real estate uses which are in separate sections of the same building though functionally and physically integrated in one single property.

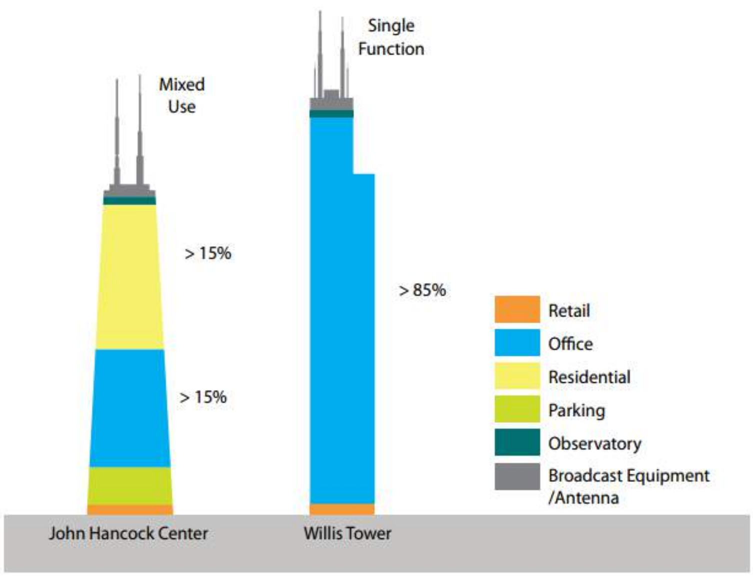

Fig. 106. Single-Function Tall Building and Mixed-Use Tall Building According to CTBUH

3.2 History

Mixed-use tall buildings first appeared in North American cities in the 1960's. Among the earliest of this kind of development was most likely Penn Center in Philadelphia, followed by buildings such as the Midtown Plaza in Rochester, New York and the Prudential Center in Boston.[160] Mixed-use towers evolved as an option for the necessities of more and more increasing urban densities in cities. Often these structures are considered as a solution for helping urban areas which are "lifeless" during non-working hours through the addition of new residential, hotel, hospitality or

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[159] CTBUH, *Criteria for the Defining and Measuring of Tall Buildings,* 4.

[160] Dean Schwanke, *Mixed-use development handbook*, 1987, 18.

recreational activities.[161] Until the last turn of the century, the big majority of the world's high rises were office buildings, however, there has been a significant turn since then and it has shifted toward residential and even more substantially toward mixed-use functions.[162]

3.3 Function

Mixed-use high rises mean extreme management, planning and capital resources to deal with from a business point of view, although developers look at these projects as financially attractive and less risky for several reasons. Firstly, there is a synergy between the uses. If a person wants to live near where he or she works, this person is more likely to get a space leased in this environment by the employer. If this person is present not only during the day as a worker but at night as well, then this favors also the restaurants, shops which want to be nearby to provide their service. This is true the other way around too since people want to live where they are close to work, shops and entertainment possibilities, so the loop is closed. It is a win-win situation for everyone. Secondly, the risk is lessened as project success depends on multiple uses instead of a single one. For instance, even if there is a low request for hotel rooms, demand for retail and office space might be still significant. Furthermore, sustainability is enhanced through the reduction of commutes, travel distance, vehicle use or similar resource demanding activities. A few trucks are able to gather the trash from a large amount of tenants, workers, restaurants etc. instead of driving endless distances with many more vehicles to assemble the same amount of waste in other urban or suburban arrangements as they normally do. This is a significant factor for sustainability.[163]

Fig. 107. Midtown Plaza in Rochester, New York

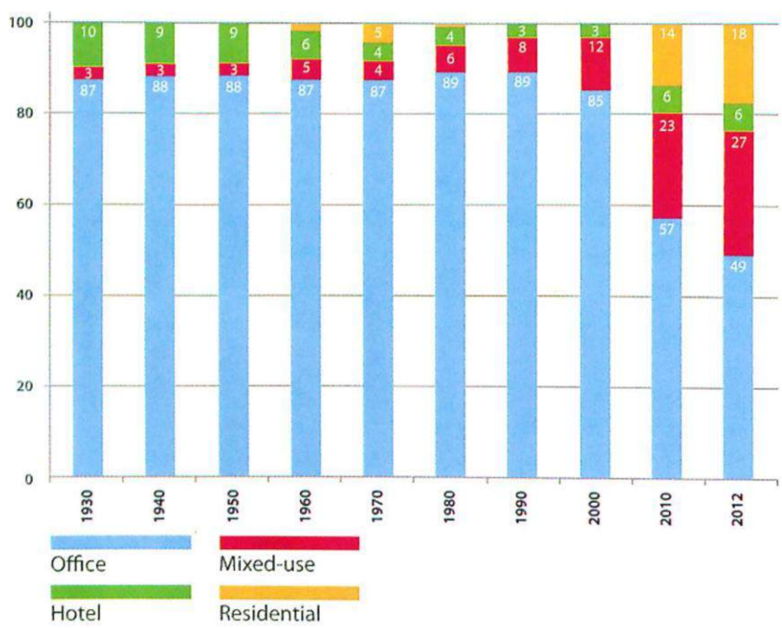
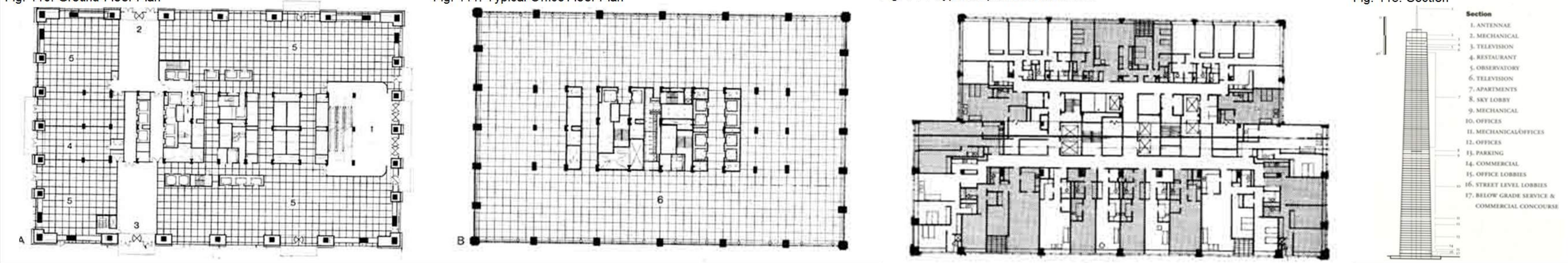
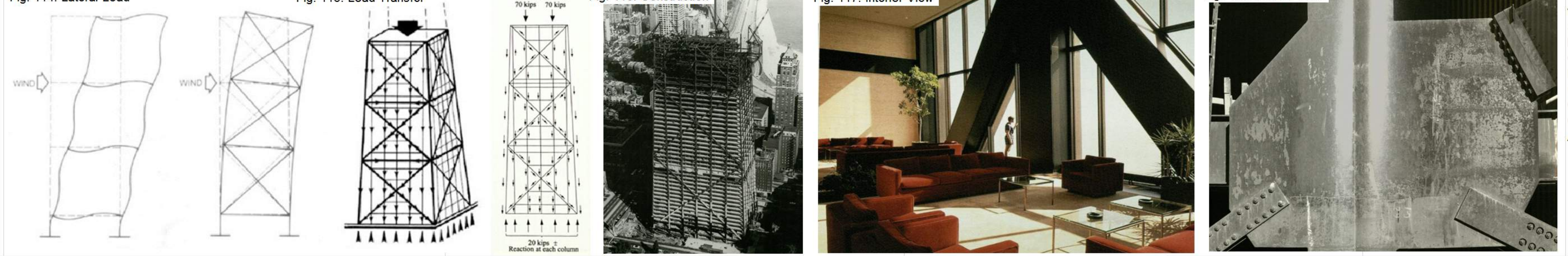
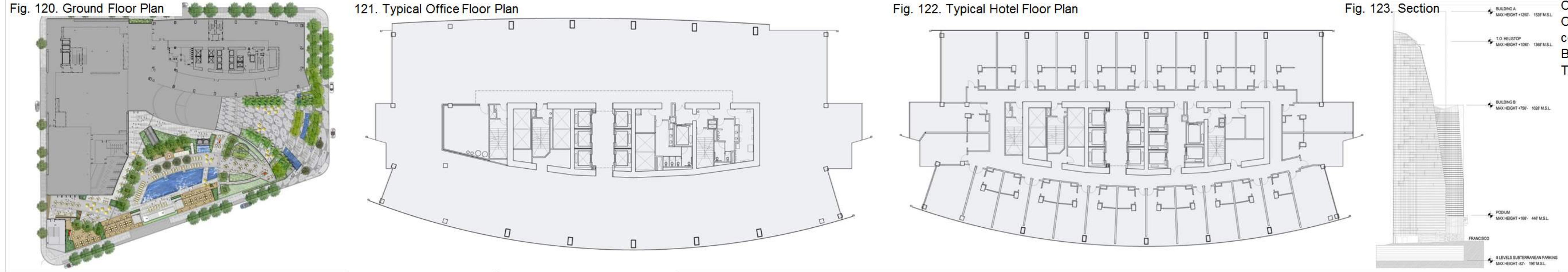
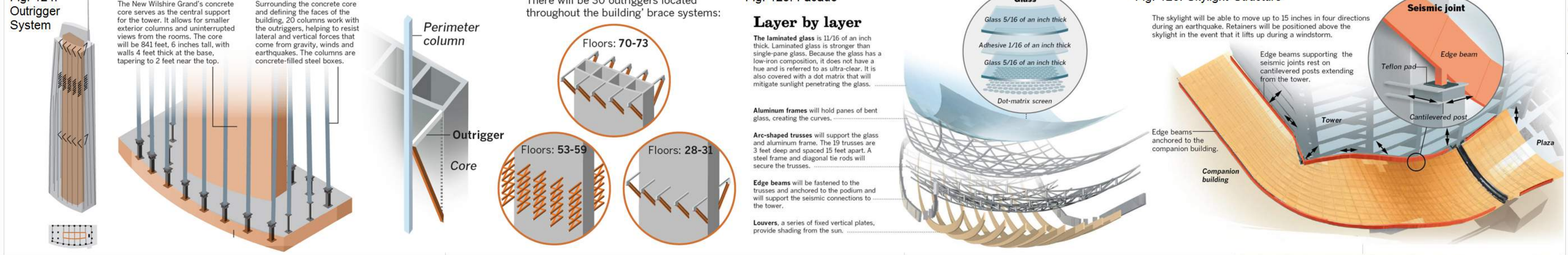
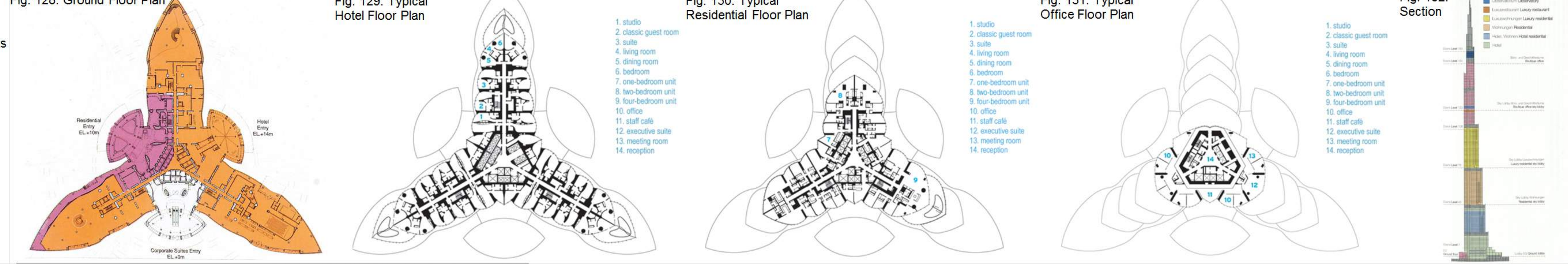
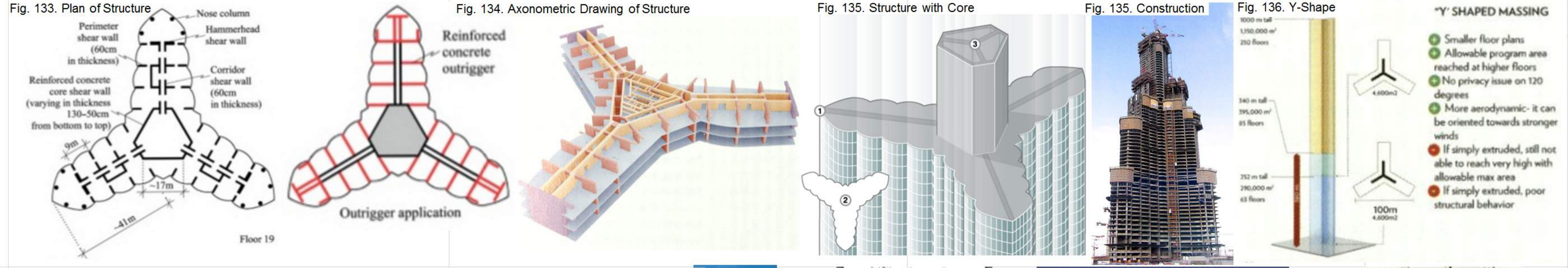
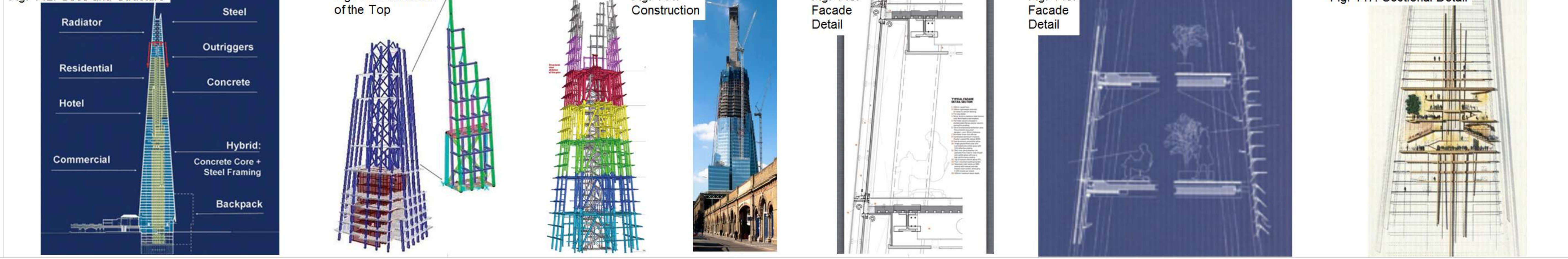


Fig. 108. 100 Tallest Buildings of the World by Function between 1930 and 2012

[161] Dean Schwanke, *Mixed-use development handbook*, 1987, 46.
[162] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 54.
[163] Lerch Bates, *Vertical Transportation and Logistics in Mixed-Use High-Rise Towers*, 2012, 5.

3.4 Mixed-Use High Rise Precedents

Photo	Building	Place	Year	Story / Height	Form	Use	Plans	Structure		Other Features
	John Hancock Center Fig. 109. J. H. Center	Chicago USA	1970	100 stories 342 meters 1,127 feet	Slender, linear upward tapering obelisk	Retail Office Apartments	Fig. 110. Ground Floor Plan Fig. 111. Typical Office Floor Plan Fig. 112. Typical Apartment Floor Plan Fig. 113. Section 	Tubular system X-braced steel exterior The X-bracing is generally 20 stories high[163] No inner support beams needed Mechanical floors coincide with the intersections of the diagonals and the corner columns[164] The outer skin of high-density black aluminum contrasts with glare-proof, bronze glass windowpanes[165]	Fig. 114. Lateral Load Fig. 115. Load Transfer Fig. 116. Construction Fig. 117. Interior View Fig. 118. Interior View 	Observatory on the top of the building that is home of the world renown tourist attraction, 360° Chicago Swimming pool on the 44th floor that is America's[166] highest indoor pool Garden plaza Fitness center Ice rink[167] Own post office Own refuse collection Art galleries[168]
	Wilshire Grand Center Fig. 119. W. G. Center	Los Angles USA	2017	73 stories 335 meters 1,100 feet	Sail-shaped	Retail Office Hotel	Fig. 120. Ground Floor Plan 121. Typical Office Floor Plan Fig. 122. Typical Hotel Floor Plan Fig. 123. Section 	Concrete core with outrigger system Outriggers form giant triangles and extend from the core to the perimeter columns Belt trusses and column covers are aluminium clad The building incorporates high performance glass[169]	Fig. 124. Outrigger System Fig. 125. Facade Fig. 126. Skylight Structure 	Sky lobby with infinity pool Observation deck on the top[170] It is configured to maximize views of Santa Monica, the Pacific Ocean, the Hollywood Hills and LA's sunset The tallest building west of Chicago[171]
	Burj Khalifa Fig. 127. Burj Khalifa	Dubai UAE	2010	163 stories 828 meters 2,717 feet	Y-shape The three wings allow maximum outward views and inward natural light	Retail Residencies Hotel Luxury Apartments Office	Fig. 128. Ground Floor Plan Fig. 129. Typical Hotel Floor Plan Fig. 130. Typical Residential Floor Plan Fig. 131. Typical Office Floor Plan Fig. 132. Section 	Bundled tube system Three wings are arranged around the central core[172] Setbacks occur in a spiraling pattern on the facade as the building reaches toward the sky The core is buttressed by the three wings that form the Y-shape[173] Special mixes of concrete are used in order to withstand the extrem pressures of the building weight[174] The facade consists of reflective glazing, aluminium and textured stainless steel spandrel panels with vertical tubular fins The cladding system withstands the locality's extrem hot temperatures[175]	Fig. 133. Plan of Structure Fig. 134. Axonometric Drawing of Structure Fig. 135. Structure with Core Fig. 135. Construction Fig. 136. Y-Shape 	Tallest building in the world[176] The site has 110,000 m2 (1,184,030 ft2) of greenery and water features It also includes two tennis courts, the Dubai's fountain, a children's playground and wading pool 4 story fitness and recreation annex[177] Highest outdoor observation deck in the world Elevator with the longest travel distance in the world[178] Double decker elevators Exclusive sky lobbies with jacuzzis House swimming pools Gourmet market Resident's library[179]
	The Shard Fig. 137. The Shard	London UK	2012	87 stories 310 meters 1,016 feet	The form of a "shard" refers to the spires of London's churches and the masts of the tall ships that used to ship on the Thames River[178]	Retail Office Hotel Residences	Fig. 138. Ground Floor Plan Fig. 139. Typical Office Floor Plan Fig. 140. Typical Hotel Floor Plan Fig. 141. Section 	Steel framing around vertical concrete core Mid-level steel outrigger[179] Post tensioned concrete frame through the apartments and hotel levels[180]	Fig. 142. Uses and Structure Fig. 143. Structure of the Top Fig. 144. Construction Fig. 145. Facade Detail Fig. 146. Facade Detail Fig. 147. Sectional Detail 	Tallest building in Europe[181] Observatory deck on the building's top Winter gardens at the ground level[182]

[163] Mario Campi, Skyscrapers - An architectural type of modern urbanism, 2000, 76.
[164] I. Abalos, J. Herreros, Tower and Office, 2002, 236.
[165] Mario Campi, Skyscrapers - An architectural type of modern urbanism, 2000, 76.
[166] David Bennett, Skyscrapers form and function, 1995, 62.
[167] G. Binder, Sky High Living - contemporary high-rise apartment and mixed-use buildings, 2002, 21.
[168] Andres Lepik, Skyscrapers, 2004, 88.
[169] http://graphics.latimes.com/wilshire-grand-earthquakes/ Accessed May 2016
[170] http://www.wilshiregrandcenter.com/images/WG_Design_Fact_Sheet_2_5_13.pdf May 2016
[171] http://www.skyscrapercenter.com/building/wilshire-grand-center/9686 May 2016
[172] P. C. Schmal, M. Busenkell, Best High Rises 2010-11, 2010, 68.
[173] David Parker, Antony Wood, The Tall Buildings Reference Book, 2013, 465.
[174] Terri Meyer Boake, The evolution of tall buildings in the Gulf, From the sensational to the Sensitive, 2015, 61.
[175] David Parker, Antony Wood, The Tall Buildings Reference Book, 2013, 465.
[176] Terri Meyer Boake, The evolution of tall buildings in the Gulf, From the sensational to the Sensitive, 2015, 55.
[177] Kate Ascher, The heights - Anatomy of a skyscraper, 2011, 184.
[178] http://news.bbc.co.uk/2/hi/middle_east/8439467.stm Accessed May 2016
[177] Kate Ascher, The heights - Anatomy of a skyscraper, 2011, 184.
[178] T. Riley, G. Nordenson, Tall buildings, 2003, 122.
[179] T. Riley, G. Nordenson, Tall buildings, 2003, 122.
[180] http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/FeaturedTallBuildingArchive2013/TheShardLondon/tabid/6020/language/en-US/Default.aspx Accessed June 2016
[181] http://www.ctbuh.org/TallBuildings/FeaturedTallBuildings/FeaturedTallBuildingArchive2013/TheShardLondon/tabid/6020/language/en-US/Default.aspx Accessed June 2016

4. Sustainability

4.1 Sustainability in General

A high rise can be considered a sustainable structure in its very existence since it optimizes the use of limited land resources. However, climate change is one of the biggest challenges of our modern world and it is generally known that the built environment is a great contributor to global greenhouse gas emissions. The construction and building industry make up more than one-third of the world's energy consumption. This is mainly comprised of cooling, heating, lighting and ventilation.[183]

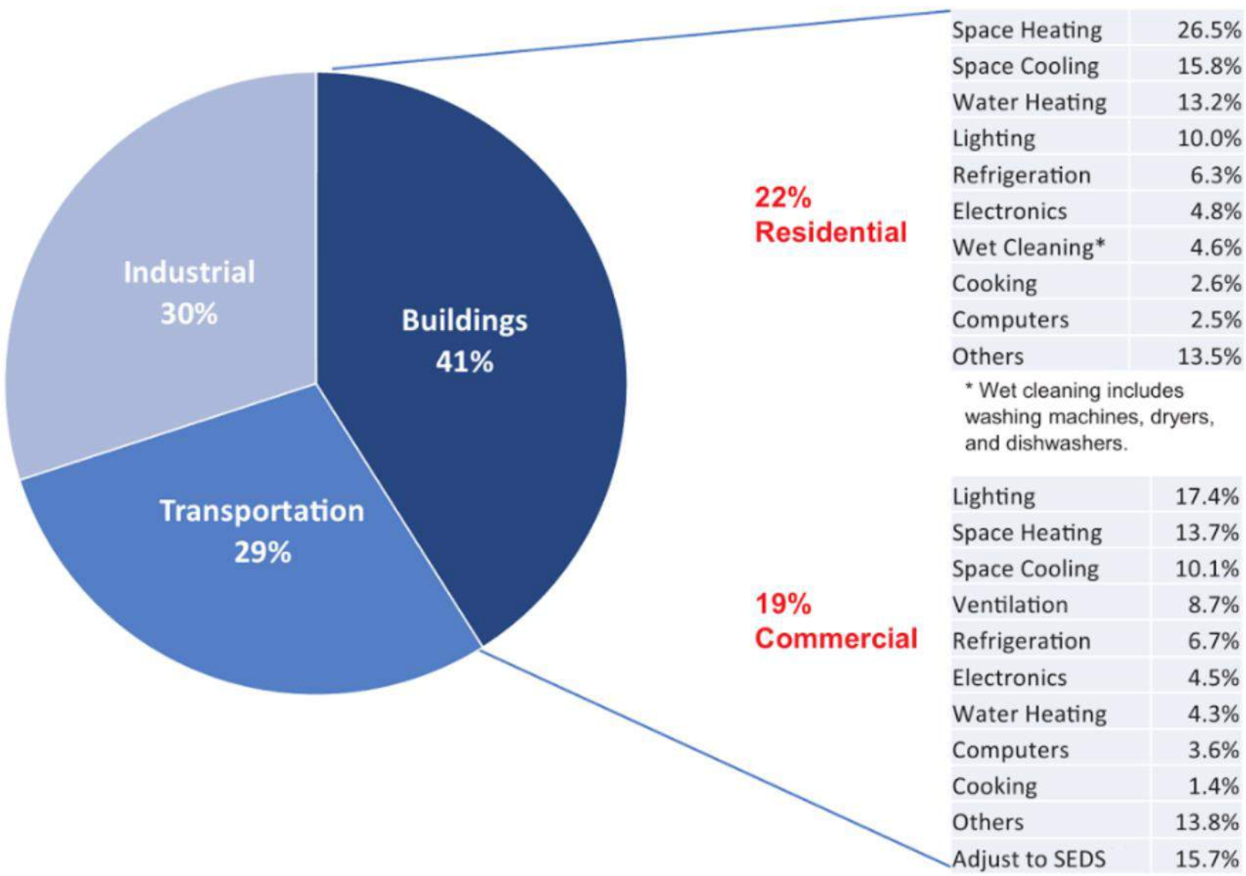


Fig. 148. Energy Use by the Building Sector

For this reason, high rises can play a crucial role in mitigating energy consumption by utilizing renewable energies, new ideas and energy efficient design strategies. Sustainability and ecological design of high rises are even more important than those of ordinary low-rise buildings since they have a much larger scale and greater material and energy usage.

[183] K. Al-Kodmany, *Eco-Towers Sustainable Cities in the Sky*, 2015, 54.

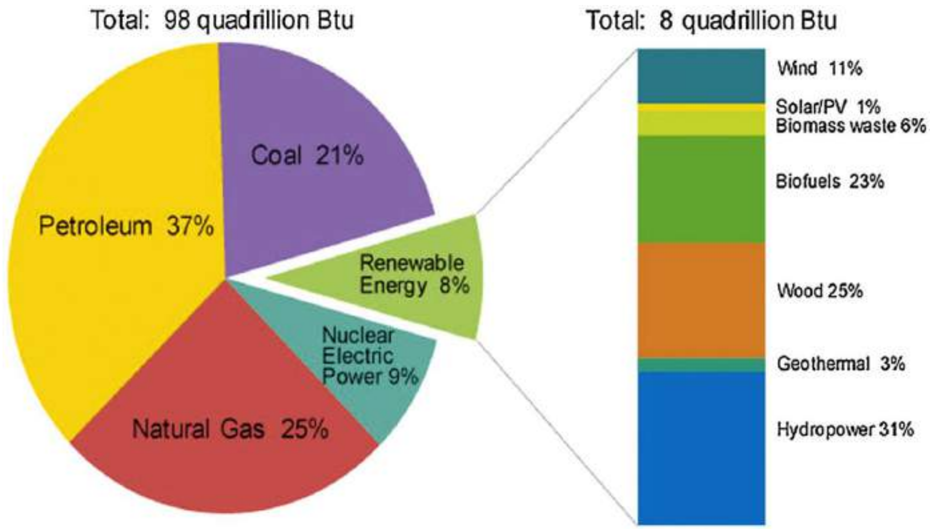


Fig. 149. Energy Usage Sources of the World

Utilizing renewable energy is a significant factor in this game and it is essential for development. In contrast to fossil fuels, it causes far less or no pollution at all to the environment. Furthermore, it is abundant and can be found everywhere in the world though today it constitutes merely around 8 percent of the world's energy demand. Sun provides the largest renewable energy source on earth and offers us inexhaustible, clean energy potential. [184] The annual amount of sun energy highly exceeds the total estimated fossil resources. USA, Africa most parts of Latin America, China and India all have good to excellent solar resources. The average annual solar energy received in Europe is about 1,200 kWh/m2 (380,398 Btu/ft2) whereas it is 1,800-2,300 kWh/m2 (570,597-729,096 Btu/ft2) in the Middle East. Even though the situation is different in Canada, Russia, Northern Europe or Alaska, these regions with cold or temperate climates still have a great amount of wind power to exploit. In the future, we need to learn how to utilize renewable energy more effectively and design sustainable, bioclimatic buildings more efficiently.[185]

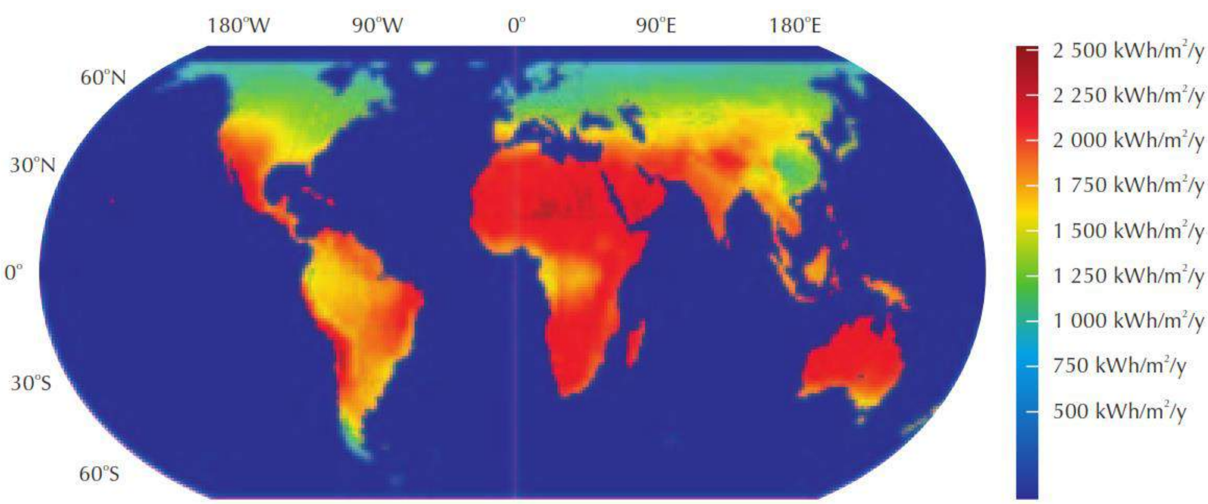


Fig. 150. The Global Solar Flux (in kWh/m2/y) at the Earth's Surface over the Year

[184] P. Lotfabadi, *Solar considerations in high-rise buildings*, 2015, 186.
[185] International Energy Agency, *Solar Energy Perspectives*, 2011, 38.

4.2. High Rise Building Development Based on Energy Consumption

In this section, five chronological generations are analyzed with respect to how energy use in the high rise building developed from its origins in the late 1800s to the current days.

4.2.1 First Energy Generation High Rises

The Home Insurance Building in Chicago, completed in 1885, is generally considered to be the first high rise thereby this is consdered the date of the high rise birth and also the first energy generation is counted from here. The first energy generation of tall buildings needed a relatively small amount of operational energy since technologies like fluorescent lighting and air conditioning were not yet invented. Artificial lighting levels were low as technologies of the time were not efficient enough yet, this usually meant 22-43 lux in office buildings. Ventilation was carried out through window opening. At this time, most of the energy was consumed by vertical transport and heating of spaces. These early high rises profited from their compact and bulky shape and since they had a great volume to little surface area ratio, this meant decreased heat loss through the envelope in the winter whereas a high degree of thermal mass in the summer.[186]

4.2.2 Second Energy Generation High Rises

The second energy generation is considered to be from 1916, when the Zoning Law in New York City was issued. Prior to this year, due to the lack of planning legislation, the tall buildings' size and their quantity in Manhattan ascended steadily. This resulted in buildings which were blocking sunlight from the street and casting a huge shadow across its surroundings. A good example of this kind of building is the Equitable Building which drops seven-acres shade to its surroundings. Therefore, the landmark Zoning Law was developed by New York City authorities, limiting tall buildings' bulkiness and requiring them to provide light and air to the street level. This led to the so called "wedding cake" set-backs that dominated the skyline of the subsequent period.[187]

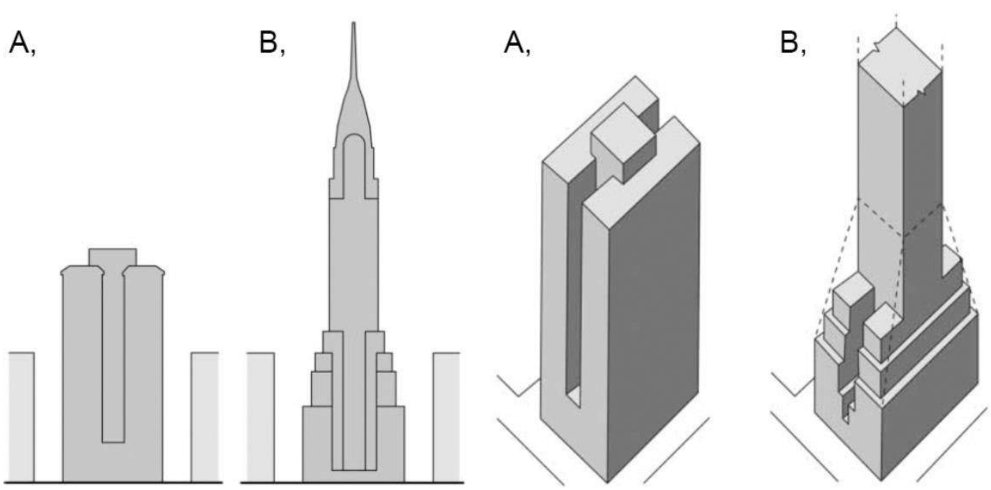


Fig. 151.
A, Pre-Zoning Law Building in New York City
B, Post-Zoning Law Building in New York City

[186] P. Oldfield, D. Trabucco, A. Wood, Five energy generations of tall buildings, 2009, 592.
[187] P. Oldfield, D. Trabucco, A. Wood, Five energy generations of tall buildings, 2009, 593.

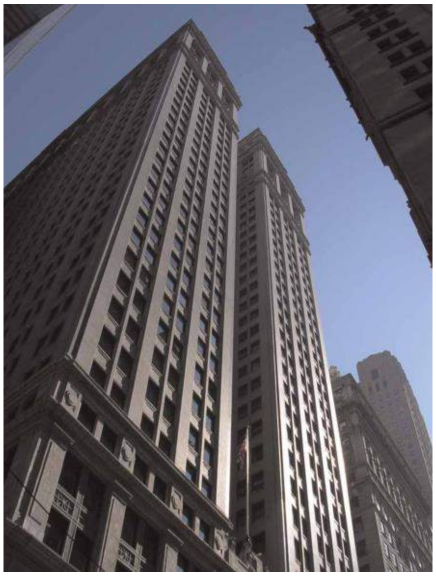


Fig. 152. Equitable Building, New York City

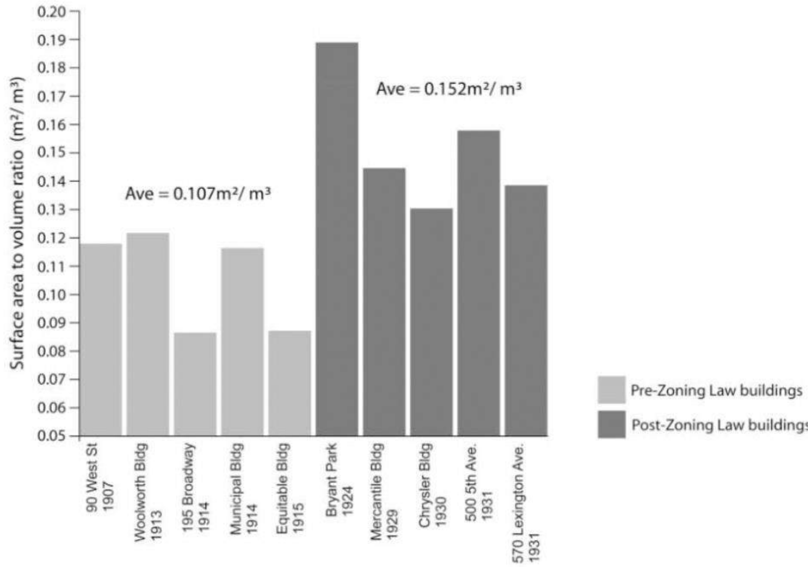


Fig. 153. Facade Surface Area to Volume Ratios for New York High Rise Buildings Completed Prior to, and After the 1916 Zoning Law

High rises built after the Zoning Law had an increased amount of envelope surface area compared to unit volume. In cities like New York City with cold winters this meant a rise of heat loss since the heating requirement is proportional to the building surface area to its volume ratio. So, the higher this ratio gets the more the heating energy requirement owing to the increased envelope area. These slender towers had smaller floor plans, at least at higher levels, than the ones from the first energy generation. Indeed, this led to greater daylight penetration thus decreasing artificial lighting loads. However, artificial lighting standards actually rose in this period by the New York City Department of Health. All these show that the 1916 Zoning Law had a direct impact on the high rises' form and energy consumption at the time.[188] Based on New York City, many North American cities developed their own zoning laws by the late 1920s, which resulted in the same architectural effects on high rises, first of all an increment of slenderness. Around this time, a big energy consumer, air conditioning, was starting to occur in the building spaces. It first became a standard feature, however, only from the 1950s and -60s. The earliest fully air conditioned high rise was the Milam Building in San Antonio, built in 1928.[189]

Fig. 154. The Milam Building

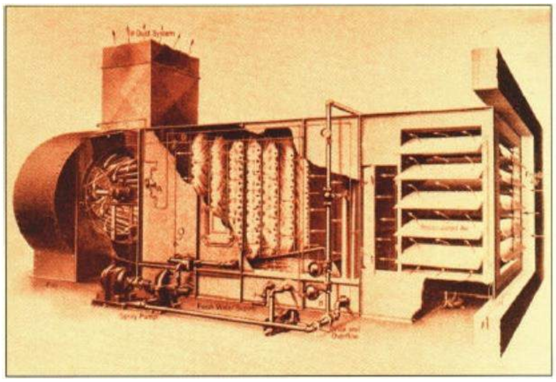


Fig. 155. Air-Handling Unit of the The Milam Building

[188] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 595.
[189] The American Society of Mechanical Engineers, *The Milam Building*, 1991, 3.

4.2.3 Third Energy Generation High Rises

The third energy generation is counted from the development of the glazed curtain wall, 1951. This was the time when the rectilinear glass, originating from Mies van der Rohe, became popular and spread around the world, with no regard to site, orientation or climate. This type of building was a symbol of economic wealth. The energy consumption of these high rises was significant. The problem was the single glazing facade through which there was a big heat loss in the winter and overheat from the large solar gain in the summer. Furthermore, the widespread usage of air conditioning made the energy consumption even greater. Due to its facade, the Lever House of SOM was one of the first high rises where the air conditioning was so fundamental that the building could not even function without it. Influenced by the International Style, the other interesting feature of this period was the high number of high rises with a fully black exterior. Only a low amount of daylight could penetrate into the office spaces through their dark-colored glass. This enhanced the need for artificial lighting, of course. Indeed, these buildings suffered from heat gain in the summer compared to those having lighter colored facades or brick.[190]

Regarding shape and form, these large rectilinear boxes with deep office floorplans were not as slender as the Zoning Law-influenced buildings in the past period. They were shaped more like the buildings from the first energy generation, bulky and very compact. So, the overall energy consumption of the bulky, hermetically sealed glass boxes at this time increased dramatically. These high rises were totally reliant on fluorescent lighting and air conditioning. As shown by a study involving 86 office buildings built in Manhattan between 1950 and 1970, the primary energy consumption of buildings in the late 1960s more than doubled compared to those constructed in the early 50s.[191]

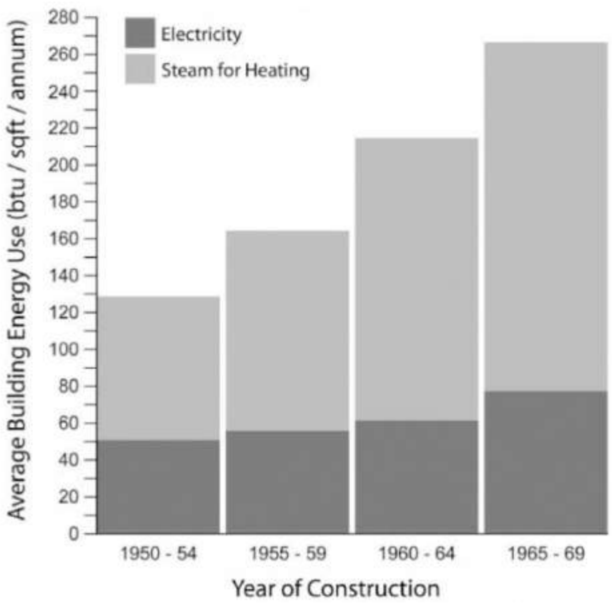


Fig. 156. Average Primary Energy consumption of 86 Office Buildings Constructed in Manhattan Between 1950 and 1970

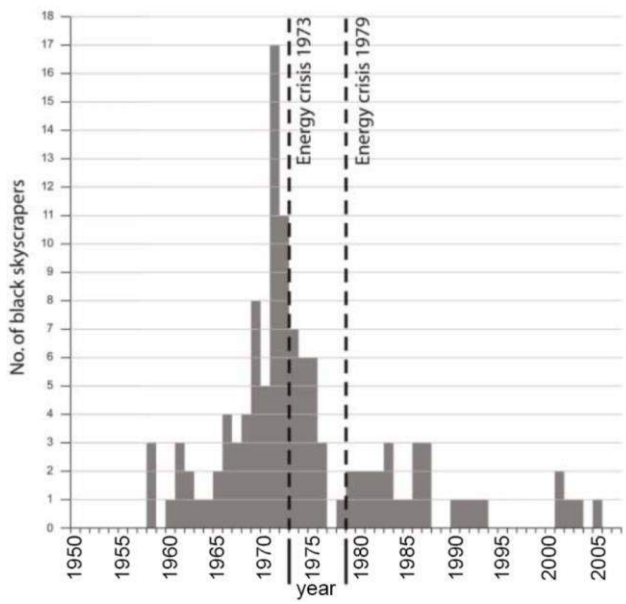


Fig. 157. Number of Black Skyscrapers Constructed in North America Since 1950

[190] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 599.
[191] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 596.

4.2.4 Fourth Energy Generation High Rises

The fourth energy generation started from the energy crisis in 1973. Due to the oil crisis in the early 1970s, energy became a significant issue for high rise buildings. The widespread use of the single-glazed curtain wall decreased very quick and as a response to the crisis, many countries came up with building energy performance codes. This forced the shift from single to double-glazing.[192]

At this time fully glazed, dark colored boxes lost their popularity and even the humble window usage on the facade was considered as an energy leak. The move away from dark glazing decreased artificial lighting loads which were further minimized through a cutback in overall lighting levels recommended by authorities. While the energy crisis led to improvements in facade performance and a decrease in the number of the black box high rises, technological progress still had a negative effect on building energy consumption. For instance, offices started to use computers in huge amounts in this period which not only needed more electricity but also raised the internal heat of the rooms.[193]

4.2.5 Fifth Energy Generation High Rises

The fifth energy generation is considered from the rise of environmental consciousness design in the 1990s. Most likely, the first fully environmentally conscious high rise was the Commerzbank in Frankfurt, built in 1997. Today, when climate change is a great challenge of our society, a growing number of high rises are trying to minimize their primary energy consumption needs as much as possible and even go beyond them.[194]

In general, these buildings have high envelope transparency, allowing for excellent daylight access and reduced artificial lighting loads. Due to the usually incorporated large atria, they also have a high surface area to volume ratio, which is not a serious problem as modern materials have great insulation qualities on the building envelope. The more and more used natural and mixed-mode ventilation strategies significantly contribute to the reduction of the energy consumption. Moreover, these buildings not only try to reduce their energy consumption through energy efficient design strategies and with the help of different technologies but they also more and more often try to explore their potential of on-site energy generation, such as using PV panels or wind turbines on the building's envelope.

Today, sustainable design is a significant factor in revenue and status generating. Companies are much more ready to pay a higher amount of money for an improved environment and quality designed space with sustainable features. According to a study by the CoStar Group, those building which achieve a Leadership by LEED, will have not only a higher percentage of occupancy than the non-LEED certified ones but they can also count on a greater rent premium per square foot.[195]

[192] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 599.
[193] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 600.
[194] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 601.
[195] P. Oldfield, D. Trabucco, A. Wood, *Five energy generations of tall buildings*, 2009, 605.

	1st Energy Generation From the Birth of Tall Buildings in 1885, to the 1916 Zoning Law	2nd Energy Generation From the 1916 Zoning Law to the Development of the Glazed Curtain Wall, 1951	3rd Energy Generation From the Development of the Glazed Curtain Wall, 1951, to the 1973 Energy Crisis	4th Energy Generation From the Energy Crisis of 1973 to the Present Day, 2008	5th Energy Generation From the Rise of an Environmental Consciousness in 1997 to the Present Day, 2008
Typical Energy Performance Characteristics	- Compact shape (large volume vs. small façade area) - High levels of thermal mass in façade - Low percentage of façade transparency - Heating and elevators main consumers of energy	- Slender shape (small volume vs. large façade area) - High levels of thermal mass in façade - Low percentage of façade transparency - The use of air-conditioning becoming more common	- Compact shape (large volume vs. small façade area) - Low performance, single-glazed curtain wall façade systems - High quantities of façade transparency with tinted glazing - Total reliance on mechanical conditioning and fluorescent lighting - Large quantity of 'black skyscrapers'	- Compact shape (large volume vs. small façade area) - Good performance, double-glazed curtain wall façade systems - High quantities of façade transparency with good solar transmittance - Total reliance on mechanical conditioning	- Slender shape (small volume vs. large façade area) - High performance double-skin & triple glazed curtain wall façade systems - High quantities of façade transparency with good solar transmittance - Natural ventilation possibilities exploited - On-site energy generation promoted
Surface area to volume ratios (m^2/m^3) [6]	- 90 West Street, *New York*: **0.118** - Woolworth Building, *New York*: **0.122** - 195 Broadway, *New York*: **0.087** - Municipal Building, *New York*: **0.118** - Equitable Building, *New York*: **0.088** ***Average: 0.107***	- Bryant Park Tower, *New York*: **0.189** - Mercantile Building, *New York*: **0.144** - Chrysler Building, *New York*: **0.130** - 500 5th Avenue, *New York*: **0.158** - 570 Lexington Ave, *New York*: **0.138** ***Average: 0.152***	- Lever House, *New York*: **0.164** - Seagram Building, *New York*: **0.123** - City National Tower, *LA*: **0.089** - One IBM Plaza, *Chicago*: **0.088** - Tour Fiat, *Paris*: **0.089** ***Average: 0.111***	- First Canadian Place, *Toronto*: **0.077** - Wells Fargo Plaza, *Houston*: **0.087** - One Canada Square, *London*: **0.079** - UOB Plaza, *Singapore*: **0.112** - Cheung Kong Center, *Hong Kong*: **0.084** ***Average: 0.088***	- Commerzbank, *Frankfurt*: **0.161** - GSW Headquarters, *Berlin*: **0.221** - Deutsche Post Building, *Bonn*: **0.152** - Hearst Tower, *New York*: **0.100** - Bank of America Tower, *New York*: **0.096** ***Average: 0.146***
Typical office lighting levels (foot-candles) [7]	**8-9**	**10 - 25**	**100 - 150**	**35 – 100**	**35 – 45**
Typical façade U-values (W/m^2K)	Information unavailable. Figures likely to be in **2.0 – 3.0** range.	- Empire State Building, *New York*: **2.6**	- Lake Shore Drive Apartments, *Chicago*: **4.2** - Lever House, *New York*: **3.3**	- Wells Fargo Plaza, *Houston*: **1.5** - Cheung Kong Center, *Hong Kong*: **0.9**	- Deutsche Post Building, *Bonn*: **1.1** - Bank of America Tower, *New York*: **0.9**
Transparency within façade	- Woolworth Building, *New York*: **21%** - Equitable Building, *New York*: **25%** - Municipal Building, *New York*: **29%**	- Chrysler Building, *New York*: **32%** - Empire State Building, *New York*: **23%** - 500 5th Ave, *New York*: **32%**	- Lake Shore Drive Apartments, *Chicago*: **72%** - Lever House, *New York*: **53%** - City National Tower, *LA*: **53%**	- Wells Fargo Plaza, *Houston*: **82%** - One Canada Square, *London*: **43%** - Cheung Kong Center, *Hong Kong*: **52%**	- Commerzbank, *Frankfurt*: **54%** - Hearst Tower, New York: **63%** - Bank of America Tower, *New York*: **71%**
Ventilation strategies	Naturally ventilated via opening lights. Later renovated to be fully air-conditioned.	Naturally ventilated via opening lights. Later renovated to be fully air-conditioned.	Hermetically sealed and totally reliant on mechanical conditioning.	Hermetically sealed and totally reliant on mechanical conditioning.	Opportunities for natural and mixed-mode ventilation exploited. Double-skin facades often utilised where climatic conditions allow.

Fig. 158. Summary of Data from the 5 Energy Generations

4.3 Energy Consumption

In developed countries over the past half-century, about 85 percent of energy consumption in buildings has accounted for cooling, heating, lighting, ventilation and other technical systems. Manufacturing, transport and construction make up only a little above 10 percent of building's energy consumption whereas maintenance has been around 4 percent.[196] Between 10-15 percent of energy savings can be achieved in a conventional office building with just little interventions involving only a small amount of architectural changes or none at all. This can mean, for instance, controlling blinds according to the solar path dynamics and availability of daylight thus reducing artificial lighting and enhancing visual comfort. Another example is to change the air conditioning system's set point for somewhat higher temperatures in the summer and lower temperatures in the winter. In order to obtain 20-30 percent energy savings, it is necessary to introduce some architectural interventions such as internal space treatment or facade design. Lastly, to reach energy savings above 30 percent, a full review of technical, architectural and cultural standards is necessary and user participation in the control of the building environmental conditions is required.[197]

Different factors can affect high rises' energy consumption though the importance of these factors depends on the building and on its environment. Usually the factors can be separated into groups, such as architectural (e.g., building shape, building height, envelope, spatial relations), natural, technology and human factors.

4.3.1 Architectural Factors

4.3.1.1 Building Shape

As study reported, that a common tower-type building consumes almost 1.5 times more energy than a plate-type building.[198] Some shapes of tall buildings increase and help the ventilation flow and improve the natural daylight inside the building which automatically means a ventilation and thermal load reduction. Some building geometry receives more solar radiation than others which might lead to enhanced cooling loads. So building shape clearly has an effect on the energy consumption and it should be extensively thought through by the designers as a first and very important step in the building design.

4.3.1.2 Building Height

Tall buildings have an increased energy use, for instance, for vertical transportation, enhanced mechanical heating and cooling or pumping water to higher levels. It also can be verified that as the building gets taller, its central core most likely will also get larger for service and structural reasons. Furthermore, in order to maintain the spaces' net to gross efficiency, the floor plates will

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[196] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 144.

[197] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 146.

[198] I. Y. Choi, S. H. Cho, J. T. Kim, *Energy consumption characteristics of high-rise apartment buildings according to building shape and mixed-use development*, 2012, 131.

grow deeper thus leading to a raised energy consumption to keep up with given indoor environmental conditions.[199] A study including 25 buildings was conducted in Hong Kong showing enhanced energy consumptions of buildings in connection with increased height.[200]

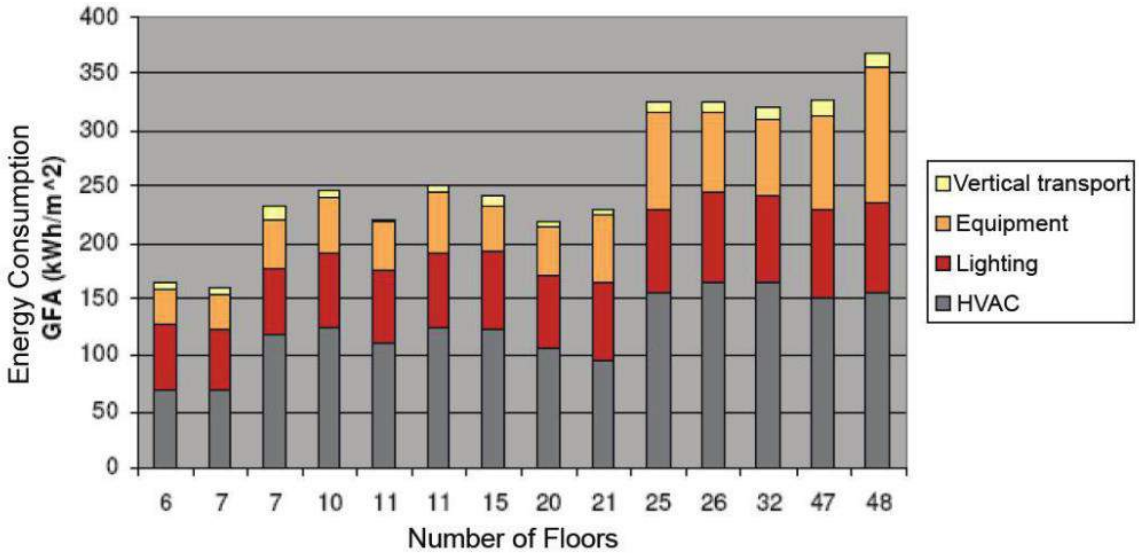

Fig. 159. Energy Consumption per Unit Floor Area Associated with Building Height

Numerous micro-climatic conditions influence tall buildings and they change gradually with the increment of the building height. The upper floors of a tall building receive more wind and extra solar radiation from the adjacent building rooftops at lower levels. Hence, tall buildings with stories that are lower than the urban canopy can obtain some shading from the higher buildings in the neighborhood. The heat loss of tall buildings is reduced in cloudy weather whereas it will increase with a clear sky. Furthermore, stories above urban canopy will have a higher rate of heat loss at night.[201]

4.3.1.3 Building Envelope

Building envelope materials have different thermal features, properties such as thermal mass, heat transfer and solar insulation. Each of these have a significant impact on the building's energy consumption since the building envelope regulates the internal environment against outer climatic conditions such as temperature fluctuation, humidity, solar radiation or wind gusts.[202]

4.3.1.4 Spatial Relations

Allocating uses with high occupancy rates at lower levels in a high rise reduces the vertical transport system's energy consumption. Placing recreational uses such as observatories or restaurants at the building top attracts a lot of visitors and thus impacts the up and down traffic

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199 J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 210.
200 H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1361.
201 H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1362.
202 H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1361.

with elevators in the building, increasing the energy consumption. On the northern hemisphere, orienting the spaces which need more natural light towards north, lowers these spaces energy consumption required by artificial lighting and heating. A well designed spatial distribution of building functions and spaces' that have a strong adjacent relationship between each other will lead to a decrease of horizontal and vertical transport elements thereby reducing the building's energy consumption.[203]

4.3.2 Natural Factors

The nature and location of the building site puts some constraints on the designer since climate plays a great role in the building energy consumption. Most of the developed countries in the world are located in cooler zones where heating load constitutes most of the building's annual energy consumption. Similarly, buildings in the warmer regions require more air conditioning though they do not usually need to heat the indoor environment. Moreover, they save significant amounts of energy through natural lighting instead of artificial lighting systems. Also, a tall building on a coastal site requires enhancements to its internal spaces with a view of the water which may have a negative impact on the building energy consumption.[204]

4.3.3 Human Factors

In the case where building occupants don't have any education or knowledge about how the building systems operate effectively, it will most likely have a negative impact on the building's energy performance in general. Not only can the existence of the occupants negatively effect energy savings, but also their non-existence in the building. When the user leaves the window blind open for the entire weekend on the building's south side during the summer, then the cooling load of this space might be multiplied on the following Monday. On the other hand, if the operable window is left wide open by the user during a cold winter night then it will most likely cause unnecessary heating loads the next day. According to a study, there was less energy used in a tall building during working hours (i.e., 44 percent) than during non-working hours (i.e., 56 percent) which mostly comes from the occupant's behaviour such as leaving the lights and other equipment on, after their work day.[205] It has been proven through reviews of case studies that the building's actual final energy performance can be even better than proposed during the design phase if the users are educated about the building systems and they use them properly.[206] Thus, the success of the building's energy performance cannot be guaranteed through energy efficient design measures only, but it also needs the user's active involvement.

4.3.4 Technology Factor

The computer-based Building Management System (BMS) aims for the most possible energy efficiency of a tall building, however, the advances in technology today that promotes prosperity

[203] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1360.
[204] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1362.
[205] J. K. Day, D. E. Gunderson, *Understanding high performance buildings The link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction*, 2014, 116.
[206] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 149.

and luxury have resulted in more and more energy consumption.[207] Most energy use of a typical office building originates not from the large amount of computers or other office equipment, though. The major part of the building energy consumption comes from heating, cooling, ventilation and lighting whereas office equipment consumption makes up only a fraction of these amounts.[208]

4.4 Passive Mode, Mixed Mode, Full Mode, Productive Mode and Composite Mode

4.4.1 Design Modes

Planning a sustainable high rise or a sustainable building in general requires the designer to adapt progressive strategies in order to improve the building's comfort conditions relative to the external conditions and at the same time trying to reduce demands on non-renewable energy sources as much as possible. Essentially, there exist five ways of doing this: the Passive Mode, Mixed Mode, Full Mode, Productive Mode and Composite Mode design.[209] Designing a high efficient sustainable building requires that firstly we start to consider bioclimatic design strategies which is the Passive Mode, then moving to Mixed Mode and so on to the other Modes thus aiming for the lowest level of non-renewable energy consumption of the building.

4.4.1.1 Passive Mode

Basically, Passive Mode (PM) is a low-energy design achieved by not employing any electromechanical systems, however, there are some who argue about the use of a pump or fan which according to them may be included within this category.[210] PM strategies include the proper building orientation in relation to the locality's climate, adopting an appropriate building configuration, service core position, use of vegetation, selection of the type of facade, building's color or shading system. Through the correct application of passive systems, indoor temperature values will be decreased in the summer and increased in the winter, spaces can be naturally ventilated, etc. Moreover, in case of an electrical power failure the building still remains at an improved level of comfort as opposed to if the designer had not optimized the building passive modes in which the building might become intolerable to its occupants. PM has to be given a priority over the other Modes since this is the best way to achieve ecological design and it uses no non-renewable energy sources.[211]

4.4.1.2 Mixed Mode

In case the building is not configured according to PM in the first instance, then some mechanical and electrical systems could be added to it. Mixed Mode systems can include, for instance, an evaporative cooling system or ceiling fan.[212]

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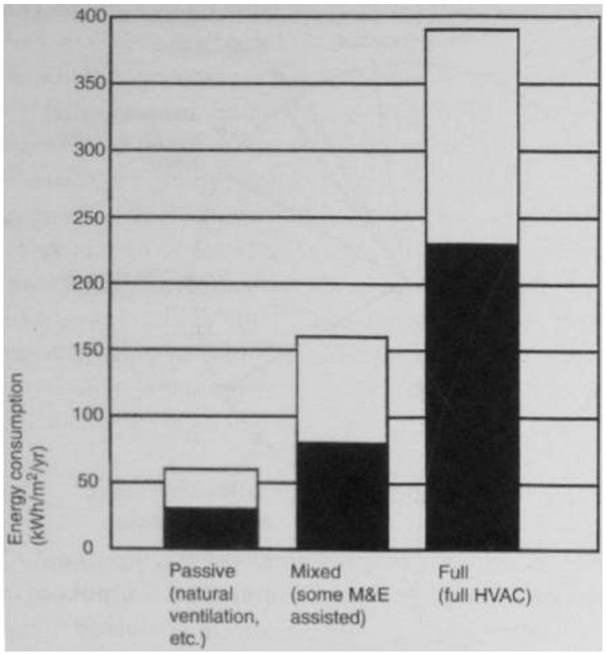
[207] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1361.
[208] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 109.
[209] Ken Yeang, *The Green Skyscraper*, 1999, 85.
[210] Ken Yeang, *The Green Skyscraper*, 1999, 203.
[211] Ken Yeang, *Designing the ecoskyscraper premises for tall building design*, 2007, 415.
[212] T. R. Hamzah and Yeang, *Vertical Ecoinfrastructure*, 2009, 140.

4.4.1.3 Full Mode

A building in Full Mode means the full use of electromechanical systems is applied in order to produce suitable internal comfort conditions. Most conventional buildings function in this mode as it is inevitable if users want to have consistent comfort conditions during the entire year. We have to see that the Passive and Mixed Mode design can never compete with the comfort levels of the Full Mode conditions. On the other hand, if the building is optimized with Passive Mode design, it still works at an effective comfort level in the course of any electrical power failure, though the building might become unbearable for occupants relatively quick whenever there is no electricity.[213]



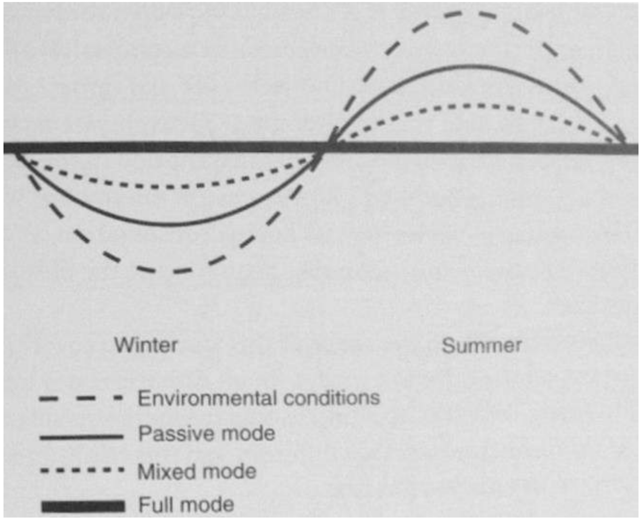


Fig. 160. Energy Consumption Targets of Passive, Mixed and Full Mode **Fig. 161.** Comfort Ranges of Passive, Mixed and Ful Mode

4.4.1.4 Productive Mode

The building in Productive Mode generates its own energy. Typical examples of this are the electricity generation via the use of wind turbines exploiting wind energy or photovoltaic panels using solar power. These systems require precise, high-efficient technological systems that subsequently increase the building's inorganic and embodied energy content thus impacting the environment in some way.[214]

4.4.1.5 Composite Mode

In case of a mixture of all the other modes in proportions that vary over the seasons of the year, we talk about Composite Mode.[215]

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[213] C. Grech, D. Walters, *Future office: Design, practice and applied research*, 2008, 108.
[214] T. R. Hamzah and Yeang, *Vertical Ecoinfrastructure*, 2009, 140.
[215] Ken Yeang, *Designing the ecoskyscraper premises for tall building design*, 2007, 416.

4.4.2 Mode Usage

It should be clear that the low-energy design not only depends on the proper application of these Modes but it significantly depends on the building occupants and on their lifestyle, as well. If for instance, the user is ready to expect warmer summer and colder winter internal environments and he or she is willing to wear lighter clothing in the summer and warmer clothing in the winter, then this significantly lessens the air conditioning use. Hence the building occupants have a very important role and have a serious effect on the building's low energy design which is the ultimate object.[216]

4.5 Representatives of Sustainable High Rises

4.5.1 Frank Lloyd Wright

Frank Lloyd Wright was most likely the first architect thinking about sustainability in the mid-1950s. He believed that tall buildings belong to a low rise environment as a free-standing sculptural element rather than being in the city. His idea was to reduce suburban sprawl and green area loss by putting a large number of humans in towers which demand smaller plots.[217]

Wright's one and only high rise design was the Price Tower in Oklahoma, built in 1956. The structure did not include a glass curtain wall which was widespread and revolutionized high rise design at that time. Instead, it had a large opaque facade, punctuated with windows thus having higher thermal mass, decreased solar gain which provided better insulation against climate conditions. In order to control light and solar gain, he also employed external louvres on the facade. The building is mixed-use in the sense of the mixture of office and residential uses within the same floors, resulting in social sustainability, though having inefficient, small office spaces.[218]

Fig. 162.
Price Tower, Oklahoma

Fig. 163.
Facade of the Price Tower

[216] C. Grech, D. Walters, *Future office: Design, practice and applied research*, 2008, 138.
[217] Antony Wood, *Sustainability A new high-rise vernacular*, 2007, 403.
[218] Antony Wood, *Sustainability A new high-rise vernacular*, 2007, 404.

4.5.2 Ken Yeang

Malaysian architect Dr. Ken Yeang is considered to be the “godfather” of sustainable, bioclimatic high rises and along with his firm T. R. Hamzah and Yeang, he is a true pioneer in this field.[219] Most of his buildings in over 20 countries are low-energy, green structures. At the time Yeang started his career, there were no eco-technologies which are available today.[220]

His towers interact with the local external environment. Yeang is well-known for employing strategies of building orientation and form relative to wind and sun in order to decrease solar gain and support natural ventilation. He also uses a lot of green in his designs. Vertical green landscapes provide shading, improve the micro-climate and assist in evaporative cooling in his tall buildings. Many of Yeang’s high rises have the name Menara in them, meaning tower in the Malaysian language, such as Menara UMNO, Menara Mesiniaga, Menara Boustead, but there are also buildings with “usual” names of course like the Plaza Atrium or MBf Tower.[221]

Fig. 164. Menara UMNO

Fig. 165. Menara Mesiniaga

Fig. 166. Menara Bousted

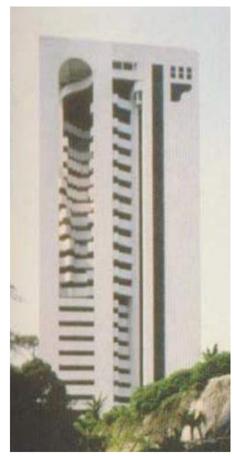

Fig. 167. Plaza Atrium

Fig. 168. MBf Tower

4.5.3 Norman Foster

Today, Norman Foster is probably the most prominent architect designing sustainable high rises. The Commerzbank in Frankfurt (1997), 30 St Mary Axe in London (2003) or Hearst Tower in New York City (2006) are known as the best sustainable, environmental high rises ever built.
In contrast with Ken Yeang who had a new aesthetic for the high rises based on materials incorporating lush and rich vegetation, Foster buildings do not really differentiate from the usual material palette of steel and glass.[222]

4.5.4 Europe

When we are talking about a region in terms of sustainable high rise design then Europe is undoubtedly leading the way. High energy costs in Europe and the tough European Community

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[219] H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 136.
[220] Tatjana Anholts, *Rethink the skyscraper*, 2012, 7.
[221] Tatjana Anholts, *Rethink the skyscraper*, 2012, 23.
[222] Antony Wood, *Sustainability A new high-rise vernacular*, 2007, 405.

(EC) regulations set the standards for energy efficient high rises. The EC proposed strict energy-use standards and introduced depth restrictions on floor plates thus providing daylight to all workers for new buildings.[223] Hence, for example, the depth of a typical office floor plan in Germany is no more than 7 meters (23 feet) compared, for instance, with the usual 12-13 meters (39-43 feet) depth in the USA.[224] It is seen that Europe is not going to rival height records of tall buildings though it will most likely remain the number one place of sustainable design for some time.

[223] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 161.
[224] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 170.

5. Energy Efficient High Rise Design

5.1 Passive Design Strategies

The basis of passive design is environmental architecture, bringing together architecture, climate and culture. Passive design strategies must be incorporated at the early design stages since they impact the building form, orientation and configuration. The need for energy resources can be significantly reduced by use of these passive design systems. The systems can lead to decreased indoor temperature in the summer, increased temperature in the winter, and enhancement of natural ventilation in the building. In case the high rise has not been configured according to the maximization of passive design strategies, then any later installed electrical and mechanical devices will need to balance this indolence that significantly amplifies the building's energy need.

5.1.1 Orientation

The orientation of the building is a very important aspect of the high rise design. The building should be oriented according to its surrounding environment as according to the sun path and prevailing winds. Considering that the path of the sun helps to increase or decrease the solar heat gain and the amount of daylight in the interior spaces.[225] Generally, the building's long axis should be directed in the east-west direction in order to maximize passive solar heat gain on its north-south faces. The passive design expert, Ken Yeang, suggested critical angles of passive building orientation for each major climate zone.[226] The building orientation, according to the prevailing winds, is an efficient design strategy for wind load reduction and to enhance natural ventilation. Indeed, it becomes even more effective in windy regions with extreme winds. Through the building rotation, within 10 degrees of the wind direction can result in a 10-20 percent decline in the wind load.[227]

Zone	Building's main orientations	Directional emphasis
Tropical	on an axis 5° north of east	north–south
Arid	on an axis 25° north of east	south–east
Temperate	on an axis 18° north of east	south–south-east
Cool	on an axis facing south	facing south

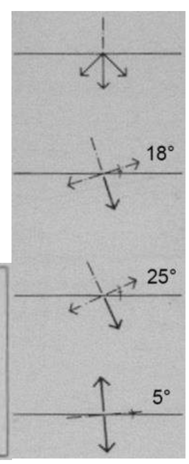

Fig. 169. Building Orientation in Response to Solar Angles

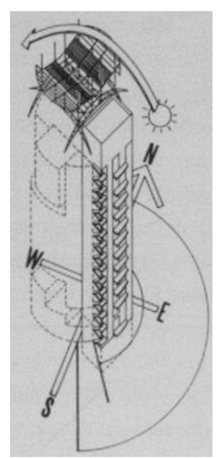

Fig. 170. Building Orientation According to the Sun Path

[225] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 97.
[226] Ken Yeang, *Bioclimatic Skyscrapers*, 2000, Influences on Built Form 2.
[227] M. H. Günel, H. E. Ilgin, *Tall buildings structural systems and aerodynamic form*, 2014, 133.

In order to provide a high-efficient natural ventilation system and daylight to the office spaces, the architecture of the Commerzbank in Frankfurt was configured in accordance with the site's solar path and predominant winds. The building's south-west orientation along with its triangular shape result in the maximum solar penetration through the envelope and natural ventilation from all directions through prevailing winds.[228]

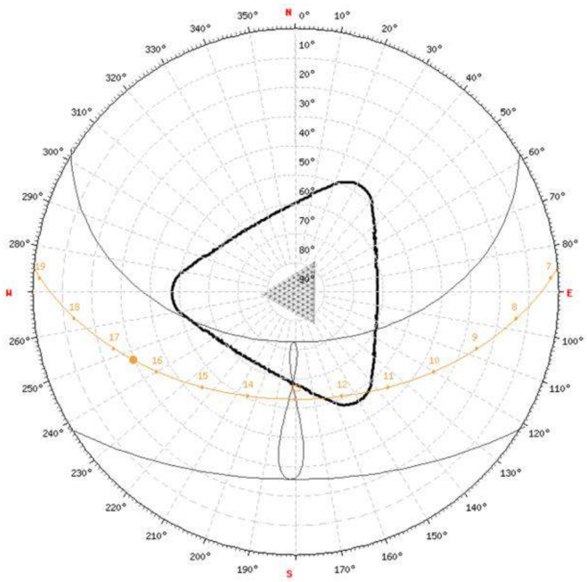

Fig. 171. Sun Path of the Commerzbank Frankfurt

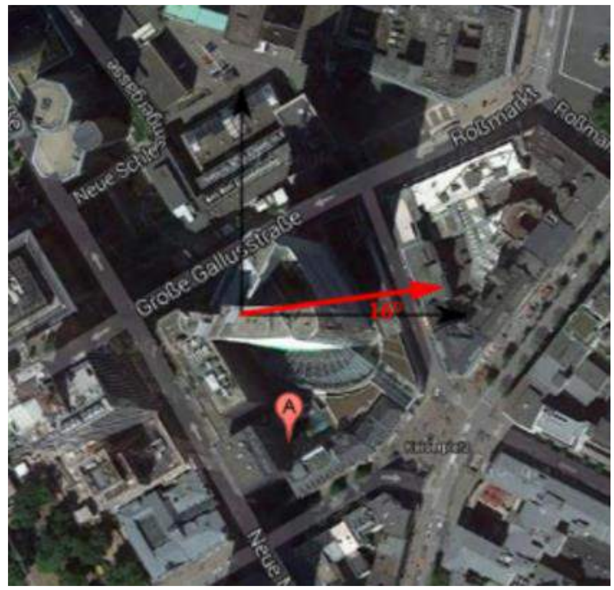

Fig. 172. Site Orientation of the Commerzbank Frankfurt

5.1.2 Form

A properly conceived building form mitigates the external climate conditions in order to provide a comfortable interior environment for the occupants, thus reducing heating, cooling, ventilation, and electrical lighting requirements. Using aerodynamic forms reduces wind turbulence around the building and creates pressure differences that helps natural ventilation. Buildings with symmetrical forms exhibit greater structural efficiency against lateral loads than buildings with asymetrical forms. The compactness level of the building has a great influence on the building's energy consumption. The more compact the building is the more energy efficient it can be.[229]

A simple geometric building's form is also important in terms of standardization and repetition. Repeating 100 times the same steps at each floor during the building's construction is a lot more efficient than 20 different design details occuring only five times each. It reduces material consumption, makes transportation and manufacturing easier, increases construction speed and decreases maintenance demands. These all greatly contribute to lower energy consumption and overall costs reduction.[230]

[228] Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1348.
[229] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1365.
[230] M. Elnimeiri, P. Gupta, *Sustainable structure of tall buildings*, 2008, 890.

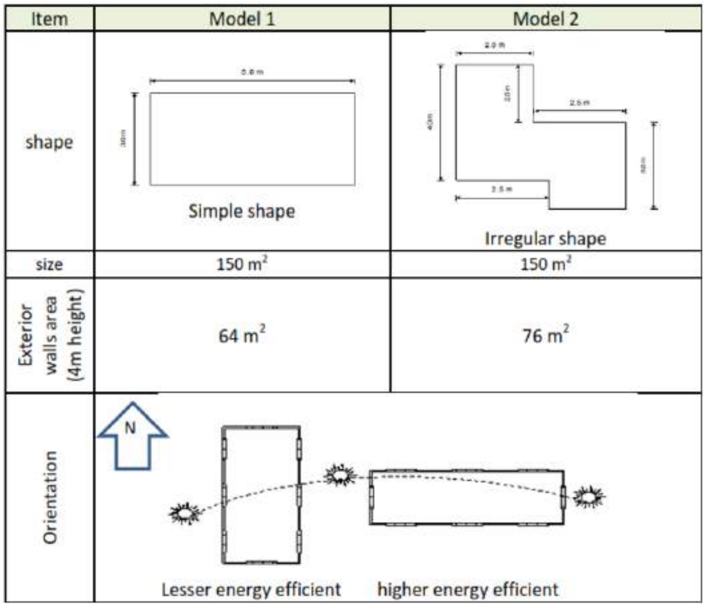

Fig. 173. Energy Efficient Building Shape

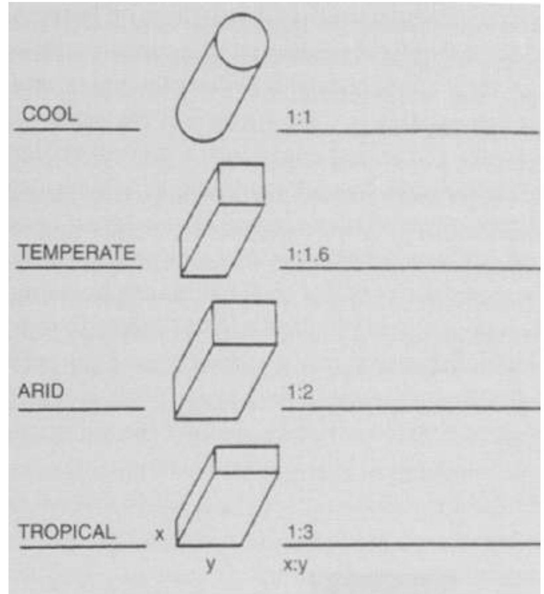

Fig. 174. The Optimum Building Form for Each Climatic Zone

Climate has a significant influence on the performance of the building form. Although a properly selected form for one climate may perform low in another climate. Fig. 174. shows the aspect ratios of building forms that were suggested by Ken Yeang depending on the climatic zone. Thus buildings in a tropical climate require an elongated form which gradually evolves into a 1:1 ratio form as we reach the higher latitudes in the north.[231]

Compact geometric forms, such as a cube, provide small surface area-to-volume ratio, thus they have less exposed surface area for heat exchange with the ambient environment. This results in minimization of heat loss in the cold winter and causes less heat gain in the summer. A square building has an equal exposure to the exterior climate in all directions. In this climate natural daylight might be limited and it is concentrated on the building's periphery for the cube form. Thus, introducing lightwells or a central atrium can eliminate this problem and provide natural light to the building's interior spaces too.[232]

A near cube form is very well-suited for cold and temperate climates where heat retention and distribution is a significant factor. Although buildings in hot climates require more oblong shapes. A rectangular-shaped building performs well in hot climates if oriented longitudinally towards the east-west direction. Thus the minimized east and west facade dimensions significantly reduce solar heat gain in the building since these building sizes receive the most intense sun heat in this climate. It is best to avoid glazing on these facades and to place shear walls or service cores serving as thermal buffers. The admission of diffused light from the north facade can provide ample natural light with reduced glare for the building with a narrow floor plate. Horizontal shading fixtures on the south facade allow the admission of low-angle winter sunlight however exclude excessive higher-angle solar radiation in the hot summer. The rectangular-shape is not efficient

[231] Ken Yeang, *The Green Skyscraper*, 1999, 205.
[232] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 6.

in cold climates since there is a higher thermal loss during the winter due to the high aspect ratio of the form.[233]

Besides the high rise's form, the building's slenderness is another important factor. In the 1960s and -70s, the all-steel towers' slenderness was ranging between about 6.0:1 and 6.7:1. Nowadays, high rises with concrete and composite materials are usually as slender as 8:1 or 9:1.[234] Although today's technology allows slenderness even higher than this, such as the 432 Park Avenue in Manhattan with an exceptional slenderness ratio of 15:1.[235] However one must also know that structure costs rise exponentially with extreme slenderness and the efficiency of the building decreases.[236]

Furthermore, a tall building is economically the most efficient in the range of 50 to 60 stories. This is considered to be a threshold where several constrains come into the picture such as spatial efficiency. The area occupied by the building services and by the structure, results in an economically unattractive development, with serious implications on the net-to-gross floor area ratios as a result of loss of lettable floor area.[237]

5.1.3 Sun

5.1.3.1 Service Core Position

The high rise's heating and cooling load, thereby the building's energy consumption, is significantly influenced by the location of the service core. The core, as primary mass, can be arranged to provide shade and thermal insulation against the outer climatic conditions. Generally, the split-core design (see: Service Core) with the cores facing east and west and with glazing facades to the south and north, has lower cooling loads than a similar building which has a central-core design. The cores on the east and west serve as solar buffers and reduce the high solar gain of the sun.[238] Fig. 175. shows the comparison of cooling loads that result by different core types at different locations.[239] As it turns out from the Figure, a split-core designed high rise orientated from east to west, has an air conditioning load of around 1.5 times lower than the same high rise oriented from north to south. The split-core configuration provides the best passive low-energy performance for the high rise.[240]

[233] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 6.
[234] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 220.
[235] https://skyscrapercenter.com/building/432-park-avenue/13227 Accessed June 2016
[236] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 220.
[237] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 19.
[238] Ken Yeang, *Service Cores*, 2000, 20.
[239] Ken Yeang, *Service Cores*, 2000, 19.
[240] Ken Yeang, *Service Cores*, 2000, 20.

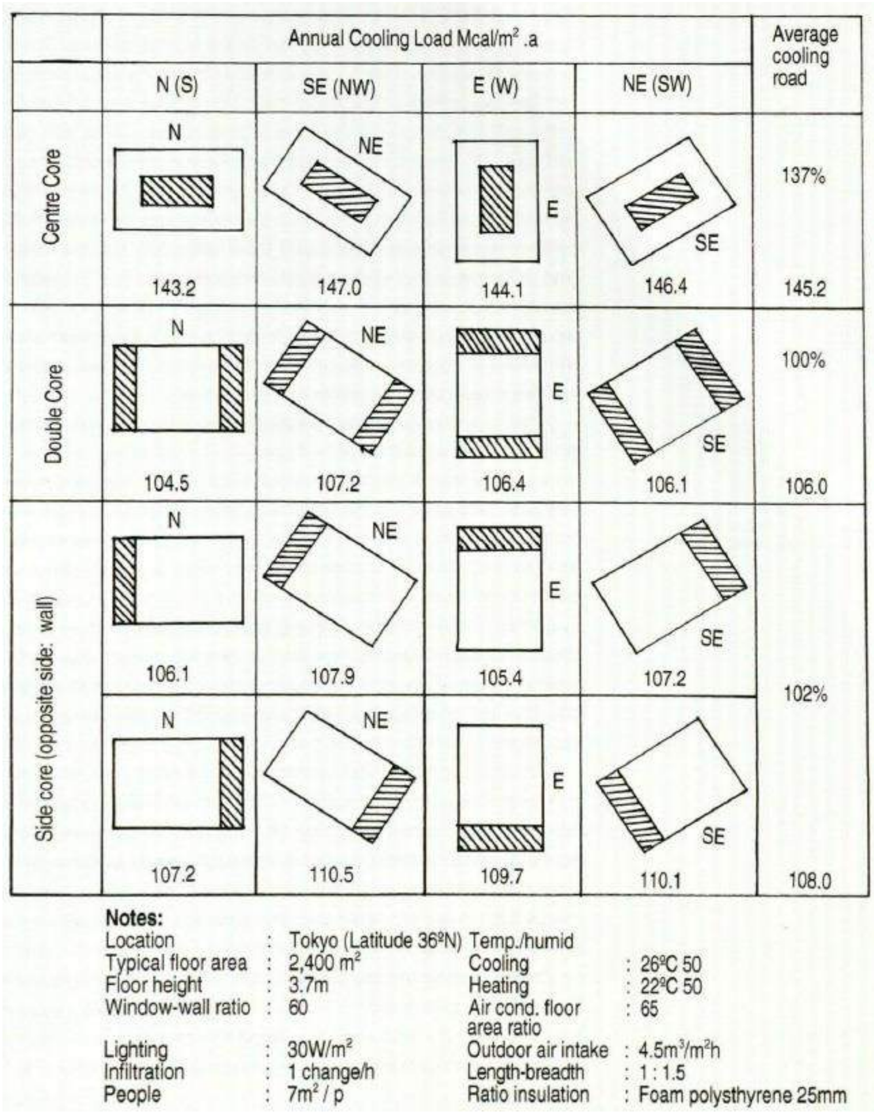

Fig. 175. Comparison of Cooling Load to Core Type

The sun path was a significant factor when designing the IBM tower in Kuala Lumpur. In the high rise design, the building's core was used as a buffer between the exterior and interior environment. Fig. 176. shows three possibilities for the service core location, with the option of it being on the east, on the north or in the center of the building. These options were evaluated using the Overall Thermal Transmission Value (OTTV). The option when the core is located on the east, has the best value OTTV=43.3 W/m2 (13.7 Btu/h/ft2), compared with the other two options 47.5 and 47.6 W/m2 (15 and 15.1 Btu/h/ft2), respectively. The split-core design of the IBM plaza placed on the building's perimeter create savings on the energy consumption between 8 and 12 percent annually.[241]

[241] C. Grech, D. Walters, *Future office: Design, practice and applied research*, 2008, 138.

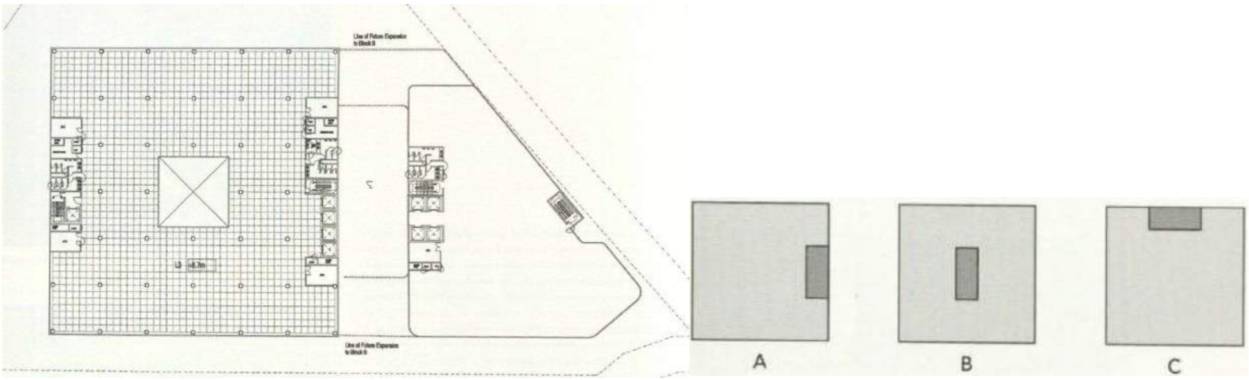

Fig. 176. Possibilities for the Service Core Location

According to another comparison of building forms and service core positions (Fig. 177.), it is shown that the split core configuration placed on the east-west along with the longitudinal form of the building running from east to west, results in a 6-10 percent less energy consumption of the building than the two other forms with other core positions.[242]

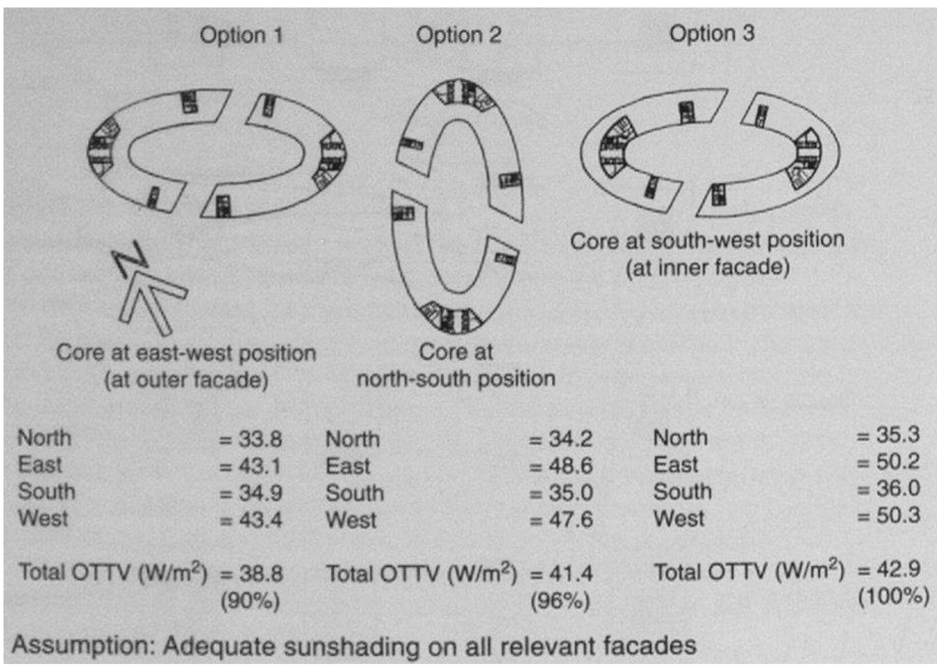

Fig. 177. Passive Mode Optimisation by Building Configuration and Core Position

While designing a tall building, one should know that generally the south facade of the building is not the real problem in terms of solar heat gain and glare, as the sun rays can be filtered by horizontal louvres since due to the relatively high position of the sun. This is especially true in hot climates. Although, this is not the case at the building's east and west facades where the sun has a lower position. At these elevations, overheating and illuminance can easily be a problem because of the lower solar irradiation. Thus, insulation by service core on these building sides offers a perfect solution.[243]

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242 Ken Yeang, *The Green Skyscraper*, 1999, 208.

243 H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 144.

In the book of *The Green Skyscraper*, Kean Yeang suggests different core positions and configurations for different climatic zones for a high rise design. Fig.178. comprises these four types suggested by the eco architect.[244] Later on, through an analysis by an extensive, scientific study of these types, it was proven that the placement of the core on the building's east and west side (with an aspect ratio of 1:3) is not only the best energy saving option in the tropical climate, that was suggested by Yeang, but it leads to a reduction in the energy consumption in every other climatic zone too. It produces an energy reduction from 6 to 32 percent depending on the climatic zone.[245]

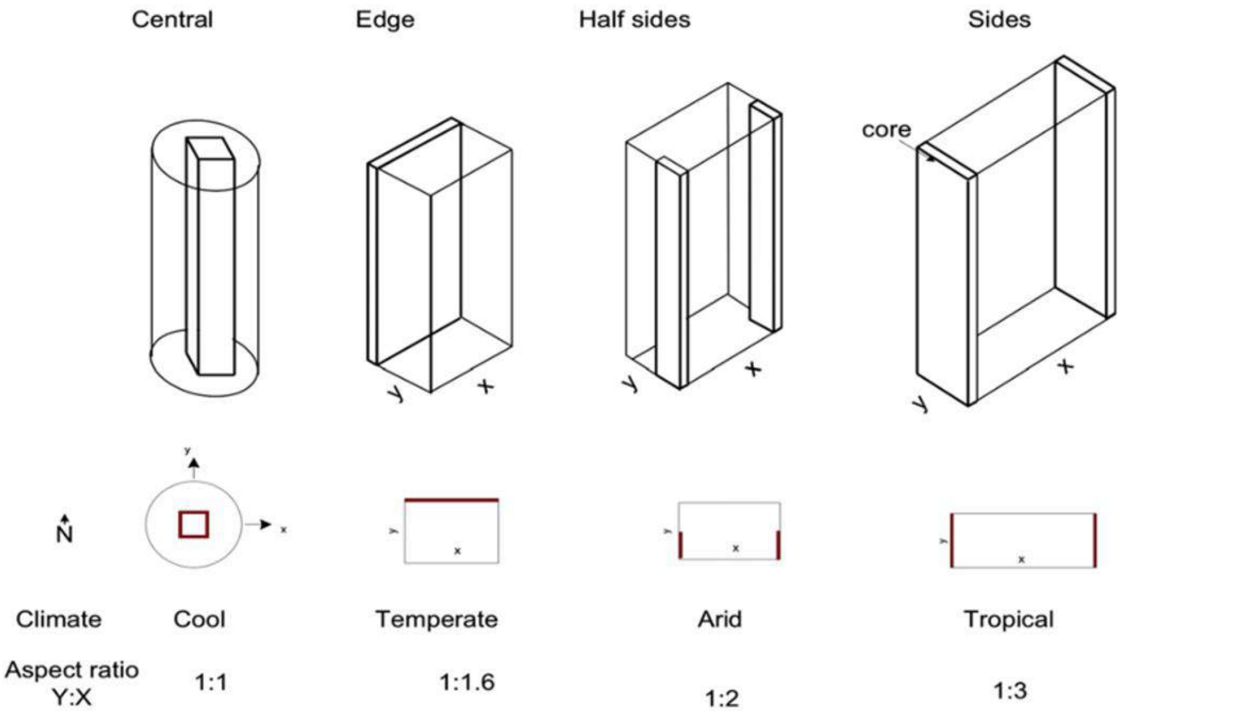

Fig. 178. K. Yeang's Proposal for Optimal Floorplan and Placement of Service Cores to Minimize Building Energy Consumption in Four Climate Zones

Placing the service core on the building's east and west sides provides the opportunity for natural ventilation and natural daylight access of lift cores, stairways, restrooms etc. This spares energy for the building in many ways.[246] The service core as a thermal buffer against solar heat gain lowers the building's cooling loads. It provides an easier dissipation of internal heat gains that are generated by services such as for lifts. The building is safer in the event of total power failure. In addition it helps in creating voids in the center of the high rise that can be used as a central atrium increasing the natural ventilation and daylight for the interior building spaces. Besides these, there is no need for additional mechanical pressurization ducts for fire protection. It is not a negligible factor either, for instance important guests of the office spaces can take an elegant glass elevator on the building's perimeter with a view out to the city, instead of travelling in the darker central core in the building center. [247]

[244] Ken Yeang, *The Green Skyscraper*, 1999, 206.
[245] M. Krem, S. T. Hoque, S. R. Arwade, S. F. Brena, *Structural Configuration and Building Energy Performance*, 2013, 39.
[246] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1361.
[247] D. Trabucco, *An analysis of the relationsip between service cores and the embodied, running energy of tall buildings*, 2008, 944.

5.1.3.2 Passive Solar Heating

Passive Solar Heating means the use of sunlight for heating purposes without active mechanical or electrical systems. Thus, this system turns sunlight into usable heat for the building.

5.1.3.2.1 Thermal Mass

The building's structural mass can be used to absorb and store solar heat. This mass absorbs heat from the sun during the daytime, stores it for many hours and starts to release it when the sun sets and the outside temperature is getting lower. Thermal mass also slows the solar radiation to reach the building interior. Hot and dry climates with cool nights can take advantage of the high thermal mass which reduces strong temperature swings between day and night time. If needed, the building's interior can be cooled down through ventilation by opening windows at night thereby also cooling down the thermal mass for the next day.[248]

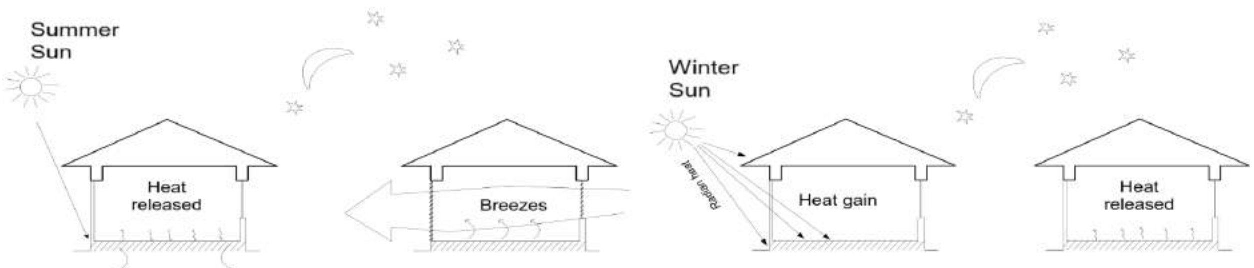

Fig. 179. Thermal Mass Principle in the Summer and Winter

Materials featuring good thermal mass are usually those which have high density and are conductive. Although too high conductivity is a problem since this type of material absorbs and radiates heat too quickly thus having low thermal mass characteristics (e.g., steel). Insulation materials have almost no thermal mass, whereas normal weight concrete has higher thermal mass than light weight concrete.[249]

Exposed concrete floor slabs, trombe walls or deep basements with concrete foundation all provide excellent thermal mass properties.[250] High rise spaces can also be preheated or precooled by using water tubing embedded in the mass of the floor slabs (see: Chilled Ceiling System). With the decrease of the building's floor-to-floor height, the thermal mass becomes more effective since there is less space which needs to be conditioned.[251] Natural heat sinks can also provide efficient thermal mass such as a swimming pool. It is well known that the climate near a lake is cooler and much more tolerable in the summer than it is far away from it. This occurs because of its thermal mass which absorbs the ambient heat as a swimming pool does on a smaller scale.[252]

[248] Mohamed Krem, *Effect of Building Morphology on Energy and Structural Performance of High-Rise Office Buildings*, 2012, 16.
[249] Mohamed Krem, *Effect of Building Morphology on Energy and Structural Performance of High-Rise Office Buildings*, 2012, 14.
[250] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 96.
[251] C. Grech, D. Walters, *Future office: Design, practice and applied research*, 2008, 108.
[252] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 96.

5.1.3.2.2 Trombe Wall

The Trombe wall consists of several layers which are basically built up from a high thermal mass material (e.g., concrete) that absorbs heat, an exterior layer from a transparent material and an air space in between.[253] Fig. 181. shows an effective composition for a trombe wall where placing a dark material or a layer of dark paint in front of the concrete is an important part of this combination.[254]

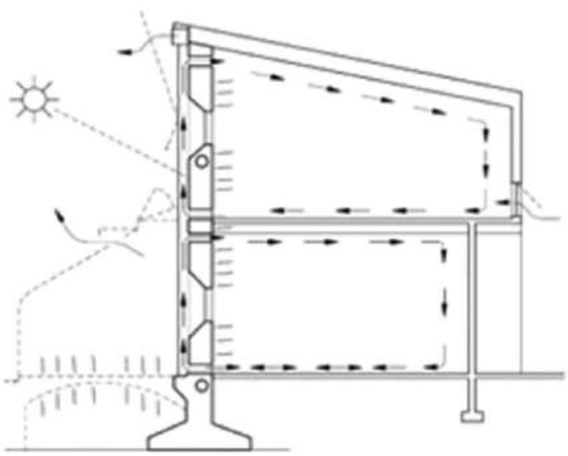

Fig. 180. Trombe Wall Principle

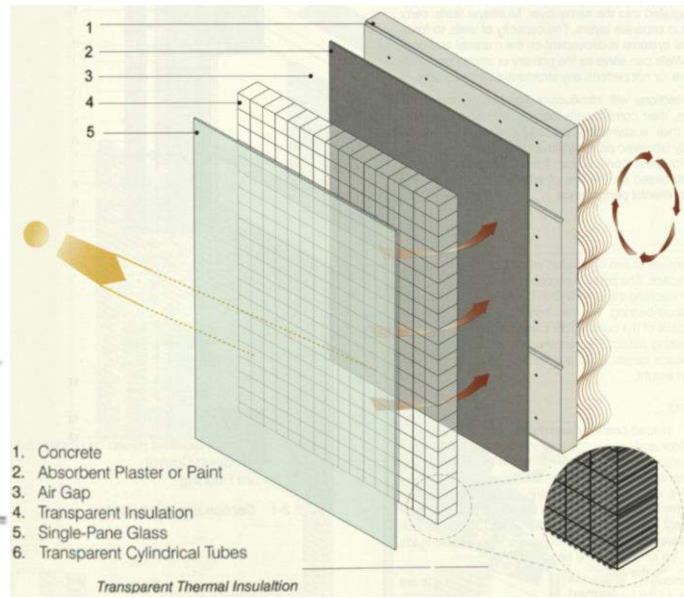

Fig. 181. Trombe Wall Composition

5.1.3.2.3 Color

Light colored, reflective materials especially on the building's envelope and roof can significantly reduce the heat-island effect and thereby cut the air conditioning loads. Darker colors might be used on surfaces where high mass is used as a design strategy (e.g., thermal mass) or in cold climates to absorb the largest amount of sun rays.[255]

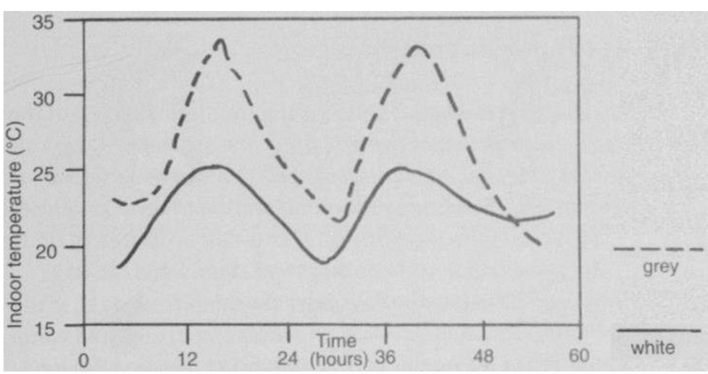

Fig. 182.
Temperature Difference of Interior Wall Surfaces with Different Colors

253 Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1350.
254 Shahin Vassigh, *Best practices in sustainable building design*, 2012, 34.
255 Ken Yeang, *The Green Skyscraper*, 1999, 237.

Ceilings and side walls closest to the windows were configured from uninterrupted planes of reflective white metal panels, in order to provide even daylight distribution and thus ensuring that any planting would thrive in the sky gardens of the Commerzbank Frankfurt in Germany.[256] In the Pearl River Tower's ground floor lobby, daylight can be redirected deep into the lobby space by curved, white fritted-glass ceilings and hanging metal panels.[257]

Fig. 183. Sky Garden of the Commerzbank Frankfurt

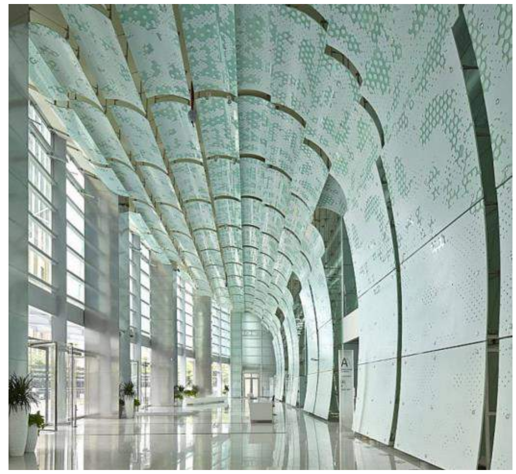

Fig. 184. Floor Lobby of the Pearl River Tower

5.1.3.3 Natural Lighting

Access to daylight is one of the basic human needs and day-lit environments enhance occupant productivity and comfort level. Furthermore, it improves visual comfort and the overall quality of the interior space. Thus, when aiming for passive design, access to daylight and also reducing artificial lighting loads is crucial.

5.1.3.3.1 Narrow Floorplate

Considering the solar path and the building orientation composed with narrow floor plates can provide adequate natural lighting for interior spaces though the amount of accessible light varies according to sky conditions. Deeper floor plans might need to be artificially lit on a larger portion of the floor area. However, this depth might vary according to the building location. For instance, a high rise in Sao Paulo may have larger floor depths than one in Northern Europe and still achieve the same daylight levels in the building interior.[258] After a certain depth, atriums can bring more daylight to the floor plate's deeper areas.

The Poly Real Estate Headquarters Complex in Guangzhou, China designed by SOM is oriented to face north and since the two towers have 15 meters (50 feet) wide floor plates and glass curtain walls they enjoy full penetration of natural light into the building interiors.[259]

[256] Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1350.
[257] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 16.
[258] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 151.
[259] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 88.

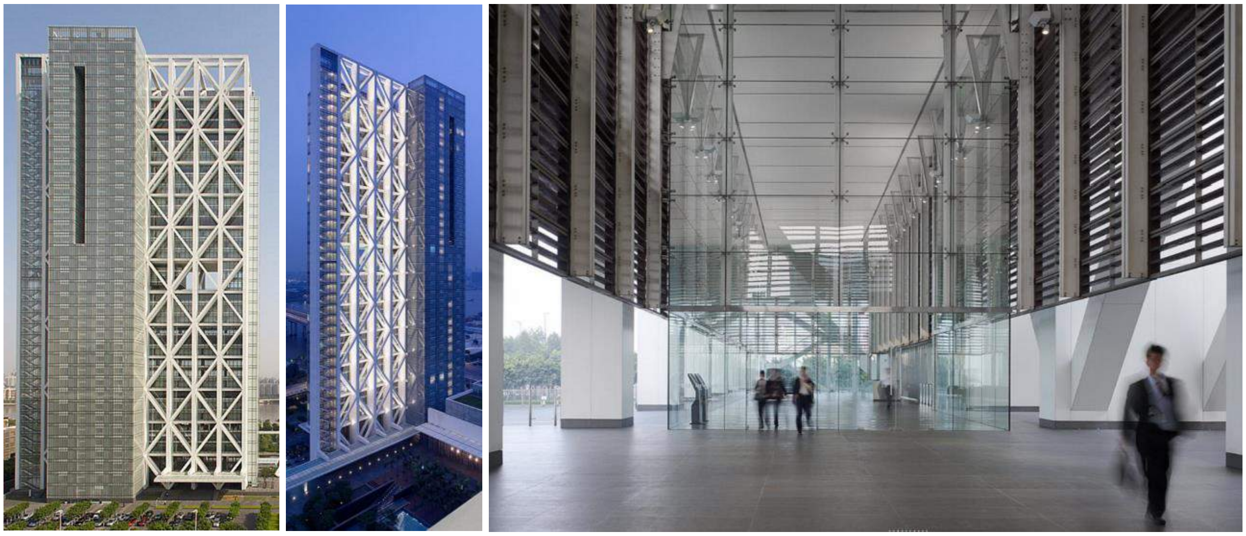

Fig. 185. Poly Real Estate Headquarters Complex in Guangzhou, China

The NBF Osaki Building in Tokyo has a form of a thin vertical plate and its narrow sides are positioned against predominant winds. As a result of the narrowness, the building interior does not need any columns, thus creating open plan offices which are entirely naturally lit.[260]

Fig. 186. NBF Osaki Building in Tokyo, Japan

Fig. 187. The Index Tower, Dubai

The 80-story Index Tower in Dubai has a narrow floor plate as well and the building's broad facades are oriented to the north and south with deep shading devices. Its narrow sides are facing east-west thus employing passive design strategies and providing natural light for the interior spaces.[261]

[260] A. Wood, S. Henry, D. Safarik, *Best tall buildings - Global overview of 2014 Skyscrapers*, 2014, 217.
[261] Terri Meyer Boake, *The evolution of tall buildings in the Gulf, From the sensational to the Sensitive*, 2015, 67.

5.1.3.3.2 Light Shelf

Light shelves are light redirection systems at the upper level of the window which increase the effectiveness of natural light into the interior space. They change the path of the incident sunlight and redirect it towards the room depth in order to provide an even distribution and uniform illumination. Thus, this system decreases the need for artificial lighting and thereby the building energy consumption. It not only enhances natural light access for the occupants but it decreases sun glare and works as a shading device at the same time. Various types of light shelves exist such as light shelves with mirror reflectors, prismatic and holographic systems or the so called suncatchers.[262]

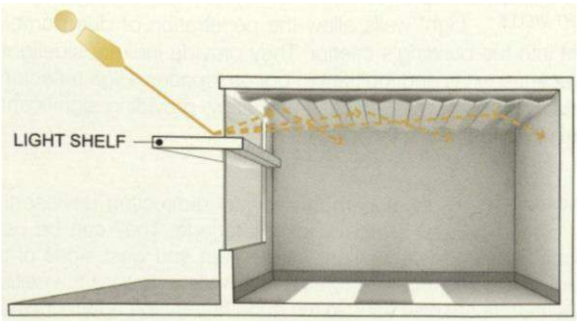

Fig. 188. Light Shelf, Mirror Reflectors

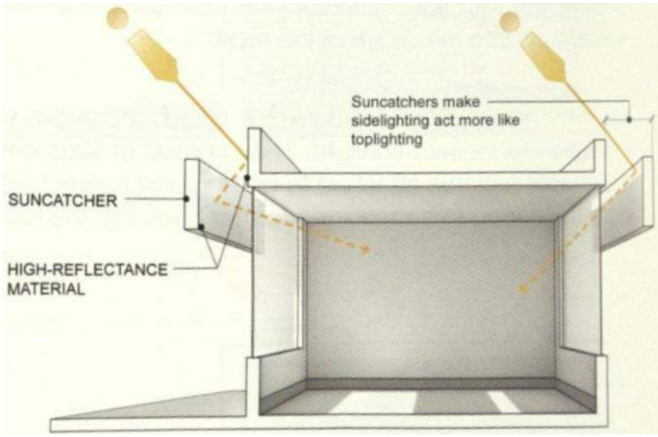

Fig. 189. Light Shelf, Suncatcher

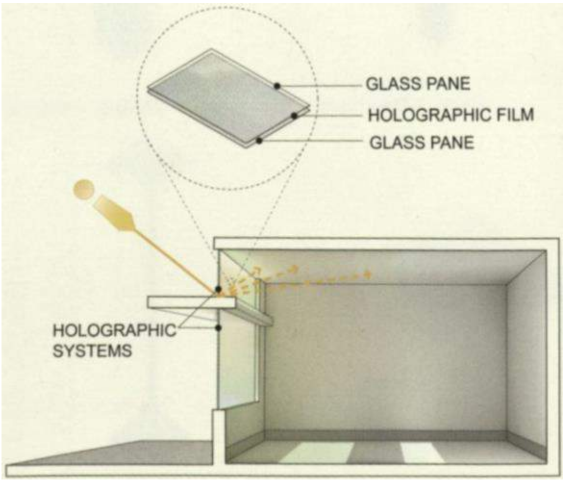

Fig. 190. Light Shelf, Holographic System

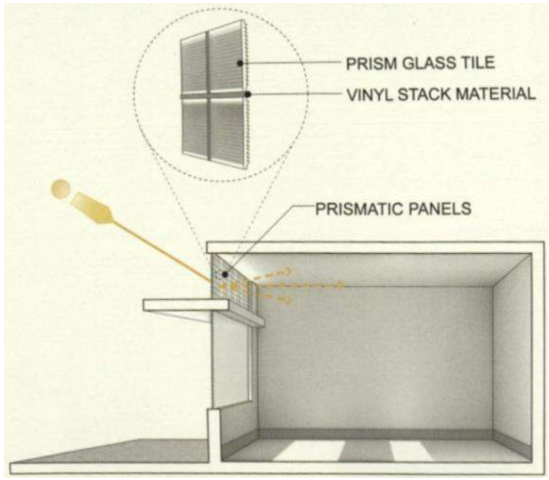

Fig. 191. Light Shelf, Prismatic System

Several light shelves are installed on the facade of the Shaklee's Headquarters building in California as well as on the National Library in Singapore. These systems provide direct light into the building reflecting excess sun rays.[263] [264]

[262] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 183.
[263] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 87.
[264] H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 176.

Fig. 192. Light Shelves of Shaklee's Headquarters, California

Fig. 193. Light Shelves of the National Library in Singapore

5.1.3.3.3 Lightwell

The lightwell serves the penetration of daylight into the interior spaces of the building and it may be used to bring natural ventilation to these spaces, too. It can be a shallow integrated slot in the building's volume as well as a large atrium running through the entire building. Without the use of the lightwell these interior spaces would otherwise be artificially lit and ventilated. This technique gives indirect sidelight to the adjacent indoor spaces as well as top light to the area on the well bottom. Indeed, efficiency is increased with the use of high reflectance surfaces in the lightwell while employing light colors.[265]

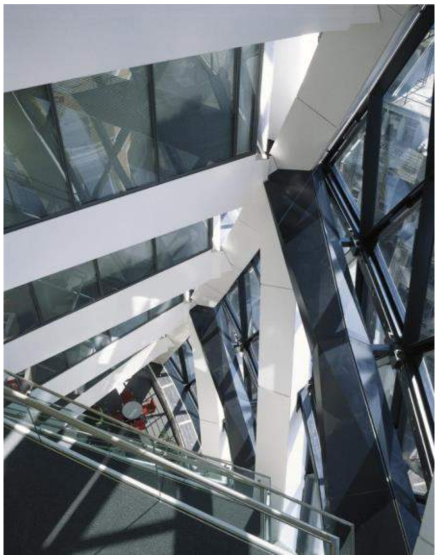

Fig. 194. Lightwell of the 30 St Mary Axe, London

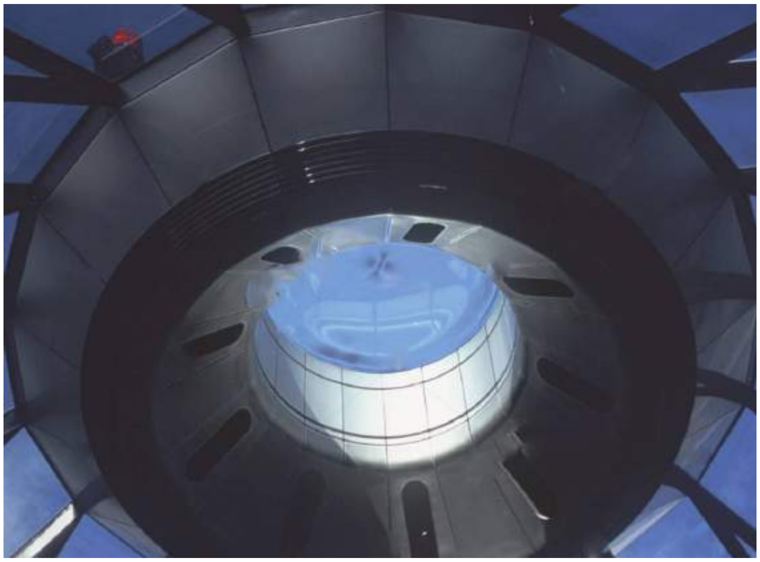

Fig. 195. Lightwell on the Top of the 30 St Mary Axe, London

[265] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 184.

Fig. 196. Central Atrium of the 1 Bligh Street, Sydney

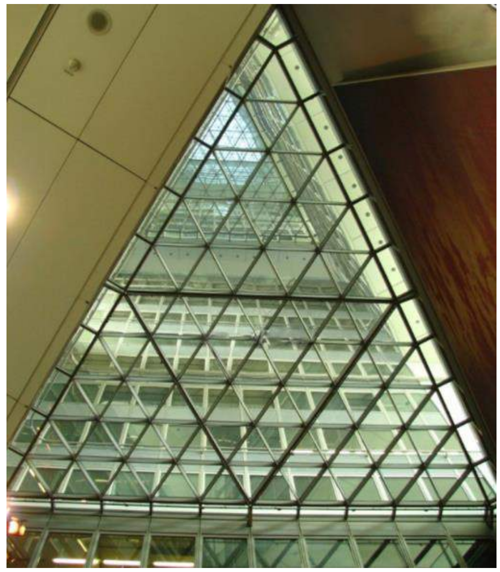

Fig. 197. Central Atrium of the Commerzbank, Frankfurt

5.1.3.3.4 Light Pipe

Light pipes are basically light guiding systems implemented when the designer wants to bring natural light into the depth of the building interior where the light shelves are not sufficient. In general, this depth is calculated to be around 10 meters (32.8 feet). Light pipes comprise three elements starting with light collection, transport of light and light distribution at the end of the tube.[266]

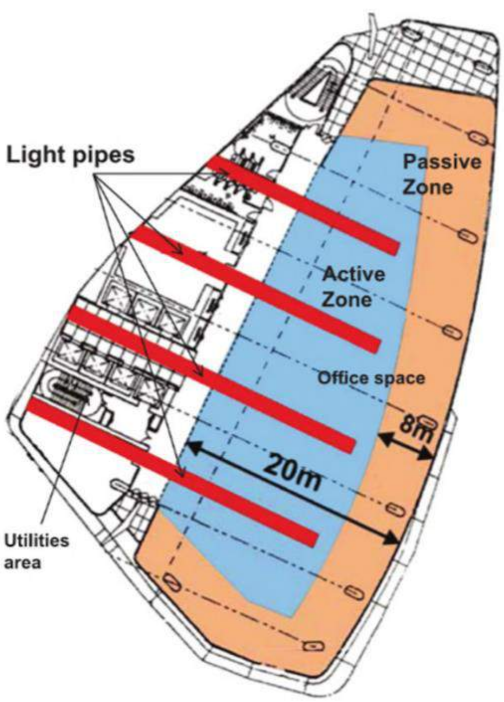

Fig. 198. Light Pipes in Plan

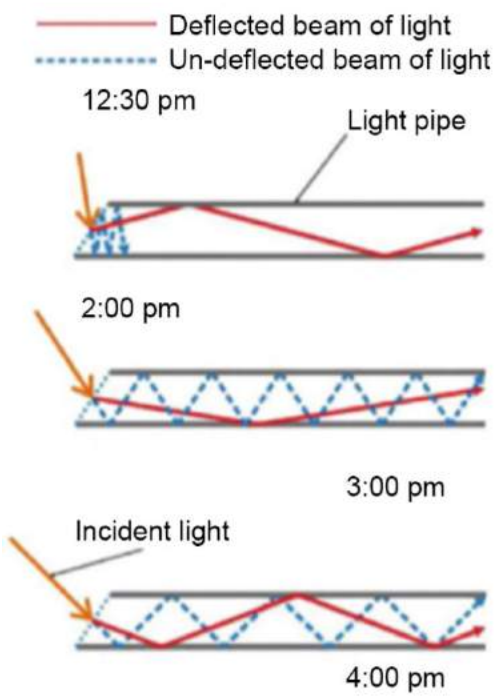

Fig. 199. Transmission of Light Through the Light Pipe

[266] K. Al-Kodmany, *Eco-Towers Sustainable Cities in the Sky*, 2015, 62.

Light pipes are usually used on the roof of low rise buildings in order the bring light into lower floors. Facade mounted systems are not as well developed yet as it is more difficult to catch the sun rays on a vertical surface and transport it horizontally than it is to do so on the roof and lead it down vertically. Therefore, the collector parts of light pipes on the facade usually stick out from the building's facade to be more efficient. However, as inquiry increases more efficient and better integrated technologies occur.[267]

Fig. 200. Heliobus System on the Rooftop of a School

Fig. 201. Tubular Daylight Guidance System TDGS

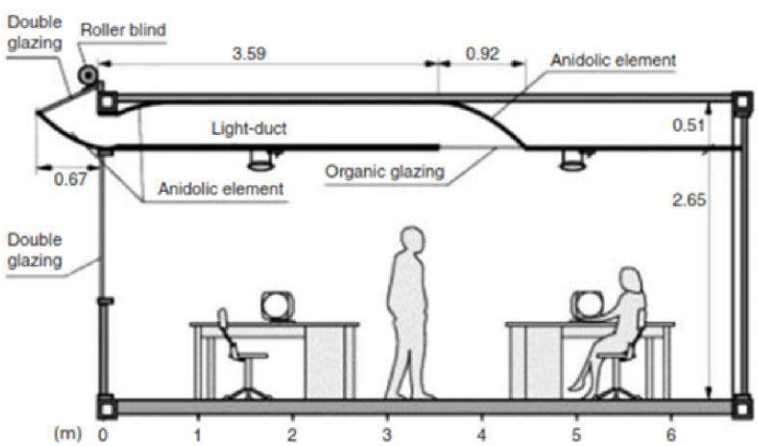

Fig. 202. Light Pipe Sticking Out from the Facade

Fig. 203. Light Pipes on the Facade

5.1.3.3.4.1 Solar Canopy Illumination System

The Solar Canopy Illumination System invented by the University of British Columbia in Vancouver is an innovative light guidance technology which can be integrated into the building facade to provide an even facade surface. It is based on little mirror arrays which are repositioning themselves in union according to the sun path and reflecting the sun rays further into the canopy guide pipe in the perfect angle in order to be distributed evenly in the interior space.[268]

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[267] MS. Mayhoub, DJ. Carter, *Towards hybrid lighting systems - A review*, 2009, 52.

[268] A. Rosemann, M. Mossman, *Development of a cost-effective solar illumination system to bring natural light into the building core*, 2007, 302.

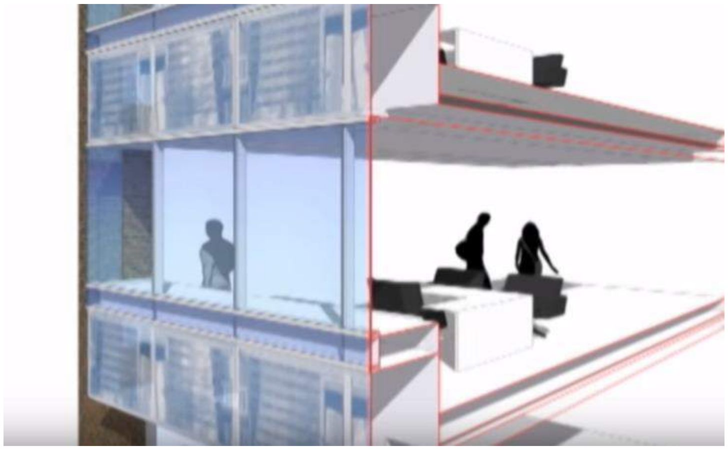

Fig. 204. Even Facade Surface with Solar Canopy Illumination System

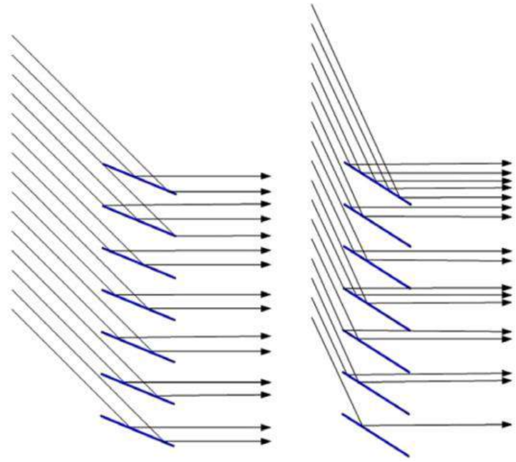

Fig. 205. Mirror Arrays Reflecting the Sun Rays

However, the movement of the mirrors costs some energy. It is very inexpensive since they are all controlled using two simple linear actuators. Moreover, it is possible to install photovoltaic cells between the space of the mirror arrays which can contribute energy to the mirrors' movement or provide power for the building.[269] This system is able to carry natural light into the building interior up to 40 meters (131 feet). In case the weather conditions are not sufficient or the solar radiation changes quickly there are fluorescent lights integrated into the system which automatically adjust themselves in order to maintain the desired illuminance in the interior space.[270]

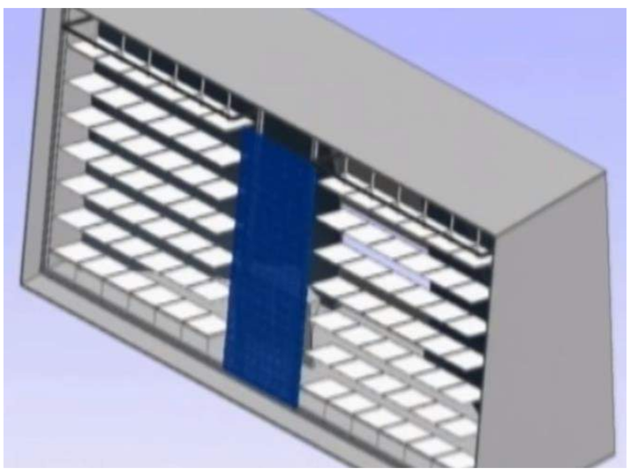

Fig. 206. Photovoltaic Cells Between the Mirror Arrays

Fig. 207. Room Lit by the Solar Canopy Illumination System

5.1.3.4 Shading

Solar shading is essential for glazed walls if we are designing an energy-efficient high rise thereby reducing glare and limiting the quality of light that enters the interior spaces. Sunlight also delivers heat that usually needs to be minimized, in addition to maximizing useful daylight at the same time. Large amounts of direct sunlight might cause significant contrast between lit and shaded

[269] A. Rosemann, M. Mossman, *Development of a cost-effective solar illumination system to bring natural light into the building core*, 2007, 303.
[270] https://www.youtube.com/watch?v=7M304wiuUYo 2:33 Accessed June 2016

areas, generating reduced visibility and visual discomfort. There exist different kinds of sun protections, of which type and application depend also on the building location, strength of the sun and if they need to be fixed or be adjustable.

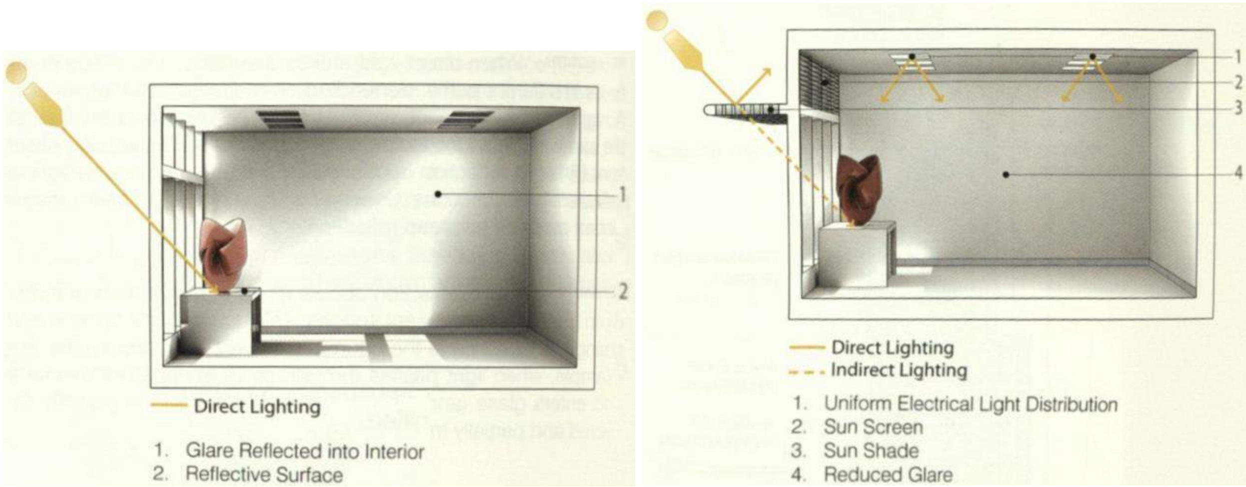

Fig. 208. Room with Glare and without Glare

Adjustable, intelligent shading operates by automated angle control, which takes into account the outside weather conditions and the sun's current incident angle. At certain times of the day, passive solar radiation can be taken advantage of and the shading louvres position themselves at different angles; in other periods, solar gain is not wanted in the building interior.[271]

The solar shading can be placed inside or outside of the building. Internal shading systems are inexpensive, and they need low maintenance and can be deployed even in bad weather conditions. However, they have a great drawback. This is the heat of the sun rays that they let into the interior space. Thus, these systems are considered to have an ineffective control on the interior temperature. In contrast to this, exterior systems can be about 3-5 times as efficient although they need to withstand harsh weather conditions and might have more complicated maintenance, too.[272]

Today, there is a third way to apply solar shading, which is installed neither in the building's exterior nor in its interior. It is located in-between, installed in the facade's cavity that is usually a double-skin facade (see: Double-Skin Facade). This solution is highly efficient since the shading is not affected by the weather and does not let the sun's heat into the building's interior space either.[273]

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[271] Ken Yeang, *The Green Skyscraper*, 1999, 219.
[272] Petra Liedl, Michael de Saldanha, *Climate Skin Building-skin concepts that can do more with less energy*, 2008, 46.
[273] Petra Liedl, Michael de Saldanha, *Climate Skin Building-skin concepts that can do more with less energy*, 2008, 47.

Fig. 209.
A Variety of Techniques are Available for Improving the Thermal Performance of the Facade in Ways that Don't Obstruct Views from the Building

5.1.3.4.1 Building Form

By considering the sun path of the site there are different building forms that inherently provide shading for a structure. The Al Hamra Tower in Kuwait has an asymmetrical form that resembles the traditional robes of the Kuwaitis and thus minimizes the tower solar heat gain while it maximizes views from windows to the Arabian Gulf. The south wall openings are constructed to limit solar penetration.[274]

Fig. 210. Al Hamra Tower, Kuwait

[274] Terri Meyer Boake, *The evolution of tall buildings in the Gulf, From the sensational to the Sensitive*, 2015, 68.

The Commerce Bank at Jeddah, in Saudi Arabia built in 1984 was one of the first high rises where an environmental approach was truly followed. This tower introverts its glass facade away from the harsh desert sun, thus creating an internal face to the high rise shielded by the ambient environment. The building's exterior central atrium shades the glass facade and filters the direct lights out from the interior. With the help of this form and other features the building has an even temperature of 20°C (68°F) for the inside skin of its curtain wall.[275]

Fig. 211. Commerzbank at Jeddah, Saudi Arabia

5.1.3.4.2 Horizontal Shading

Building orientation is very important for solar screening. In general, horizontal solar shading can block out direct sun rays on the south facade of the building with no or very little effect on the view outside. Thus, entering light is diffused and has low energy, providing a comfortable interior environment and mitigating artificial lighting and cooling loads.[276] The fixed overhangs on the 21-story TTDI Phase 6D1 residential tower in Kuala Lumpur were configured according to a sun path study and how the sunlight falls on the building's east and west facades.[277]

Fig. 212.
Solar Shading of the TTDI Phase 6D1, Kuala Lumpur

275 David Bennett, *Skyscrapers form and function*, 1995, 65.
276 Petra Liedl, Michael de Saldanha, *Climate Skin Building-skin concepts that can do more with less energy*, 2008, 46.
277 Ken Yeang, *Eco Skyscrapers*, 1998, 117.

The 81-story high Aqua Tower in Chicago has large cantilevered terraces on its facades and they work as shadings for the interior rooms beneath as well as providing a foil to wind pressure, confusing the flow of winds around the tower. The high rise does not have any identical floors.[278]

Fig. 213. Shading System of the Aqua Tower in Chicago

During the day, the south facade offices and rehearsal spaces of the 42nd Street Studios in Manhattan are flooded with diffused natural light owing to its perforated stainless steel louvres. They start at 1.8 meters (6 feet) high above the floors and expand to the next story up above. At night, there is a light show projected on the canvas of these louvres.[279]

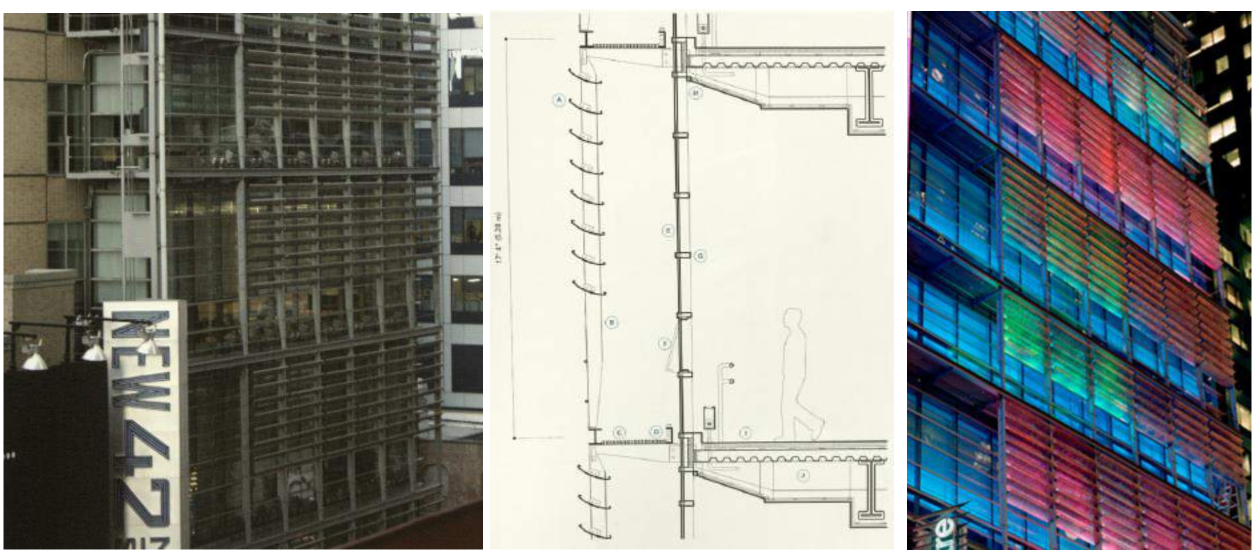

Fig. 214. Horizontal Steel Louvres of the 42nd Street Studios in Manhattan

[278] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 364.
[279] Scott Murray, *Contemporary Curtain Wall Architecture*, 2009, 88.

The 52-story New York Times Tower located in Manhattan also has an outer layer of sun shading from ceramic rods. The facade represents a brise-soleil concept on a huge scale with the positioning of the ceramic tubes around 0.46 meters (1.5 feet) in front of the glass facade, thus achieving up to 50 percent solar heat reduction. These rods also define the building's character since they reflect external weather conditions thus altering their color. That means a white facade color by sunshine, grey by overcast sky, and pink and orange by sunset or sunrise.[280]

Fig. 215. Ceramic Rods of the New York Times Tower in Manhattan

The 17-story Torre Cube in Guadalajara, Mexico, has a different kind of external brise-soleil system in order to protect the building from solar gain. Welded steel frames are suspended in a distance of 0.60 meters (2 feet) in front of the glass facade, holding horizontally laid heat-treated pine slats.[281]

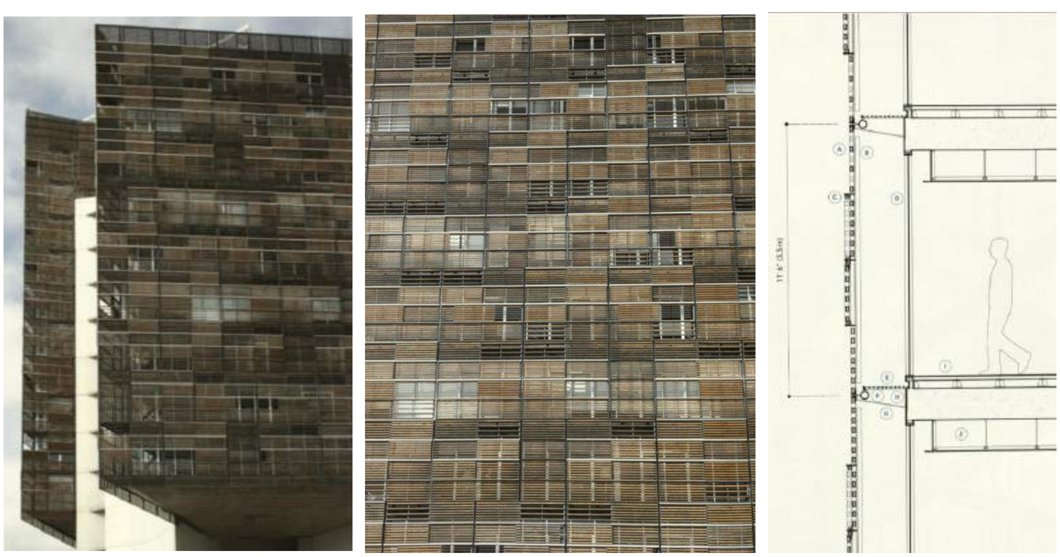

Fig. 216. Brise-Soleil System of the Torre Cube in Guadalajara, Mexico

[280] Scott Murray, *Contemporary Curtain Wall Architecture*, 2009, 208.
[281] Scott Murray, *Contemporary Curtain Wall Architecture*, 2009, 150.

5.1.3.4.3 Vertical Shading

Usually, the application of vertical shading louvres might be a good option on the building's east and west facades because of the lower position of the sun.[282] Thus, the north-west facade of the Federal Building in San Francisco is provided with light-diffusing translucent glass fins for shading purposes. The vertical fins are fixed in front of a fritted glass facade, which reduces solar transmittance while allowing views outside.[283]

Fig. 217. North-West Facade of the Federal Building in San Francisco

The One Omotesando in Tokyo incorporates external vertical fins of laminated wood in its facade thereby reducing direct sunlight that falls on the floor-to-ceiling glass panels. These 0.46-meter (1.5-foot) deep fins give a unique texture and color to the building. The use of wood on the building exterior was permitted as a large amount of water sprinkler heads were installed on the curtain wall exterior.[284]

Fig. 218. Vertical Fins of the One Omotesando in Tokyo

[282] Petra Liedl, Michael de Saldanha, *Climate Skin Building-skin concepts that can do more with less energy*, 2008, 47.
[283] Scott Murray, *Contemporary Curtain Wall Architecture*, 2009, 184.
[284] Scott Murray, *Contemporary Curtain Wall Architecture*, 2009, 102.

5.1.3.4.4 Egg-Crate Shading

Using egg-crate shading provides benefits from both the horizontal and vertical shading system characteristics. The Tehran International Tower's total energy consumption is reduced by one-third compared to a usual high rise in the same district owing to the use of an egg-crate shading system along with a few other energy efficient design strategies.[285]

Fig. 219. Egg-Crate Shading of the Tehran International Tower, Iran

5.1.3.4.5 Mashrabiya

The traditional Islamic form Mashrabiya often occurs in the vernacular Arabic architecture. Today, high rises in the Middle East often use this motif on the building surface in order to achieve privacy and proper shading. The cladding system of the 46-story Doha Tower in Doha refers to the Mashrabiya motif. This facade system reduces the building's cooling load by up to 20 percent.[286]

Fig. 220. Mashrabiya Motif of the Doha Tower, Doha

[285] Pooya Lotfabadi, *High-rise buildings and environmental factors*, 2014, 288.
[286] Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 23.

The exterior of the Al Bahar Towers in Abu Dhabi derives from the traditional Islamic patterns, as well. Both towers comprise more than 1,000 individual shading devices. These shading systems response to the sun path in the desert and thus are open or closed depending if they are located on the building's most severely exposed parts to the sun or on less exposed ones. This shading system results in a 25 percent total cooling load reduction for the two buildings.[287]

Fig. 221. Al Bahar Towers in Abu Dhabi

5.1.3.4.6 Exoskeleton

The O-14 office tower in Dubai is constructed by an 0.46-meter (18-inch) thick concrete exoskeleton facade that contains more than 1,000 openings. This not only serves as a solar screen, giving great shade to the tower, but it also naturally ventilates the building's facade through the stack effect since there is a 1-meter (3.3-foot) gap between the exoskeleton structure and the glass surface. This facade technique reduces the building's overall energy consumption by 30 percent. The exoskeleton structure absorbs all the lateral forces, as well (see: Structures).[288] The COR Tower in Miami (not yet completed) has a similar design concept as the O-14 building in Dubai.[289]

Fig. 222. O-14 Tower in Dubai

287 CTBUH, *2012 Awards Book*, 2012, 172.
288 David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 476.
289 Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 20.

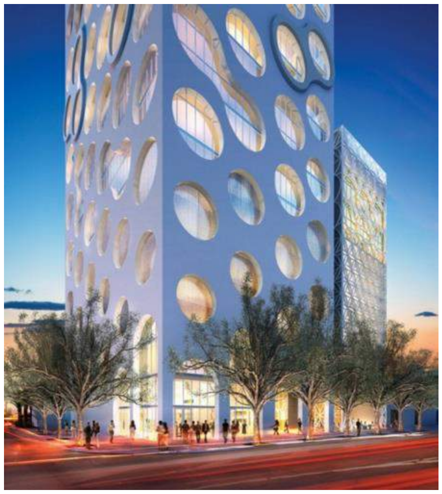

Fig. 223. COR Tower, Miami

5.1.3.4.7 Canopy

Canopies are often used on the building structure since they shelter from different weather conditions such as snow, rain or hail; however, they are mostly used for shading purposes against the sun rays. The canopy can also be a great design element for the building and it is usually applied on the roof or on the ground level. The Capital Gate in Abu Dhabi and the Al Hamra Tower in Kuwait both have an extensive solar canopy above the building entrance while the Singapore National Library has a similar structure on the rooftop.[290]

Fig. 224. Capital Gate, Abu Dhabi

Fig. 225. Al Hamra Tower, Kuwait

Fig. 226. National Library, Singapore

[290] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 472.

5.1.4 Wind

Wind is a significant factor in high rise passive design in order to reduce the building's energy demand. It can be exploited on the building's facade to cool the exterior surface as well as it may provide natural ventilation for the interior spaces.

5.1.4.1 Building Exterior

5.1.4.1.1 Building Form

The shape of the high rise has a great effect on the wind's behavior around the building. The 30 St Mary Axe in London has an elliptical shape which facilitates natural ventilation for the high rise as the wind generates air pressure differences along the facade.[291] After studying the predominant winds of the locality, the form of the National Library in Singapore helps to significantly reduce its air conditioning loads. The building uses about 170 kWh/m2 (53,890 Btu/ft2) energy annually compared to a typical office building with around 230 kWh/m2 (72,910 Btu/ft2). One needs to take into account, also, that the air conditioning in the library is turned on non-stop during the entire week.[292]

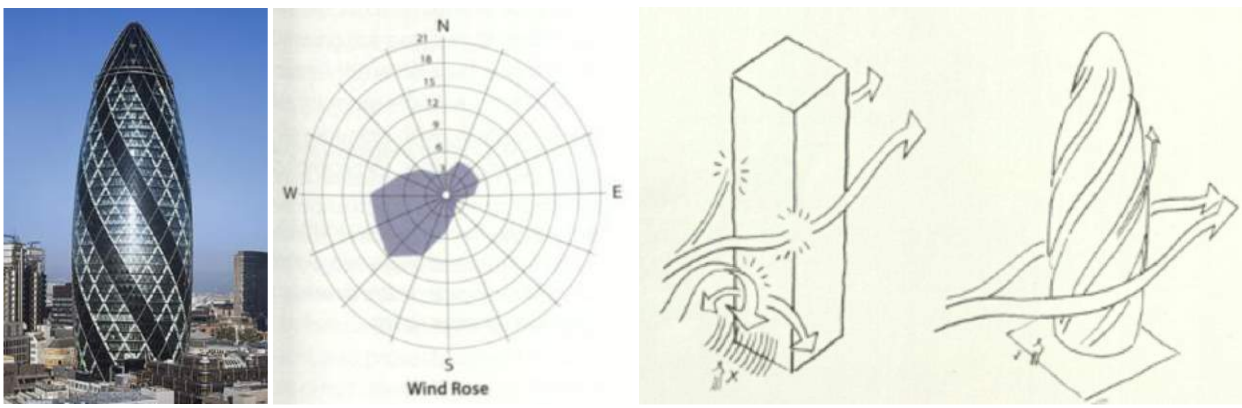

Fig. 227. Form of the 30 St Mary Axe, London

Fig. 228. National Library, Singapore

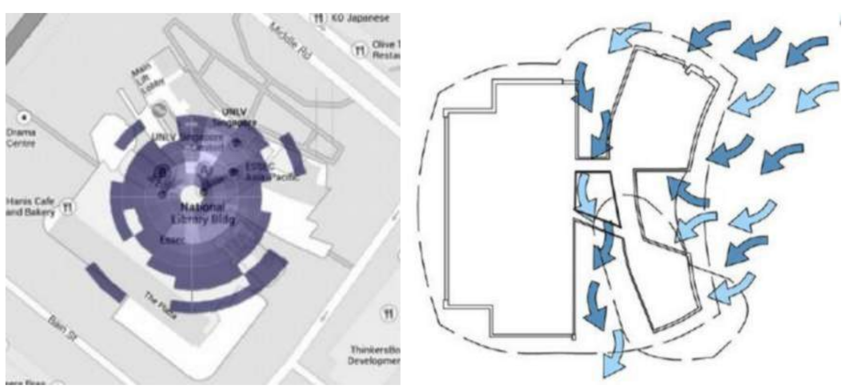

Fig. 229. Wind-Rose Diagram and Air Circulation of the National Library, Singapore

[291] T. Riley, G. Nordenson, *Tall buildings*, 2003, 72.
[292] C. Grech, D. Walters, *Future office: Design, practice and applied research*, 2008, 137.

5.1.4.1.2 Wind Scoop

This system helps to cool the building exterior through scooping up prevailing winds or breezes and transfers them quickly along the wind scoop. The 24-story Plaza Atrium, in Malaysia designed by Ken Yeang has a giant open-air atrium incorporated in its facade serving as a giant wind scoop.[293]

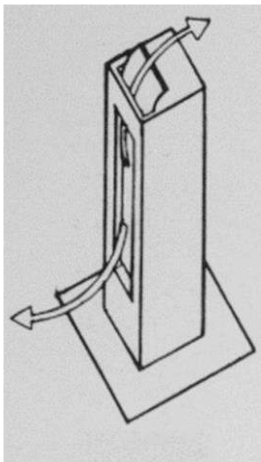

Fig. 230. Wind Scoop

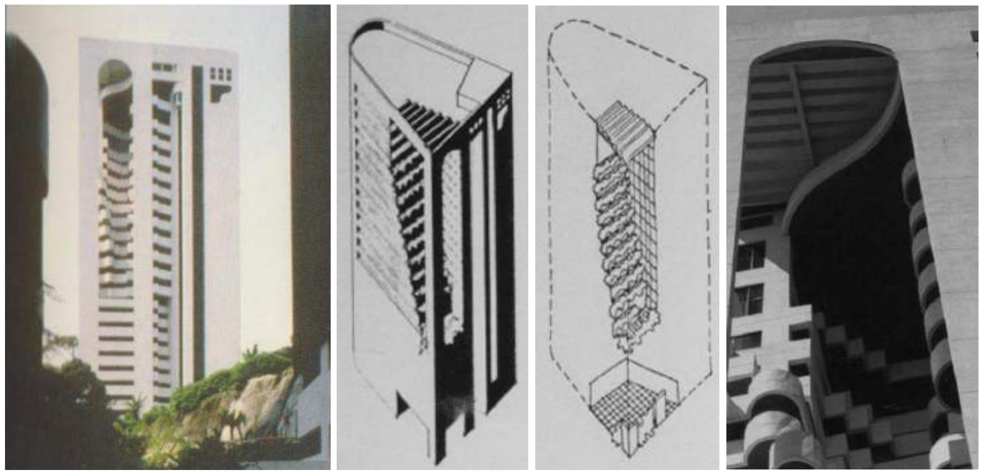

Fig. 231. Wind Scoop of the Plaza Atrium, Malaysia

5.1.4.1.3 Wing Wall

The wing wall is a vertical solid panel placed next to facade openings on the windward side of the building. It accelerates the wind speed, and creates pressure differences, thereby, inducing ventilation and a cooling effect. Wing walls with different positions generate different pressure differences which influence the speed of the air flow and thus the ventilation effectiveness.[294]

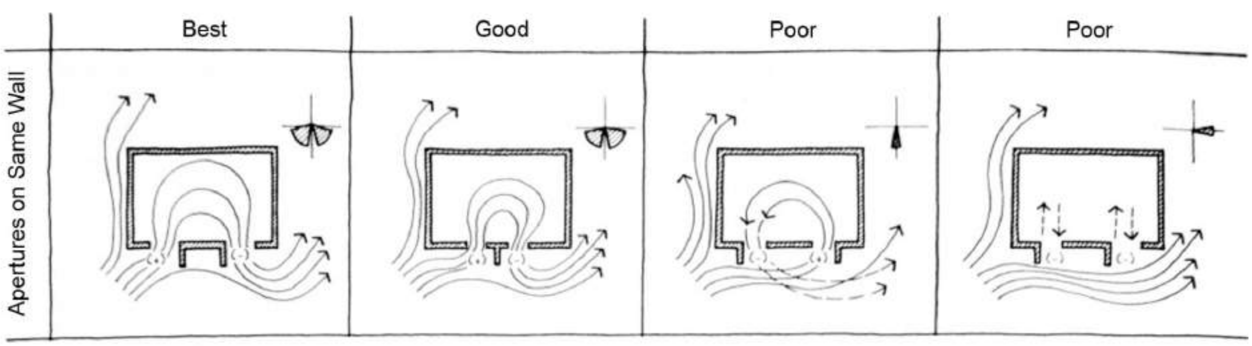

Fig. 232. Wing Wall Apertures on the Same Wall

[293] Ken Yeang, *Bioclimatic Skyscrapers*, 2000, 54.
[294] http://passivesolar.sustainablesources.com/ Accessed June 2016

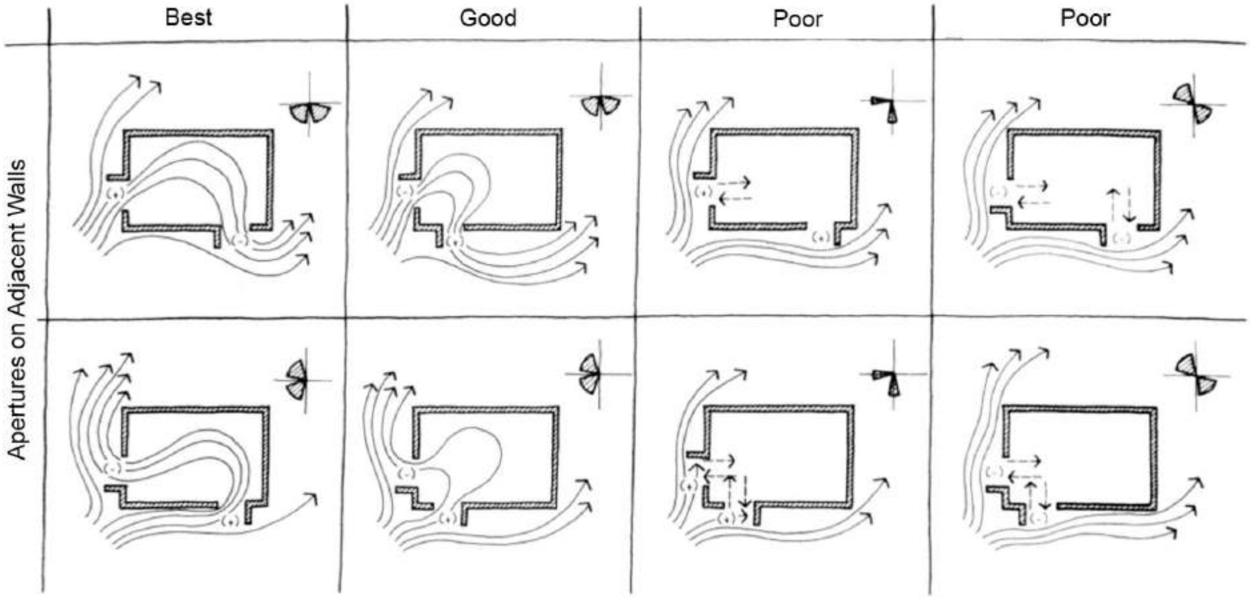

Fig. 233. Wing Wall Apertures on Adjacent Walls

The Post Tower in Bonn, Germany is designed with a double skin facade in which outer layer extends beyond the high rise, thereby, creating large vertical wing walls on the north and south sides of the building. Wind studies showed that this technique helps to create pressure differences, inducing cross-ventilation through the building's interior atrium.[295]

Fig. 234. Wing Wall of the Post Tower in Bonn, Germany

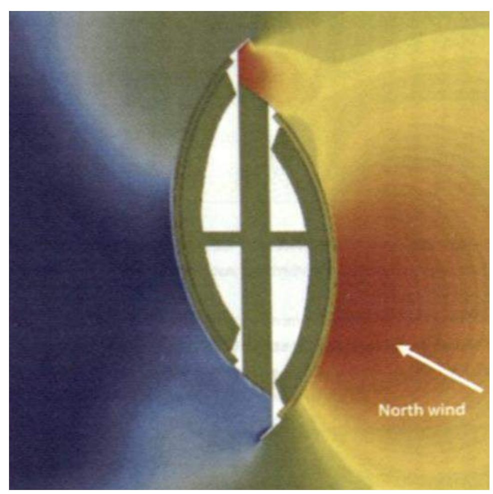

Fig. 235. Wing Walls Creating Pressure Differentials

The 21-story Menara UMNO designed by Ken Yeang is located in Malaysia and employs wing walls in its design, as well. The tower's vertical projecting wing walls run through the entire height of the building and direct a great amount of the prevailing winds into the building interiors. This is a crucial element of the high rise design since these walls channel air into the inner spaces at higher speeds thus providing natural ventilation in Penang that has a hot and humid climate.[296]

[295] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 88.
[296] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 54.

Fig. 236. Wing Wall of the Menara UMNO, Malaysia

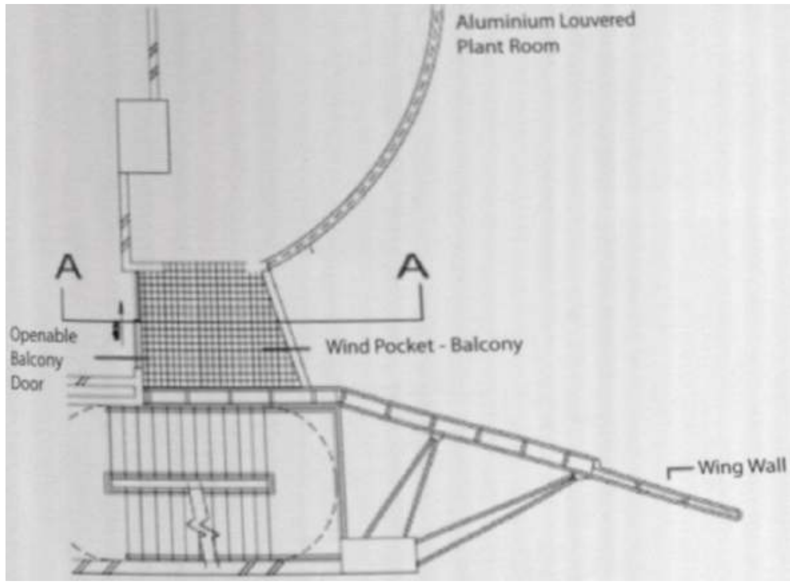

Fig. 237. Wing Wall Detail of the Menara Umno, Malaysia

5.1.4.2 Natural Ventilation of the Building Interior

Natural ventilation is very important in passive design since it has a significant effect on the building's energy consumption. It is not only energy efficient but it also offers a great way to provide fresh outside air to the building occupants thus enhancing their feeling of comfort. Natural ventilation may not fully displace air conditioning though it can reduce the need for it. An analysis of the locality's prevailing winds might be necessary in order to appropriately configure the building's facade and to determine the best locations for facade openings.[297]

Air movement between 0.4-3.0 m/sec (1.3-9.8 ft/sec) can generate cooling of occupants. Heat loss is increased by air movement and an air movement of 1.0 m/sec (3.28 ft/sec), which corresponds to walking speed, decreases 30.3 °C (86.5 °F) air temperature to 27.3 °C (81.1 °F) effective temperature.[298] Accordingly, little air movement in the building interior can also cause an efficient cooling effect.

5.1.4.2.1 Facade Elements

5.1.4.2.1.1 Double-Skin Facade

The facade is not anymore the envelope of the high rise only but it significantly contributes to the building's efficient energy performance. It has a great impact on daylight penetration, air ventilation and on the interior environment. For this reason, most of today's high rises employ double skin facades since it offers so many benefits.

[297] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 5.
[298] Ken Yeang, *The Green Skyscraper*, 1999, 246.

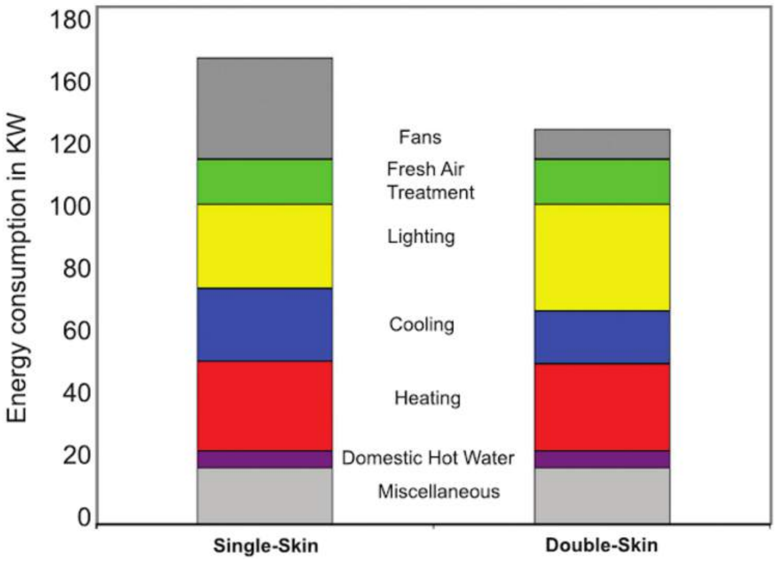

Fig. 238. Energy Consumption of Single-Skin Facade Compared to Double-Skin Facade

Fig. 239. Interior Louvres in the Double-Skin Facade

Basically, the double-skin facade is composed of two glass layers which are separated by an air cavity to provide insulation and air ventilation. This buffer zone should be deep enough to be able to provide sufficient air movement in hot climates as well, in case the facade is not mechanically ventilated by fans. This gap is a perfect place for implementing solar shading devices, thereby, hindering the admission of sun rays into the interior.[299] For instance, there are two types of shading devices incorporated on the facade of the Cambridge Public Library, USA. Besides the horizontal shading elements attached to the outer layer of the glazing there are also horizontal louvres in the cavity of the double-skin facade.[300]

Fig. 240. Horizontal Shading Systems of the Cambridge Public Library, USA

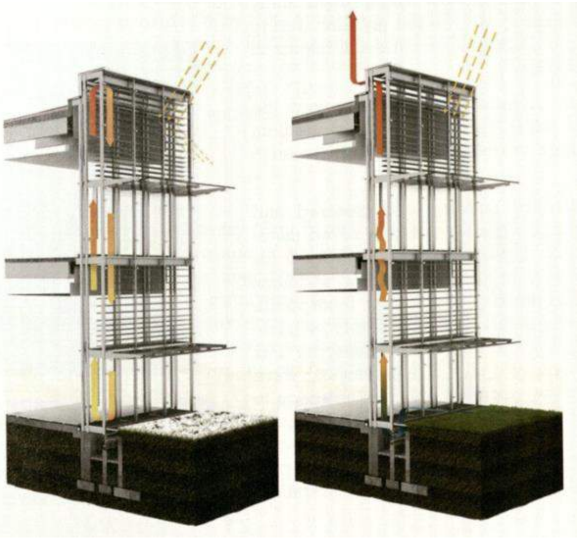

Fig. 241. Facade of the Cambridge Public Library in Winter Mode and Summer Mode

[299] N. Guariento, S. Roberts, *Building Integrated Photovoltaics - A Handbook*, 2005, 51.

[300] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 321.

The exterior glass layer of the double skin usually mediates outer climatic conditions as long as the inner one seals and insulates the building. The double-skin facade can be one continuous vertical system linking the floors or constructed from single units thus being isolated systems by the floors.[301]

Fig. 242. Multi-Story Double-Skin Facade

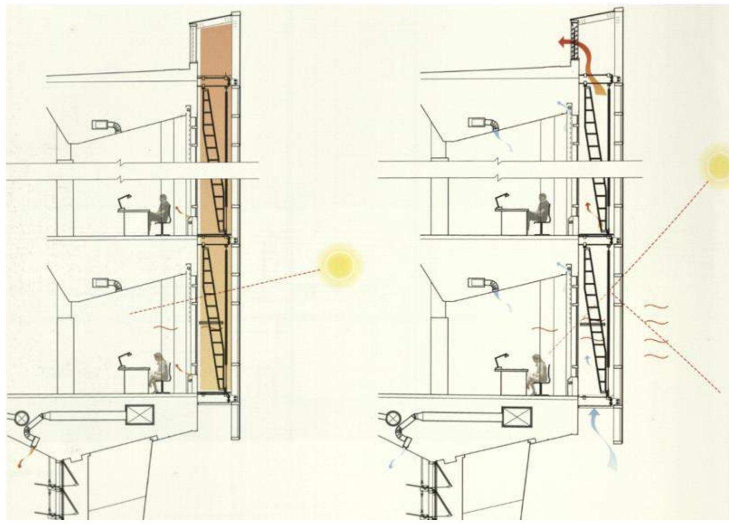

Fig. 243. Double-Skin Facade's Performance as Continuous Vertical System

One of the greatest advantages of the double-skin facade is that it can have operable windows in the inner, as well as on the outer, skin thus providing fresh air regardless of the weather conditions and can cool the interior spaces when needed. During cold weather the outer openings can be kept closed, using the cavity as a thermal buffer.[302]

The glazing type influences heat gain too. Using spectrally selective glazing in hot climates leads to block the major part of infrared radiation which raises the air temperature. Meanwhile it lets most of the visible parts of the light spectrum inside. In order to keep heat in or even to support solar heat gain, low emissivity coatings are used in cold and temperate climates.[303]

Fig. 244. Double-Skin Facade from Single Panels

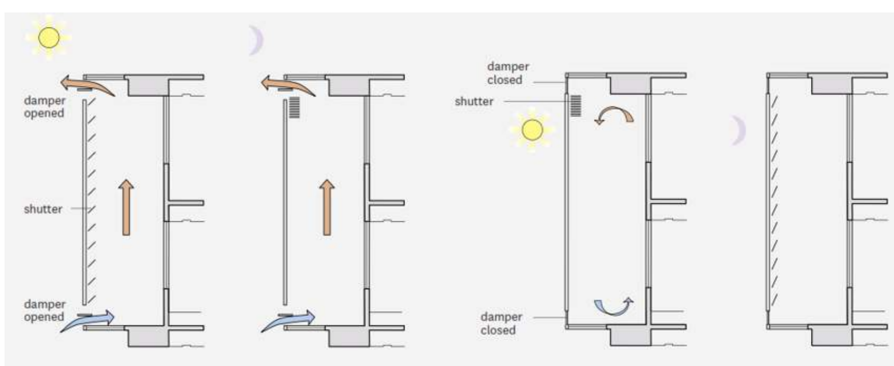

Fig. 245. Double-Skin Facade's Performance in the Summer and in the Winter

[301] H. Elotefy, K. S.S. Abdelmagid, E. Morghany, T. M.F. Ahmed, *Energy-efficient Tall buildings design strategies: A holistic approach*, 2015, 1367.
[302] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 88.
[303] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 97.

The Sowwah Square in Abu Dhabi features a novel building envelope configured by an extensive double-skin facade that works perfectly in the hot desert climate as a buffer between the exterior and interior environment. The building has a double-skin facade that not only encompasses the entire four elevations of the building, but it continues on the building's top, as well. This provides the high rise a fully glazed envelope surface with a cavity in the facade running around and above the building, meeting the high rise's atrium in the centrum. This is utilized by the building's cooling system whereby conditioned exhaust air from the tenant floors is ventilated to the top of the building and circulated into the cavity of the double-skin facade in order to mitigate the hot outside air temperature by the cooled air from the interior spaces. Modulating dampers make it possible to direct the cooled air to the building's elevation, which is the most exposed to the current solar radiation. The air is channeled to the fourth floor's mechanical room, where it is exhausted outside or routed to the VIP car park.[304]

In the winter, when the outer air temperature is cooler than the exhausted air from the interior spaces, outside fresh air is supplied into the facade's cavity. In the hot summer months, the average air temperature of the exterior environment is around 49 °C (120 °F), whereas the cavity wall's temperature is around 32 °C (89 °F). The savings of this innovative cooling design is estimated to be 702 tons in the summer while 537 tons in the winter. Conditioned exhaust air that would normally be wasted to the atmosphere is thereby reused in an economic way and contributes to an efficient cooling system.[305]

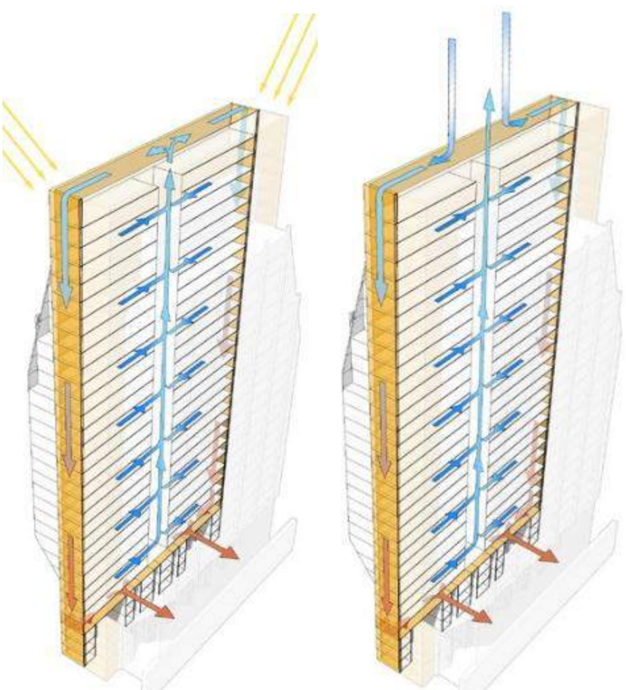

Fig. 246. Sowwah Square's Cooling System in the Summer and in the Winter

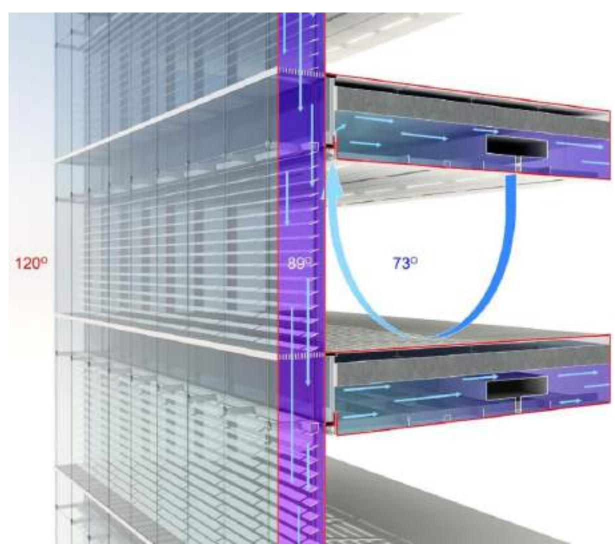

Fig. 247. Double-Skin Facade as Insulation Barrier of the Sowwah Square

304 http://www.archdaily.com/401224/sowwah-square-goettsch-partners Accessed June 2016

305 http://www.archdaily.com/401224/sowwah-square-goettsch-partners/51de2d86e8e44eed7200007f-sowwah-square-goettsch-partners-diagram Accessed June 2016

5.1.4.2.1.2 Operable Windows

Operable windows are usually one of the most highly appreciated features of the high rise building by the occupants since they allow the direct control of human over their environment. This not only enhances tenants' satisfaction but also their productivity. However one should know that operating windows are not always accessible by the occupants and sometimes these are operated by the building's BMS.

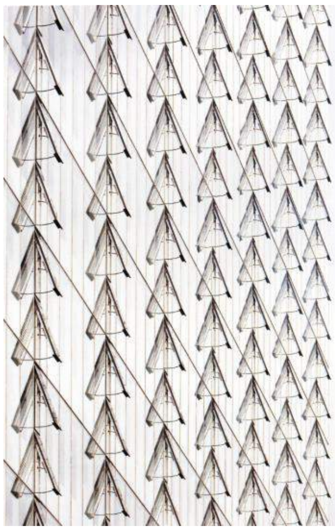

Fig. 248. Operable Windows of the Manitoba Hydro in Winnipeg, Canada

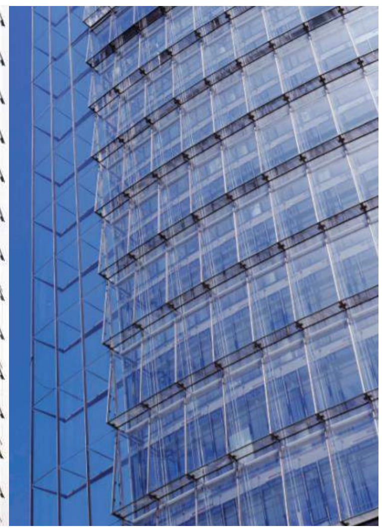

Fig. 249. Operable Windows of the Post Tower in Bonn, Germany

Fig. 250. Pivoting Glass Louvres of the Atrium Tower in Potsdamer Platz, Berlin

5.1.4.2.2 Natural Ventilation Types

5.1.4.2.2.1 Single-Sided Ventilation

There is single-sided ventilation when the air enters and exits the interior on the same side of the space. The space depth should not exceed 2.5 times of its height.[306]

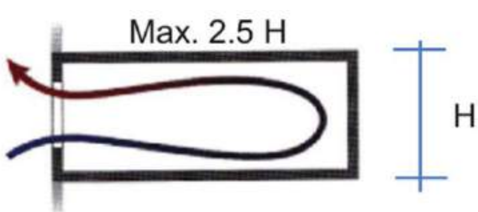

Fig. 251. Single-Sided Ventilation

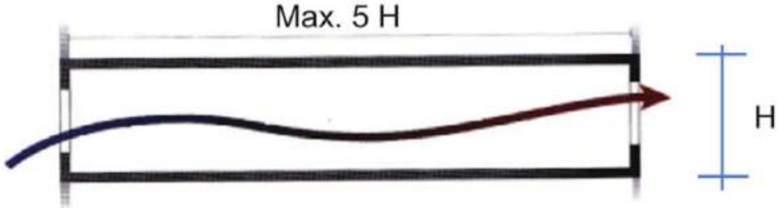

Fig. 252. Cross-Ventilation

[306] K. Al-Kodmany, *Eco-Towers Sustainable Cities in the Sky*, 2015, 66.

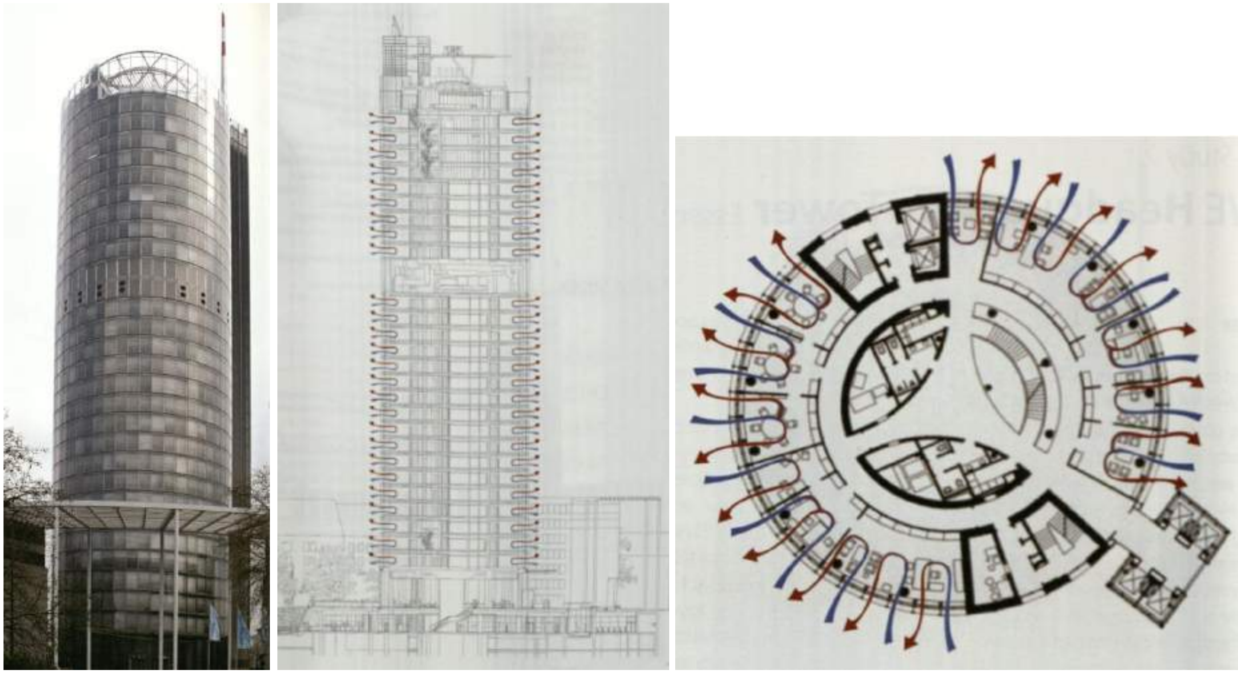

Fig. 253. Single-Sided Ventilation in the RWE Headquarters in Essen, Germany

5.1.4.2.2.2 Cross-Ventilation

We are talking about cross-ventilation when the air enters from one side and leaves at the opposite side of the interior space. This occours owing to the pressure differences between the two openings. This system is effective when the space depth does not surpass five times its height.[307]

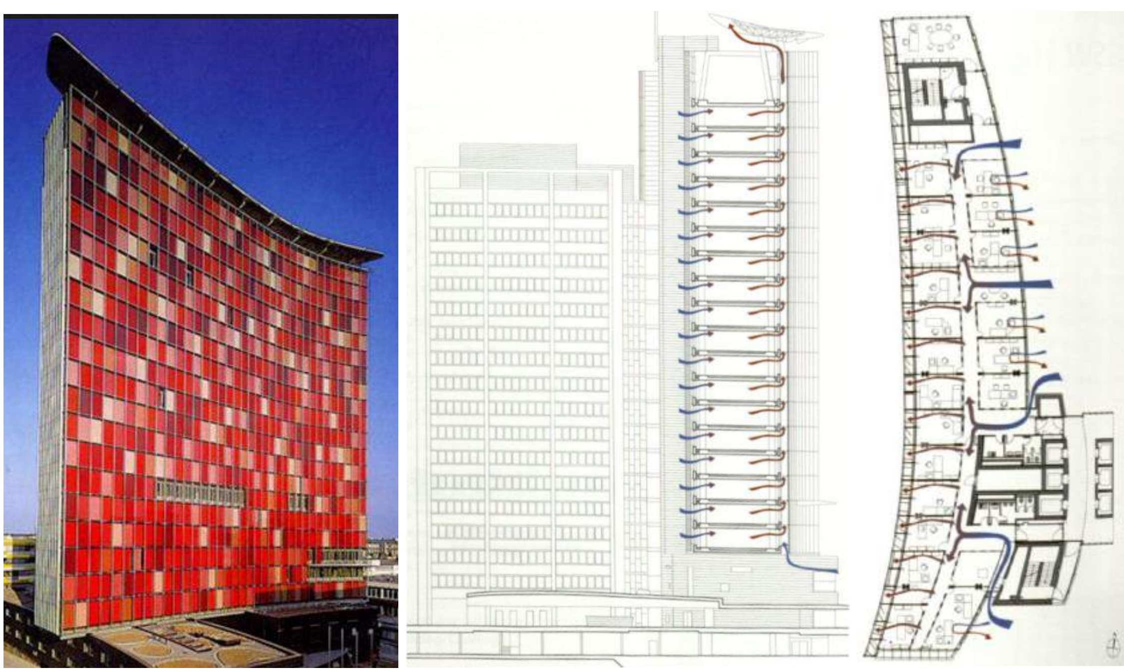

Fig. 254. Cross-Ventilation of the GSW Headquarters Tower, Berlin

[307] K. Al-Kodmany, *Eco-Towers Sustainable Cities in the Sky*, 2015, 66.

5.1.4.2.2.3 Stack-Ventilation

Stack-ventilation, also known as stack or chimney effect, occurs as a result of pressure differences between the interior and exterior spaces or between certain zones in the high rise. Buoyancy induced air rises up and exits the space at a higher level. This effect is used in atriums and in sky courts of buildings.[308]

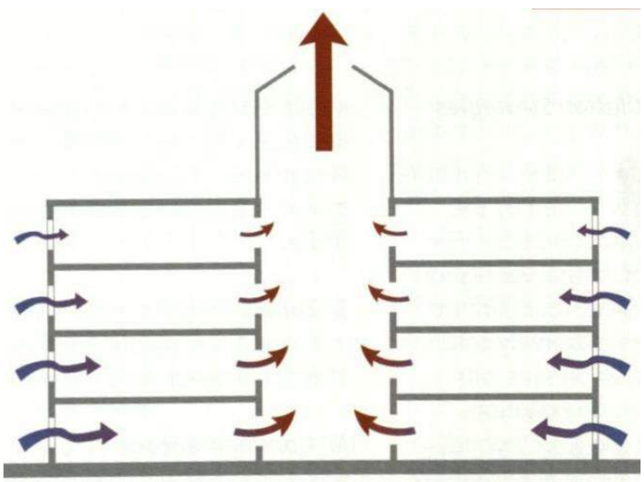

Fig. 255. Stack-Ventilation

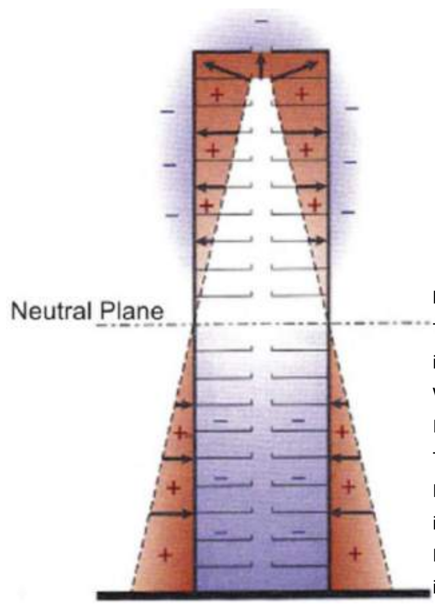

Fig. 256. Thermal Buoyancy in Tall Buildings Where Indoor/Outdoor Temperature Differences Result in a Different Pressure Gradient in the Building

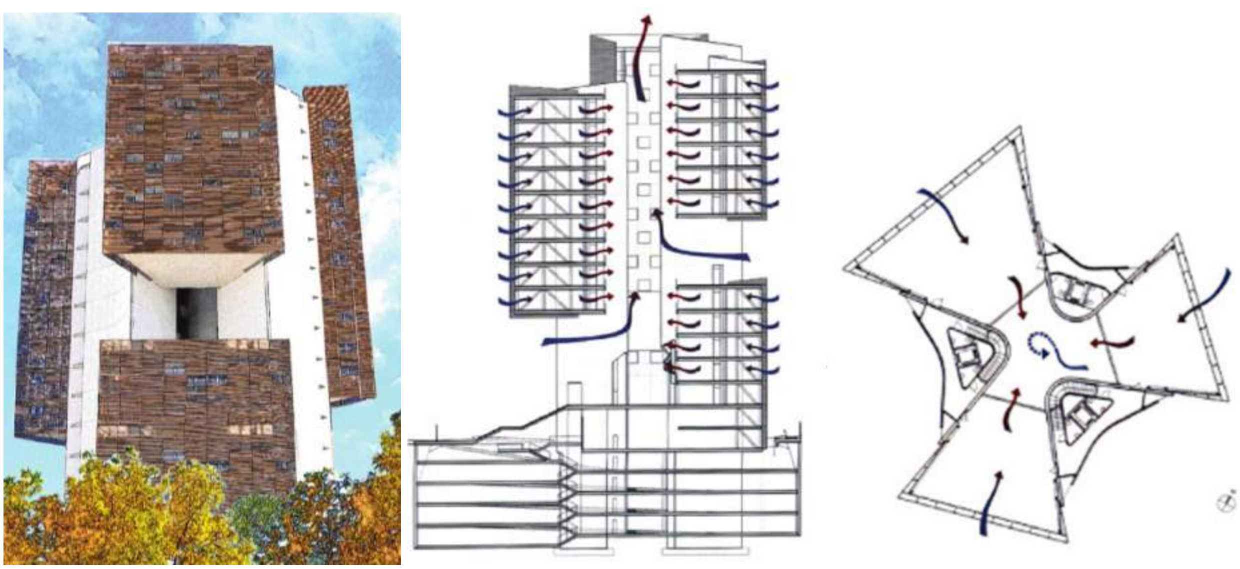

Fig. 257. Stack-Effect in Torre Cube, Mexico

308 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 18.

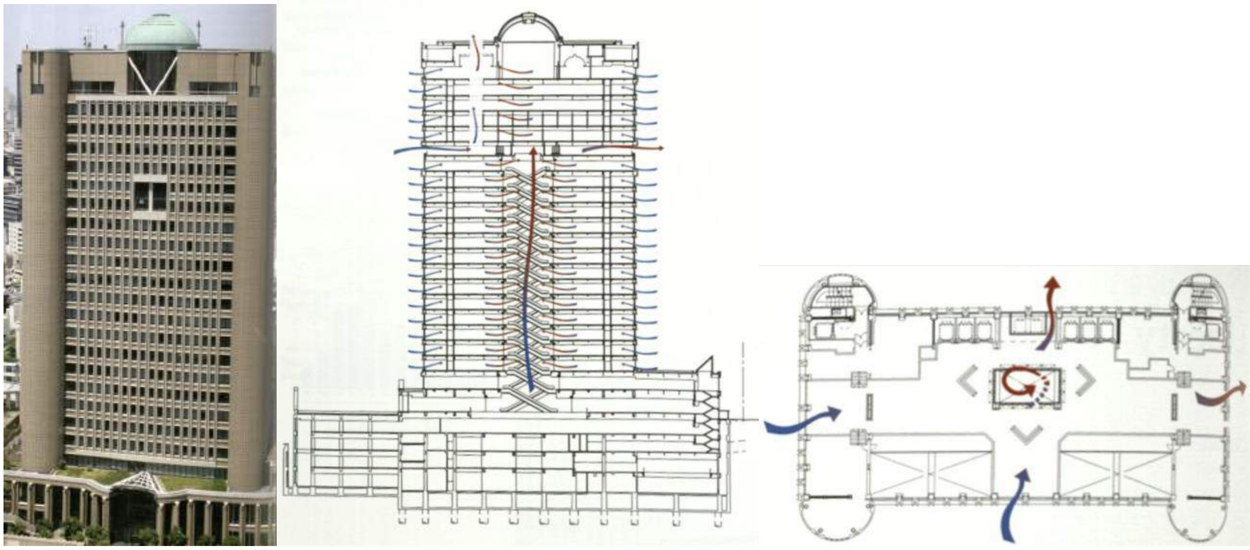

Fig. 258. Stack-Ventilation Through the Escalator Atrium in the Liberty Tower of Meiji University, Tokyo

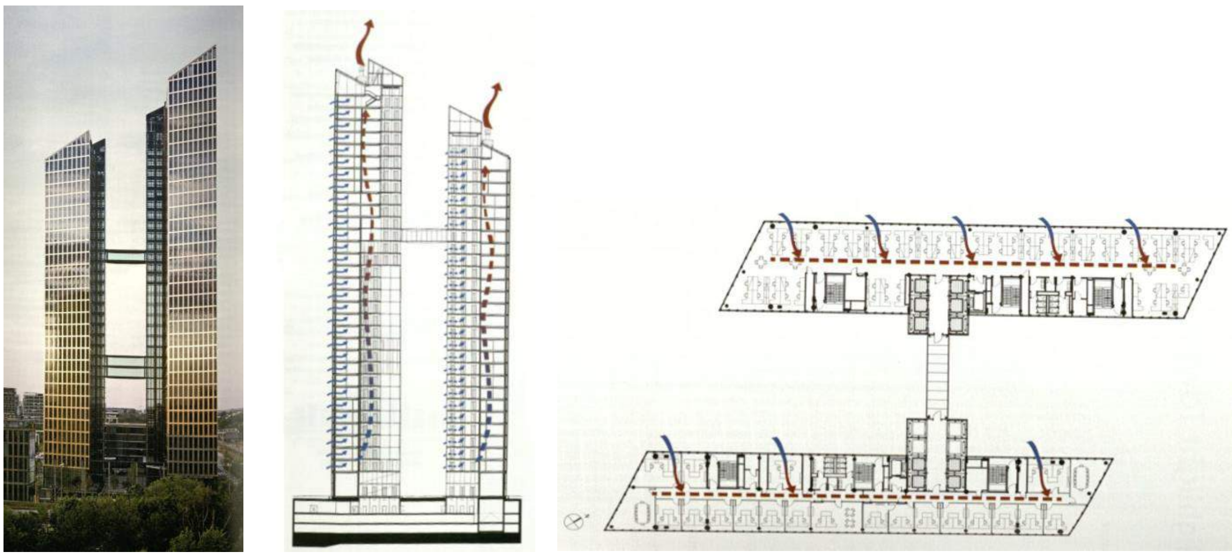

Fig. 259. Chimney Effect in the High Light Towers, Munich

5.1.5 Vegetation

Integrating vegetation in high rise design has plenty of ecological and aesthetic benefits. Plants generate oxygen and absorb carbon dioxide thus creating fresh air for the building environment. Next to the air quality improvement they also passively regulate the air temperature. Studies have shown that vegetation lowers the air temperature through evapotranspiration cooling by a few degrees in the direct surroundings thereby also mitigating the urban heat island.[309] Furthermore, they provide shade and planted areas on the high rise facade may work as buffer zones between the building exterior and interior.

309 Ken Yeang, *Reinventing the skyscraper*, 2002, 133.

5.1.5.1 Green Roof

Green roofs can play a great role in the high rise design, however, they have limited size. The vegetated rooftop provides a great acoustical, as well as thermal insulation for the building, and in general, limits heat loss in the winter and reduces solar heat gain in the summer. It also works effectively in combination with a roof canopy system. Moreover, the plants retain and evaporate the rain water thus cooling their environment and providing fresh air. It may also give home to small wildlife, too, thereby enhancing the locality's biodiversity.[310]

Fig. 260. Green Roof of the City Hall in Chicago

5.1.5.2 Street Level

Planting vegetation around the building on the street level works similarly as it does on the rooftop. However, great improvements can be achieved by planting trees which contributes to reducing energy demands. Instead of absorbing and reflecting the sun rays by the pavement, tree crowns hold them up and provide shade on the street level. Thereby, significantly reducing the urban heat island, as well. Cool air produced by a tree is small compared to its volume. Although a larger number of trees and an extensive vegetation contributes to a more comfortable, shaded and cooled environment around the high rise.[311]

Fig. 261. Public Park at the Manitoba Hydro Tower, Canada

[310] Ken Yeang, *The Green Skyscraper*, 1999, 236.
[311] Ken Yeang, *The Green Skyscraper*, 1999, 237.

5.1.5.3 Vertical Landscaping

Vertical landscaping on the building facade or in the building interior contributes to a cooler and healthier environment for the occupants. Vegetation on the facade helps to improve the building's thermal performance and works as a buffer between the exterior and the interior environment. It acts as an additional layer of thermal insulation and provides shade from the incoming solar radiation. Furthermore, if it is implemented on the facade exterior then it protects from the wind exposure, as well. This vegetation on the facade filters polluted air from the outside and reduces urban noise from the city.[312] In temperate climates, facade planting can contribute to a decrease of the ambient temperature by as much as 5 °C (41 °F) at street level and heat loss can be reduced by around 30 percent in the winter.[313]

Fig. 262. Facade Vegetation of Consorcio Santiago Building Santiago, Chile

Fig. 263. Unrealized Spireedge & Santa Fe Tower by Ken Yeang

Fig. 264. Bosco Verticale in Milano, Italy

[312] D. Safarik, A. Wood. P. Bahrami, *Green Walls in High Rise Buildings*, 2014, 212.
[313] Ken Yeang, *The Green Skyscraper*, 1999, 237.

5.1.5.4 Ecocell

The high rise does not need to have a continuous vertical landscape but it may have strategically placed, separate units which might be configured with vegetation. Considering the sun's path, for instance, these greenery areas are best located on the south side of the building in temperate climates serving as buffer zones. These locations in the building are called ecocells, skycourts or sky gardens and basically feature the same qualities as discussed above.[314]

However, they are not only implemented as buffer zones between the inside and outside, bringing sunlight into the interior, generating oxygen as the high rise's green lungs but they also increase occupants' general satisfaction.[315] Furthermore, tenants' productivity and overall performance is also enhanced when they feel a direct connection to environmental elements. These green zones provide a perfect place for gatherings, meetings and relaxation.[316]

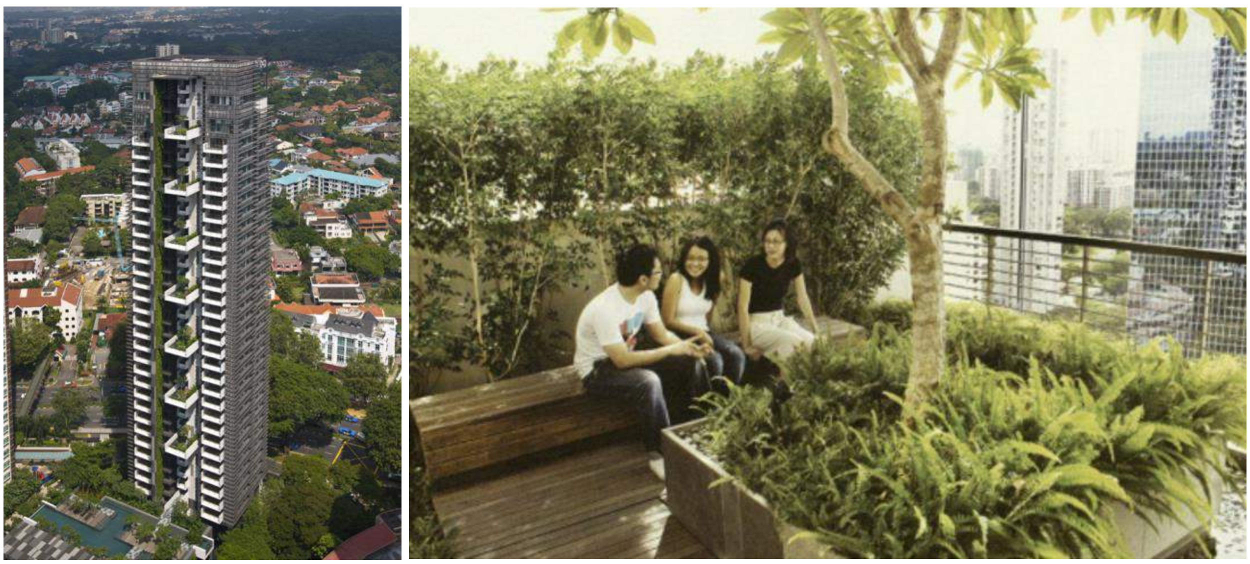

Fig. 265. Ecocells of the Newton Suites, Singapore

Ecocells are often located above the mechanical floors since these floors might not require the same floor height as occupied floors in the building thus providing greater possibilities for the planting of larger plants, or trees with greater roots embedded in the floor slab.[317] Another reason for this solution is that the mechanical floors usually separate different zones in the high rise, often with different functions, and this provides a great place to bring people from these distinct zones together.

[314] Ken Yeang, *Reinventing the skyscraper*, 2002, 137.
[315] Ken Yeang, *Eco Skyscrapers*, 1998, 95.
[316] D. Safarik, A. Wood. P. Bahrami, *Green Walls in High Rise Buildings*, 2014, 10.
[317] E. Colz, *Skyscraper for New York*, 2012, 91.

Fig. 266. Ecocell of the Commerzbank Frankfurt, Germany

Fig. 267. Sky Garden of 20 Fenchurch Street in London, UK

5.2 Sustainable Techniques

5.2.1 Sun

The energy of the sun is the most significant renewable energy source. There is more than enough solar energy heating the earth to power the earth energy consumption many times over.[318] Solar energy can be used directly for daylighting, heating or even generating energy. Solar thermal conversion and photovoltaic effect are the main approaches towards energy generation today.

5.2.1.1 Photovoltaic

Photovoltaic (PV) panels convert the sun-light into useful electricity and if the energy is more than the building's current needs the excess can be fed into the city's power grid. This system eliminates the need for batteries; instead the public network is used as a storage system. On the other hand, during periods of bad weather or at night the building can take electricity from the grid.[319]

The Heron Tower's offices in London are clustered around 11 multistory atria that are called villages consisting of three floors each. This is not the only feature of the high rise though. The tower incorporates 3,374 m2 (36,317 ft2) PV array on its facade that was the second largest PV array in England at the time of its completion.[320]

318 https://www.youtube.com/watch?v=IZ__PjmC6Fg 0:20 Accessed August 2016

319 Petra Liedl, Michael de Saldanha, *Climate Skin Building-skin concepts that can do more with less energy*, 2008, 142.

320 David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 163.

Fig. 268. PV Array of the Heron Tower, London

5.2.1.1.1 Shading

Next to energy generation, PV systems might provide shade for the building thus reducing heat gain, glare and the need for cooling. They can be implemented on roofs as shading canopies as well as on the building facade as awnings. Semitransparent modules limit the amount of solar radiation entering the space while maintaining the view out.[321]

Fig. 269. PV Panels in the Pompeu Fabra Library Used for Shading

Fig. 270. PV Roof in Ludesch C. Center

In general, the building's south facade can be easily shaded by horizontal shading fixtures because of the relatively high position of the sun. However this is not the case on the east and west facades due to the low sun position. This can be solved with PV panel installations which limit the incoming light's quantity depending on the type. Owing to the low solar irradiations on these building sides and because light is usually reflected horizontally between buildings in the city, these facades welcome vertically placed PV panels as well.[322]

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321 Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 90.

322 H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 143.

Fig. 271. PV Panels Integrated in Shading Devices of an Office Building in London

Fig. 272. PV Shading Louvres from the Facade at Caltrans Building, USA

5.2.1.1.2 Types

Next to the Monocrystalline Silicon solar panels there exist Polycrystalline Silicon solar panels and Thin-Film solar panels. Usually, the Monocrystalline panels are the most efficient ones. However, Thin-Film panels are only a few millimeters thick and can be applied on any kind of surface in any shape. Therefore, they are easily portable and also able to tolerate more shade and heat.[323]

Today, there are innovative PV technologies and inventions which will most likely replace the current PV panel types in the near future. Ubiquitous Energy is a leading photovoltaic developing company in Silicon Valley and has an award-winning ClearView Power technology which basically means fully transparent photovoltaic panels. This technology applies a thin transparent film on any device which generates energy from the solar power. This film can cover, for instance, mobile phone displays thereby eliminating their battery life limitations. The film can also cover building windows without even noticing it or degrading the window's clarity. It converts invisible ultraviolet and infrared light into electricity while it selects and transmits the visible light through its surface.[324]

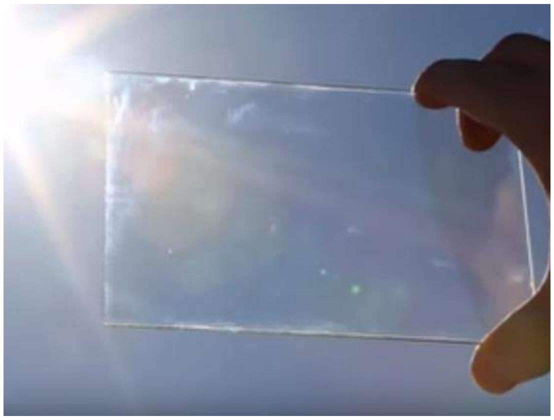

Fig. 273. Fully Transparent PV Panel by Onyx

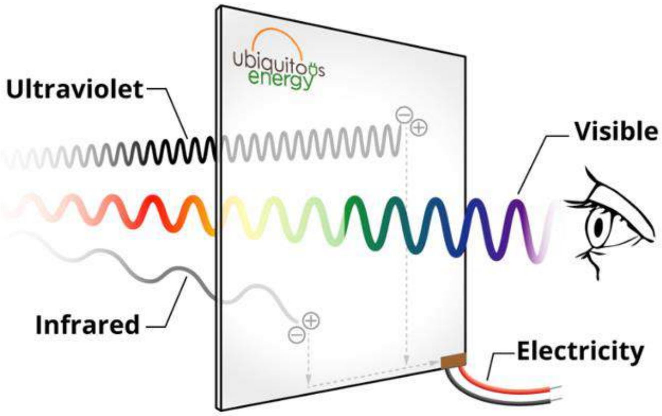

Fig. 274. UV, Infrared and Visible Light Selection by Clearview Power Technology

[323] Christian Schittich, *In Detail - Building Skins*, 2006, 51.
[324] http://ubiquitous.energy/technology/ Accessed June 2016

Onyx Solar is a Spanish based innovative company with over 30 different winning awards among the title of the "Most Innovative Glass 2015". Onyx Solar offers not only fully transparent PV glass but the customer can choose between different transparency degrees, depending on the required luminosity. Furthermore, these panels also filter UV and infrared radiation. They offer colorful versions as well with the same efficiency rate as the regular ones.[325]

Fig. 275. Colored PV Panels in Bejar, Spain

Fig. 276. Transparent and Semi-Transparent PV Panels as Skylights in Madrid and in Biscay, Spain

Onyx Solar also released PV integrated safety glass and walkable PV floor.[326] Even though this technology still has a little less efficiency than the earlier versions (i.e., around 10 percent compared to 15-30 percent) it has almost unlimited possibilities for implementation and can be used at any part of the building surface with many design options. The Genyo Building in Granada, Spain designed by Onyx has double-skin facades and implements different types of PV panels of the company on its facades. These panels provide around 20 percent of the building's energy needs.[327]

Fig. 277. Double-Skin Facade of the Genyo Building

Fig. 278. Walkable Onyx PV Panels

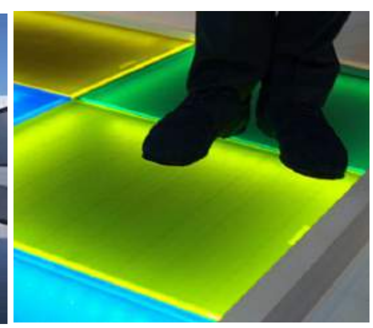

Fig. 279. Walkable Colorful PV Panels

5.2.1.1.3 Building Integrated Photovoltaic Thermal System

Building Integrated Photovoltaic Thermal (BIPVT) system means the implementation of the PV panel in the cavity of the double-skin facade. This system unites electricity generation by the PV panel and heating by the stack effect in the facade cavity. Thereby the stack effect removes the

[325] http://www.onyxsolar.com/photovoltaic-transparent-glass.html Accessed June 2016
[326] http://www.onyxsolar.com/walkable-photovoltaic-roof.html Accessed June 2016
[327] https://www.youtube.com/watch?v=xnjx73K18pk 5:54 Accessed June 2016

heat produced by the PV panel thus cooling it in order to raise its electricity efficiency and decreases the chance for overheating. The air heated by the PV panel rises up to heat the double-skin facade serving as a buffer zone between the outside and the building interior or it is led to the building's HVAC system in order to decrease heating and ventilation loads.[328]

5.2.1.2 Solar Heating

In most cases solar heating means solar thermal heating, however, it can be used for solar air heating as well.[329] Both systems work with sunlight absorption in order to generate heat. While the solar thermal system heats up water, or some type of fluid in indirect systems, which will be circulated to provide warm water or thermal heat for the occupants, the solar air heating system circulates air for heating purposes.[330] The most important part of the system is the solar collector which is installed on the building's envelope. It can consist of several forms, sizes and types such as pipes, flat plate or concentrator collectors. Compound Parabolic Collectors (CPC) concentrate the radiation of the sun on the absorber. They also accept the diffused radiation and do not need to track the sun or be tilted.[331]

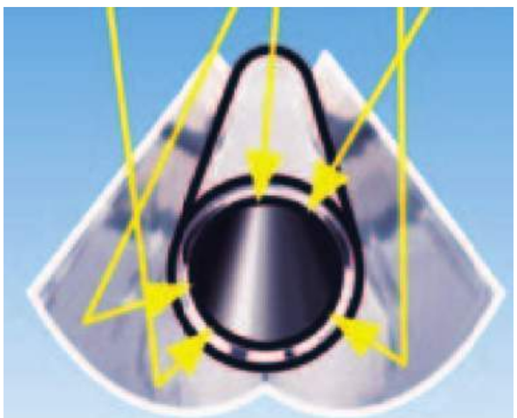

Fig. 280. CPC Concentrating Diffuse Light

Fig. 281. CPC Tubes

All new homes in Germany since January 2009 are required to install renewable heating systems which must provide at least 20 percent of the building's hot water demand.[332] Whereas the city of Sao Paulo, Brazil requires a minimum of 40 percent annually for all new buildings. A hotel high rise in the city employs 72 solar collectors on a 310 m2 (3,337 ft2) surface area which covers most of the building's hot water demand.[333] One must consider that the demand for hot water is one of the highest in buildings with hotel uses. Solar thermal systems can replace up to 80 percent of the building's solar hot water requirements, depending on the surface size covered with solar collectors, the solar radiation intensity, etc.[334]

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[328] R. Charron, A. K. Athienitis, *Optimization of the performance of double-facades with integrated photovoltaic panels and motorized blinds*, 2005, 1.
[329] http://solarwall.com/en/home.php Accessed June 2016
[330] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 95.
[331] International Energy Agency, *Solar Energy Perspectives*, 2011, 127.
[332] A. C.-Santos, J. V.-Vale, D. B.-Diez, R. R.-Perez, *Solar thermal systems for high rise buildings with high consumption demand: Case study for a 5 star hotel in Sao Paulo,* Brazil, 2013, 483.
[333] A. C.-Santos, J. V.-Vale, D. B.-Diez, R. R.-Perez, *Solar thermal systems for high rise buildings with high consumption demand: Case study for a 5 star hotel in Sao Paulo,* Brazil, 2013, 488.
[334] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 95.

The Solar Wall system can be used on large surfaces of a building without windows. This system heats the ventilated air in the building and it is able to displace up to 50 percent of the traditional heating loads.[335] One of the facades of the Edwards Manor residential building in Ontario and the Manitoba Building in Manitoba, is fully equipped with the Solar Wall system while the Manchester Housing in Alberta applies this system only at certain areas of its facade around the windows.[336]

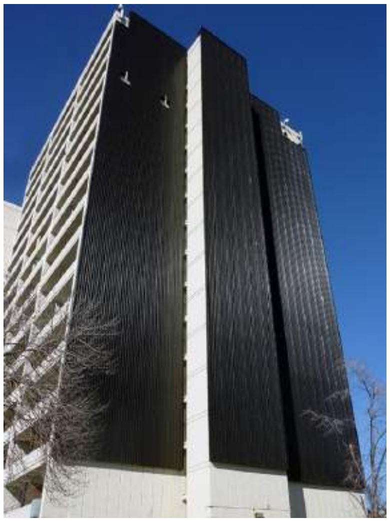

Fig. 282. CPC on the Facade of the Edwards Manor Building in Ontario, Manitoba Building in Manitoba and Manchester Housing in Alberta, Canada

5.2.2 Wind

In order to generate electricity by wind energy, the designer needs to integrate wind turbines in the building. Indeed, this is not as easy as doing so with PV panels, though the efficiency of wind turbines is actually higher than it is of the PV's.[337] This is especially true with the increase of the turbine size. There are basically two ways of wind turbine implementation in the high rise. The first one is when large turbines are planned into the building's form thus giving the entire structure a very characteristic appearance. The other way is to install smaller turbines between the floors so it might not even be apparent from the outside.

5.2.2.1 Exterior Wind Turbine

The Bahrain World Trade Center in Bahrain was the first high rise integrating wind turbines into its design. The two towers have three bridges between them which have a 29 meters (95 feet) wide wind turbine each. The two high rises are facing north in order to capture the prevailing winds from the Persian Gulf and they both have the shape of a sail thereby funneling the greatest amount of wind to the turbines.[338] The buildings create an S-shape streamline for the predominant winds, thus any wind coming within a 45 degree angle to either side will get perpendicular to the turbines. The turbines are creating up to 15 percent of the towers' power consumption.[339]

335 http://solarwall.com/en/home.php Accessed June 2016

336 http://solarwall.com/en/products/uses-and-applications/multi-residential.php Accessed June 2016

337 J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 213.

338 David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 458.

339 Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 15.


Fig. 283. Bahrain World Trade Center, Bahrain

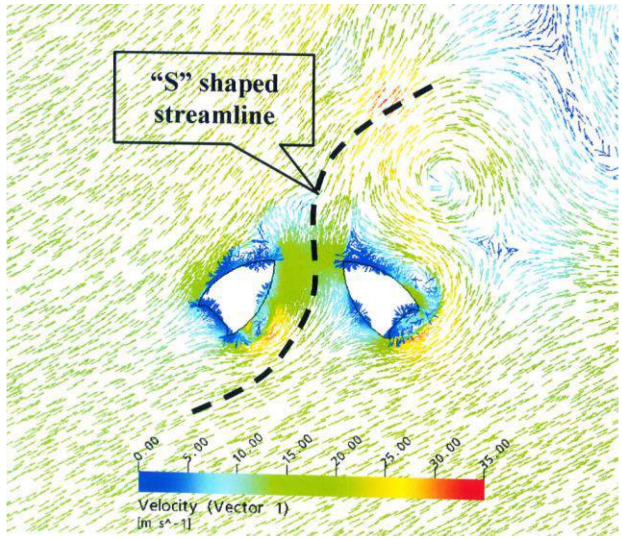

Fig. 284. S-Shape Streamline for the Predominant Winds of the Bahrain World Trade Center

The 43-story Strata Tower in London is a local landmark. It was among the first high rises incorporating wind turbines within its structure. Three 9 meters (30 feet) wide wind turbines on the top of the high rise generate around 50 Megawatts of energy per year which makes up a little under 10 percent of the building’s energy consumption.[340]


Fig. 285. Strata Tower, London


Fig. 286. Wind Turbines of the Strata Tower, London

5.2.2.2 Interior Wind Turbine

The Pearl River Tower in China has a sculpted body that directs the wind to its two facade openings at the building’s mechanical floors. These funnel-like openings incorporate wind turbines in the building that cannot be seen from outside generating energy. It is not only about the energy generation though, using the through-building channels reduces the wind load on the building by a great amount thereby a lighter and more efficient building structure was possible.[341]

[340] Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 19.
[341] K. Daniels, R. E. Hammann, *Energy design for tomorrow*, 2009, 222.

Fig. 287. Pearl River Tower, China

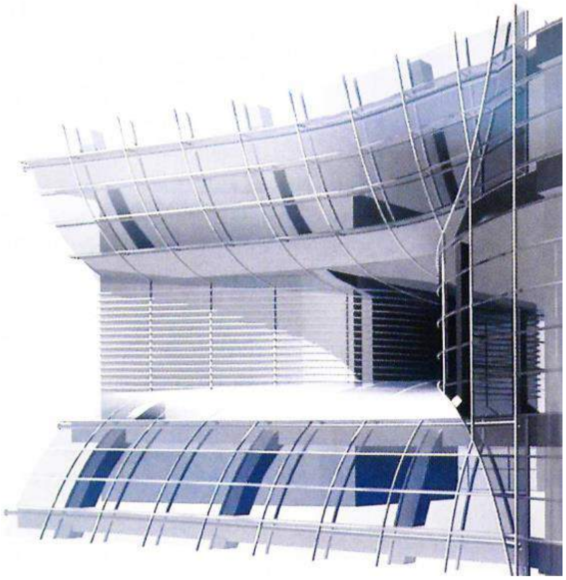

Fig. 288. Wind Funnel of the Pearl River Tower

5.2.3 Water

90 percent of the global water supply is salt water, whereas only 3 percent is in the form of fresh water, of which two-third is ice. More than half of the water on earth for washing, drinking and irrigation purposes arrives from underground, however, this water gets more and more contaminated by toxic wastes or agrochemicals.[342] Since buildings, especially high rises, are large water consumers it is important to design them with strategies saving as much water as possible and employ techniques which efficiently use the building's water supply.

5.2.3.1 Rainwater Harvesting System

As high rises have a large surface area, the amount of rainwater falling on the building is significant in certain climates. Therefore, the integration of a rainwater harvesting system needs to be considered at the design stage. This means the incorporation of a rainwater catchment system and water tanks to store water either on the building top or in the basement. A water tank on the top of the high rise also enhances the building's stability. The collected water can be used for plant irrigation or for toilet flushing purposes.

The Editt Tower in Singapore and the Chong Quing Tower in China both, designed by Ken Yeang, were planned to integrate an efficient rainwater collection and recycling system in their designs.[343] In both high rises the rainwater recycling system collects the rainwater on the top and channels it through the building with the help of gravity to the tank at the basement, meanwhile, irrigating the building vegetation.[344]

[342] Ken Yeang, *The Green Skyscraper*, 1999, 267.
[343] Ken Yeang, *Designing the ecoskyscraper premises for tall building design*, 2007, 417.
[344] Ken Yeang, *Designing the ecoskyscraper premises for tall building design*, 2007, 421.

Fig. 289. Editt Tower

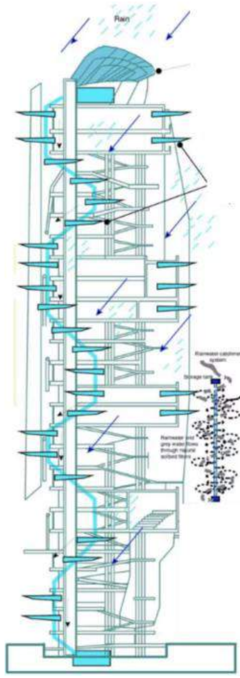

Fig. 290. Rainwater Collection and Recycling System of the Editt Tower

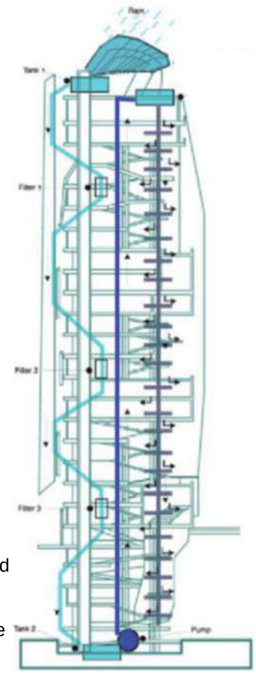

Fig. 291. Rainwater Gravity Filtration System of the Editt Tower

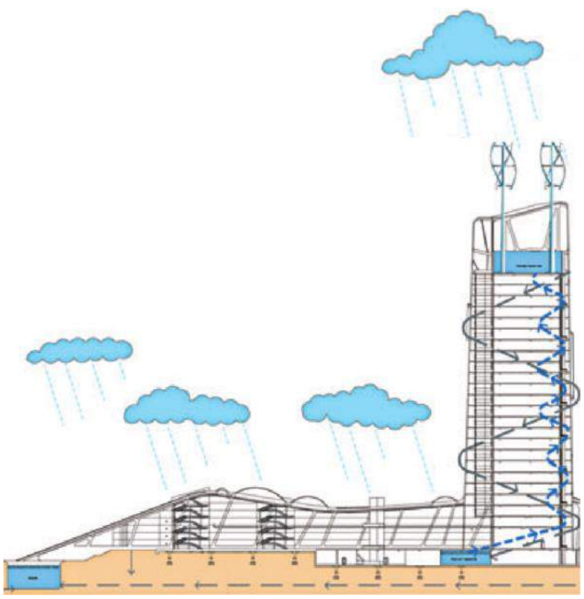

Fig. 292. Rainwater Harvesting System in the Chong Quing Tower

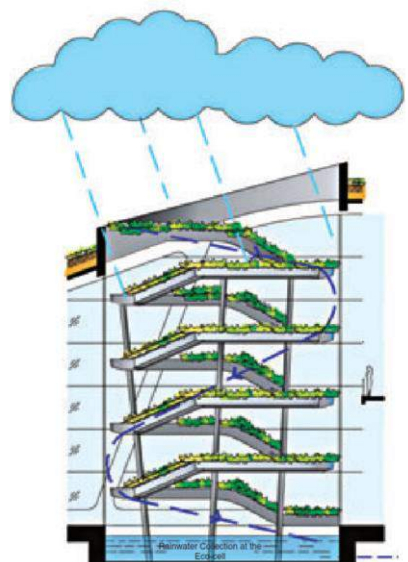

Fig. 293. Rainwater Management of the Chong Quing Tower's Podium

5.2.3.2 Water Reuse

Most of the wastewater from an average household derives not from the toilets but from showers, sinks, baths, clothes washers and dishwashers. This is called greywater and it can be easily reused to flush toilets or provide water for vegetation. Before doing so it needs to be passed through a filter system. Even the sewage from toilets, which is called blackwater, can be used for irrigation after proper treatment.[345]

345 Ken Yeang, *The Green Skyscraper*, 1999, 271.

The 35-story residential tower Visionaire by Pelli Clarke Pelli is located in Battery Park, Manhattan and it has one of the most sufficient water-processing systems in the USA. Through its rainwater collection and wastewater treatment system the building's potable water use is decreased by 40 percent.[346]

Living Machine is an ecological wastewater treatment system treating both grey- and blackwater. It uses biological and bacteriological purification techniques with the help of plants and cutting-edge technology. At the end of the process the water is recovered and can be reinjected into the building's system for maintenance, sanitary or planting irrigation purposes.[347]

The energy efficient 525 Golden Gate Avenue in San Francisco was the first office building using this technique in an urban environment thereby saving 10.2 million liters (2.7 million gallons) of water a year. Thus, the building uses 60 percent less water than a normal office building. All of the blackwater flushed by the office toilets is treated and used for watering plants, thereby, the tower does not use the sewer system at all, sparing a great amount of money.[348]

The Port of Portland Headquarters Building in Oregon uses the same technology and possesses LEED platinum certificate, just as the 525 Golden Gate Avenue does. The building demonstrates a 75 percent water use reduction and there is not a drop of water generated by the building which enters the sewer system.[349]

Fig. 294. Water Treatment System of the Visionaire Building, Manhattan

Fig. 295. Living Machine Wastewater Treatment System

[346] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 169.
[347] http://www.livingmachines.com/About-Living-Machine.aspx Accessed June 2016
[348] http://www.archdaily.com/230834/puc-building-525-golden-gate-kmd-architects Accessed June 2016
[349] https://www2.portofportland.com/Inside/HeadquartersBuilding Accessed June 2016

5.2.3.3 Water Efficient Fixtures

Water efficient fixtures and appliances can save a large amount of money and water for the building. This is probably the easiest and most inexpensive way to reduce water consumption since it does not require any complicated design solution but the employment of certain sanitary products. Fixtures saving water include low-flush toilets and urinals, low-flow shower heads and sink faucets or spray taps combined with possible use of auto-shutoff mechanisms.[350] Faucet aerator systems add air to the water thus decreasing the water amount. Toilets with pressure assistance use only a small amount of water owing to the compressed air or a water pump that assists the flushing power. Dual-flush toilets offer the user the option to use either a regular amount of water per flush or half of it.[351]

As its name already indicates, the waterless urinal does not require water at all, thereby saving millions of gallons of water for a high rise annually. Based on the trap principle, urine passes through an upper layer of liquid which serves as a barrier and does not let the odor get out. After this, the urine is led into a central tube and then to the drainpipe. Indeed, the upper fluid must be replenished every now and again though this is nothing compared with the amount of water that can be saved by this system.[352] Waterless urinals are especially useful in areas suffering droughts. For instance, the state of Arizona made their use obligatory in the government-owned buildings in 2005.[353]

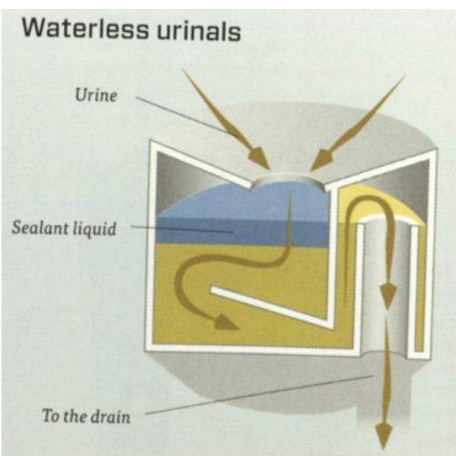

Fig. 296. Waterless Urinal

Fig. 297. Dual-Flush Toilet Flushing Button

5.2.3.4 Water Based Air Conditioning System

5.2.3.4.1 Chilled Beam System

Water Based Air Conditioning System, that is also called Radiant Cooling, is a modern technique that is used to heat and cool large buildings. The Chilled Beam, is one type of this system and it

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[350] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 95.
[351] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 168.
[352] Kate Ascher, *The heights - Anatomy of a skyscraper*, 2011, 168.
[353] http://www.ameraproducts.com/waterless-urinals-technology.htm Accessed June 2016

is very energy, and thus cost, efficient and spares a lot of space in the building. The interior air is conditioned through water circulation instead of air circulation as the traditional systems do. The Chilled Beam System uses the principle of natural convection, whereby, the warm air rises up to the ceiling where it is cooled by cold water pipes and then falls back down to the floor.[354]

Water is a lot more efficient medium to carry energy than air since it has higher density and also higher specific heat. For comparison, 0.03 m3 (1 ft3) of water is able to transport the equal amount of heat as 3,000 m3 (105,944 ft3) of air does which is a very significant difference.[355] Thus, as the water pump system can carry more energy than the fan duct for the same electricity amount, the water pipes are smaller than the large ducts for the air system. Thereby, not only the ceiling height, hence the floor height, can be reduced but mechanical rooms and the whole shaft in the service core, too, which would otherwise deal with greater sized air duct system.[356]

There exist two main types of Chilled Beams. In the first one the warm air moves only by convection to the ceiling water coils. The other system is more active and it uses fans to move air up to the heat exchange coils. Indeed, this version is more effective, however, the first one is totally silent.[357]

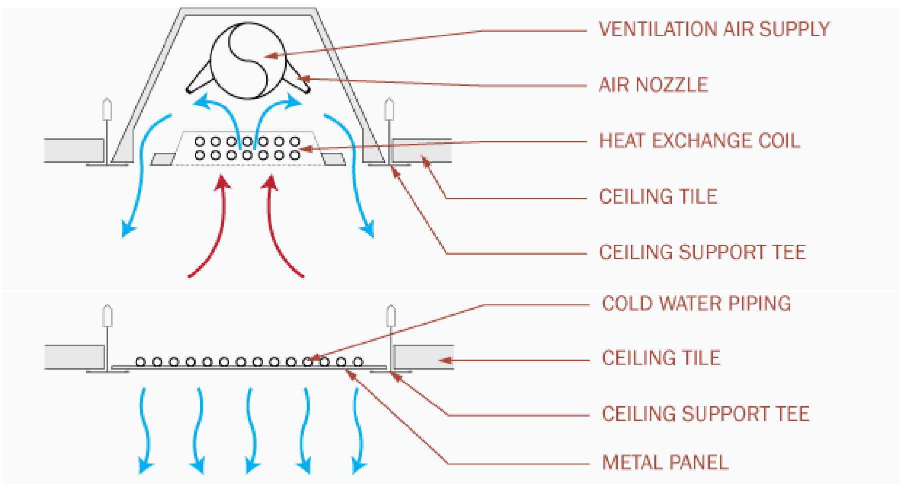


Fig. 298.
Chilled Beam System (top)
Chilled Ceiling System (bottom)

5.2.3.4.2 Chilled Ceiling System

The Chilled Ceiling System is the most employed air conditioning technique sustainable high rises use today. This system relies more on radiant air conditioning than convective heating and cooling as the Chilled Beam. It is consisted of a metal sheet with chilled coils running above it and they heat or cool the air indirectly through the metal panel. Chilled Ceiling is considered to be the most efficient and sustainable air conditioning system, since it is based on circulating water and relies on radiant properties. As a further benefit, the water that is not anymore in use by the system, can be collected and used to water vegetation in the high rise as well as for toilet flushing purposes.[358]

[354] https://www.archtoolbox.com/materials-systems/hvac/chilled-beam-ceiling.html Accessed June 2016
[355] https://www.archtoolbox.com/materials-systems/hvac/chilled-beam-ceiling.html Accessed June 2016
[356] D. Trabucco, *An analysis of the relationsip between service cores and the embodied, running energy of tall buildings*, 2008, 948.
[357] https://www.archtoolbox.com/materials-systems/hvac/chilled-beam-ceiling.html Accessed June 2016
[358] https://www.archtoolbox.com/materials-systems/hvac/chilled-beam-ceiling.html Accessed June 2016

Fig. 299. Chilled Ceiling Components

This system is even more efficient and cost saving if the building is located next to a lake, river or ocean as the water can be pumped to the ceiling coils directly from there. This solution was implemented when the Pier I warehouse in San Francisco was converted to an office building. Since historic reservation requirements prohibited the use of high-performance glazing or insulation, passive design techniques were out of question. Through the use of heat exchanger and chilled beam ceilings the building is cooled by the bay water and it works up to 30 percent better than required by the California Title 24.[359]

5.2.3.4.3 Evaporative Cooling System

Evaporative cooling is a climate control technique which is mainly used in hot and dry climates. It is based on the natural cooling process when the water evaporates as it gets in contact with dry air. The change of its state from liquid to gas results in a temperature drop.[360] Thus waterfalls in a high rise are perfect for evaporation and thereby cooling the surrounding air. However, not only are waterfalls effective systems for evaporation but fountains, sprays or water pools provide efficient cooling, as well. Hence, using a sprinkler system for instance on the top of a high rise in a hot climate can mitigate its cooling requirement by as much as 25 percent.[361]

Fig. 300. External Evaporative Cooling Wall of the Idaman Residence, Kuala Lumpur

Fig. 301. Internal Evaporative Cooling Wall

[359] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 88.
[360] Shahin Vassigh, *Best practices in sustainable building design*, 2012, 113.
[361] Ken Yeang, *The Green Skyscraper*, 1999, 24.

Fig. 302. Open-Air Lobby Space with Pools and Cascading Water Surrounding the Tower Base of the Index Tower, Dubai

These are not the only options for evaporative cooling, though. The innovative building facade of the NBF Osaki Building in Japan uses ceramic rods on the facade in order to achieve evaporation. These pipes affixed to the building side comprise rainwater which evaporates as a result of heat absorption of the sun rays. This process means a 12 °C (54°F) reduction for the building that significantly mitigates the heat island effect. This system, called Bioskin, was employed on the facade of this high rise for the first time.[362]

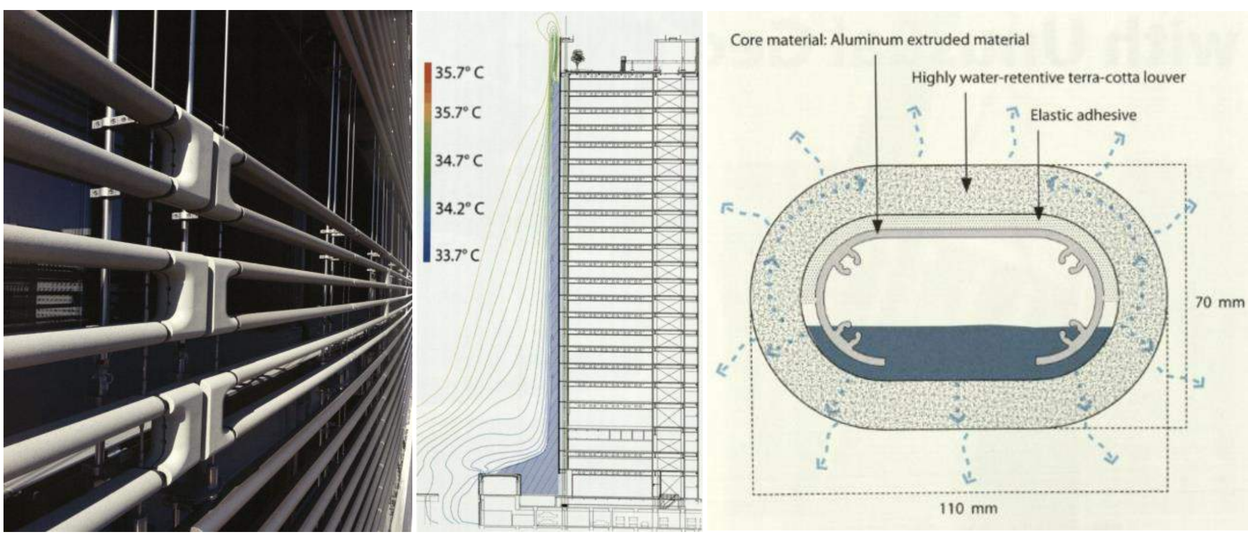


Fig. 303. Bioskin of the NBF Osaki Building

5.2.3.5 Hydro Energy

Next to harnessing sun power through PV cells and exploiting wind energy via wind turbines, there is also a way to generate energy for a high rise with the help of hydro energy. In case the building is located next to a river, or sea, hydro energy devices can be incorporated in the high rise design. Even if these devices are not directly connected to the building structure, they can

[362] A. Wood, S. Henry, D. Safarik, *Best tall buildings - Global overview of 2014 Skyscrapers*, 2014, 217.

still be considered as energy generation systems, belonging to the building. These systems work under water, usually on the bottom of the body of water, thus they are out of sight and not disturbing the traffic on the water surface.[363]

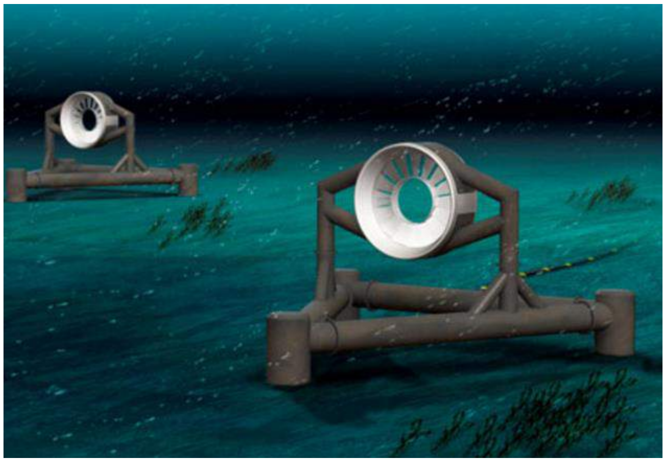


Fig. 304. Open Hydro Rim Drive Turbines on the Bottom of the Water

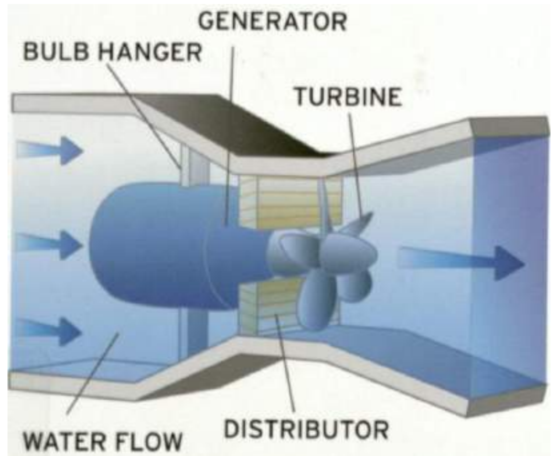


Fig. 305. Bulb Turbine

Some systems use the current of the water as submerged windmills while others generate energy harnessing the water ebb and flow movement.[364] There is also another type of these hydro energy generating systems which uses the pendulum movement mechanism. It needs to be installed on the water surface, however, as it develops power from the up and down movement of the waves. It is called the Slater Duck power generator wherein the pendulum inside the device swings for- and backward thus producing the desired electricity. If more Slater Ducks are connected in a row they calm down the waves behind them.[365]

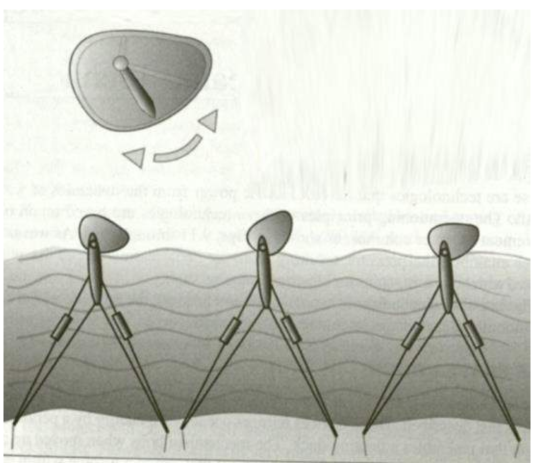


Fig. 306. Slater Duck System

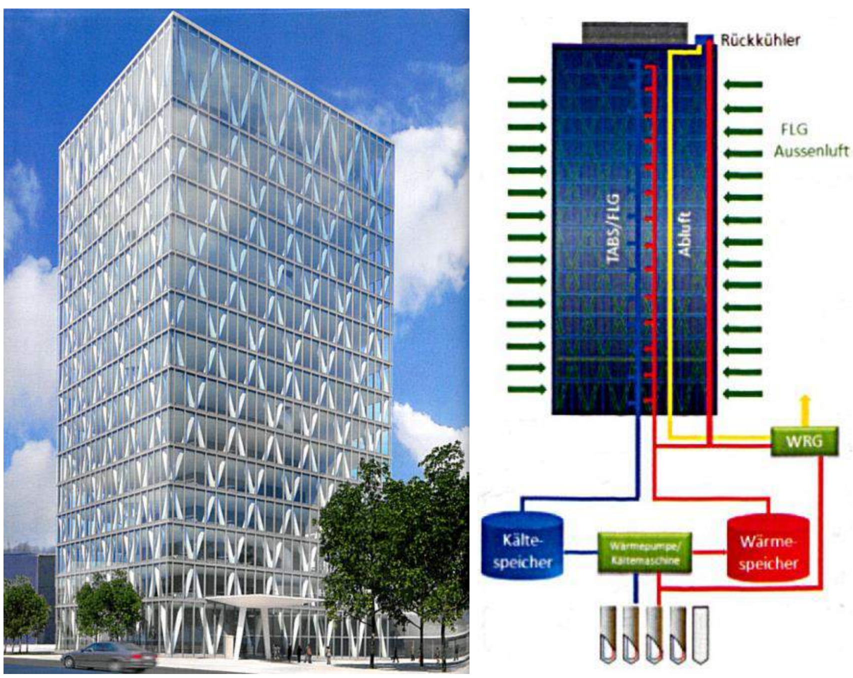
Fig. 307. Slater Ducks Connected in a Row

[363] Dr. Peter Gevorkian, *Sustainable Energy Systems in Architectural Designs*, 2006, 125.
[364] Peter Gevorkian, *Alternative Energy Systems in Building Design*, 2009, 300.
[365] Peter Gevorkian, *Alternative Energy Systems in Building Design*, 2009, 304.

5.2.4 Geothermal Energy

Basically, geothermal energy is the heat obtained from the earth. It can be used for space heating and cooling and for warm water heating. However, it is still a developing renewable energy source and it is growing exponentially as requests continue to grow.[366] Geothermal heat pumps can be used anywhere in the world usually at a cost of one third of that of an electric heating system.[367] It is a secure and dependable system since weather conditions do not change under the earth as they do in the air or water. In a closed loop system, water is circulated between the borehole heat exchanger and the heating and cooling distribution system of the building. Therefore, the most plausible use for air conditioning with geothermal energy is the radiant ceiling system (see: Water Based Air Conditioning System) that conditions the air temperature with water.

The Swiss Die Roche Diagnostics AG office building's heating and cooling demands are entirely covered by geothermal energy which is an energy resource that has become widely used in eco-friendly Switzerland.[368] A similar system has been incorporated in the WestenDuo Building in Frankfurt. The concept is based on the use of radiant ceilings and geothermal heat pumps reaching down to a depth of 140 meters (460 feet).[369]



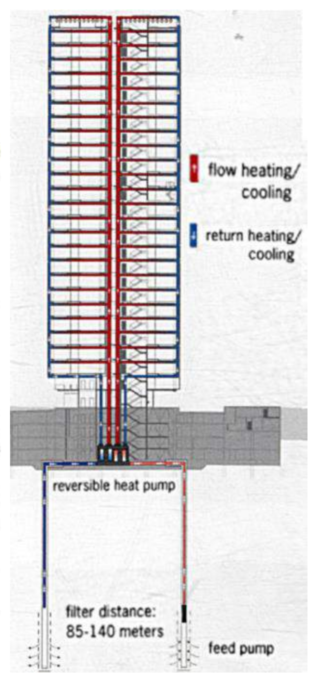


Fig. 308. Die Roche Diagnostics AG and its Geothermal Energy System

Fig. 309. WestenDuo's Geothermal Energy System

There also exists a very simple though clever option for storing thermal energy. Thermal energy storage can be described as a battery for the air conditioning system. Thus, a storage medium is cooled while the thermal energy storage stocks the energy for another time. This usually means

366 Shahin Vassigh, *Best practices in sustainable building design*, 2012, 159.
367 C. A. Coles, *Review of Geothermal Heating and Cooling of Tall Buildings*, 2009, 1.
368 Robert Stadler, *Gipfelstürmer*, 2010/11, 60.
369 M. Busenkell, P. C. Schmall, *The international Highrise Award 2008*, 2009, 75.

ice storage tanks in which ice is made during off-peak hours or at night and stored for a later time (e.g., for peak hours) or for the next day. Then it is used to cool or heat the building that is far more efficient and less expensive.[370]

5.3.1 Sustainable Building Case Studies

Presented here are different energy-efficient design strategies and sustainable techniques through case studies of innovative, pioneering sustainable high rises, which are located in different parts of the world with different types of climatic conditions.

5.3.1.1 Commerzbank Frankfurt

Location: Frankfurt, Germany

Year: 1997

Height: 259 m / 850 ft

Floor: 60

Use: Office

Designer: Norman Foster

Fig. 310. Commerzbank Frankfurt

In the late 1970s, Frankfurters still denied the architectural form of high rises as they associated them with urban decay. However by the late 1980s, their perspective had been changed and Frankfurt became today one of the commercial centers of Europe.[371]

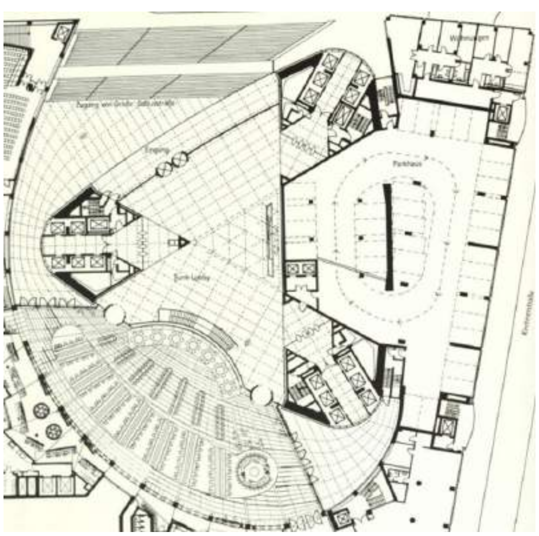


Fig. 311. Ground Floor Plan

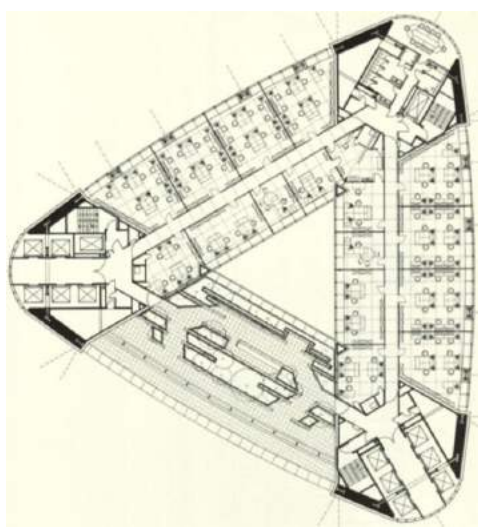


Fig. 312. Office Floor Plan

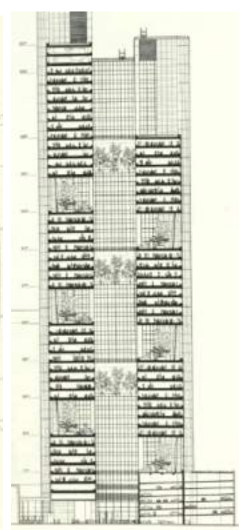


Fig. 313. Section

370 http://www.calmac.com/how-energy-storage-works Accessed June 2016

371 S. Guy, S. A. Moore, *Sustainable Architecture and the Pluralist Imagination*, 2007, 20.

The Commerzbank in Frankfurt, offering around 80,000 m2 (861,113 ft2) office spaces, was one of the first of truly sustainable high rises and is still considered as one of the most ecological tall buildings ever built.[372] It was designed to be able to be naturally ventilated about 60 percent of the year, which was estimated to cut the building's energy consumption almost 50 percent compared to a traditional, mechanical, air conditioned office building. However according to analyzing studies after its completion, it turned out that in reality the high rise consumes around 20 percent less energy than was expected and this amount declined year by year after 2000. This is connected with the building occupants who actually learned how to benefit natural ventilation around 85 percent in the course of a year that was originally predicted to be 60 percent.[373] Some parts of the building benefit from natural ventilation during the entire year.

Owing to the triangular form, offices at each level occupy only two sides of the floor plan. There are four-story high communal atrium gardens implemented in the design that create a spiraling chain of interior gardens which are positioned on each of the three faces of the building.[374] These sky gardens bring daylight and natural ventilation into the central atrium that performs as a natural convection chimney using the stack effect.[375] Natural ventilation occurs regardless of the wind direction since there is always a garden on the building's windward side letting in fresh air and another on the leeward side exhausting it.[376]

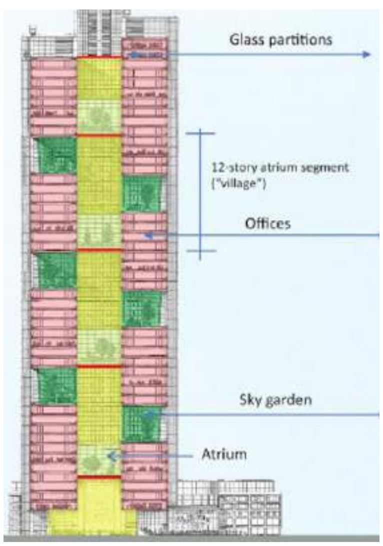


Fig. 314. Organizational Structure

Fig. 315. Sky Gardens in the Building

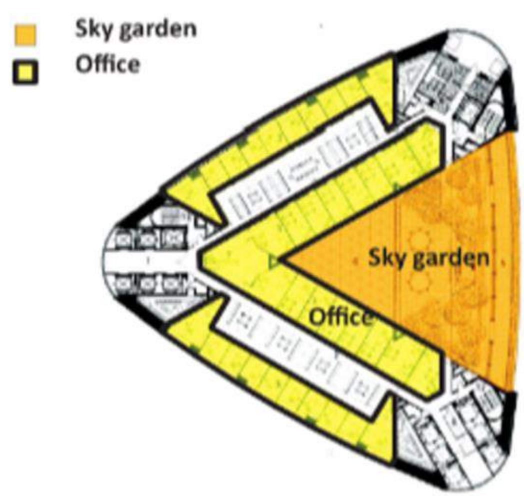
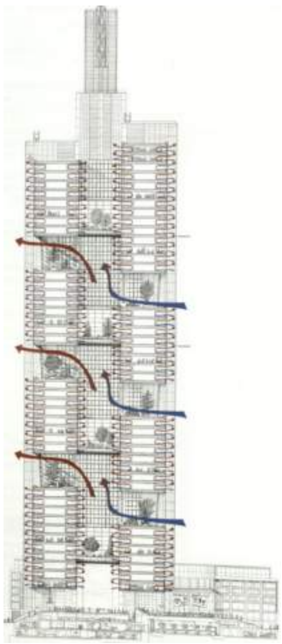


Fig. 316. Floor Plan with Sky Garden and Office Spaces

As sky gardens are spatially connected with each other through the central atrium and since each of these gardens has a great outward facing glazing with controllable pivoting windows, this whole system works as a large greenhouse. In the winter the pivoting windows are kept closed in order

372 Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1346.
373 Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1350.
374 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 33.
375 Eric Howeler, *Skyscraper-Vertical now*, 2004, 180.
376 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 35.

to warm up the air in the sky garden which acts as a climate buffer between the building interior and exterior. On warm days however these windows are opened letting in fresh air which falls down or rises up through the central atrium to the next sky garden above or underneath, depending on the air temperature and pressure differences.[377] This system provides fresh oxygen and natural air ventilation, not only for the sky gardens and the large atrium, but also to offices which are in the inner zones of the building with operable windows. In the offices, traditional perimeter radiators are used for heating purposes and radiant ceiling above the perforated-metal ceiling is employed as a backup for cooling.[378] The offices's natural ventilation strategy can be considered as single-sided ventilation whereas the ventilation in the atrium consists of cross-ventilation and a stack effect.



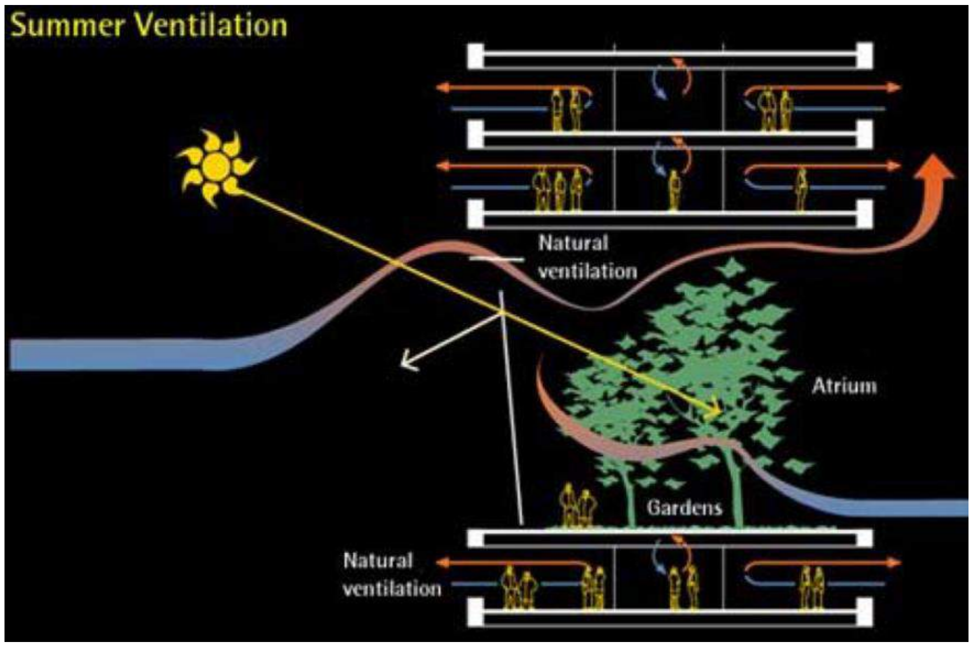


Fig. 317. Ventilation System **Fig. 318.** Natural Ventilation System of the Tower in the Summer

According to Foster, the office spaces can be described as petals of the stem, which is the central atrium.[379] Sky gardens not only help to decrease the building's reliance on mechanical ventilation, absorbing CO2 and creating fresh oxygen, but they are also privileged social garthering spaces for the occupants. People confer, drink coffee, eat lunch or simply take a break for a moment for relaxation in the sky gardens. Two gardens are equipped with buffet-style cafeterias as the others have vending machines.[380]

[377] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 41.
[378] Journal, *Architectural Record 186*, Jan-Mar 1998, 72.
[379] Pooya Lotfabadi, *Analyzing passive solar strategies in the case of high-rise building*, 2015, 1350.
[380] Journal, *Architectural Record 186*, Jan-Mar 1998, 72.

Fig. 319. Sky Garden and Atrium

Fig. 320. Pivoting Window of the Sky Garden

Fig. 321. Sky Garden as Gathering Space

The high rise sky gardens are planted according to their orientation meaning that the western gardens are planted with North American (e.g., maples), the eastern with Asian (e.g., bamboos) and the south facing ones with Mediterranean vegetation (e.g., citrus and olive trees). No two gardens are alike in the high rise.[381]

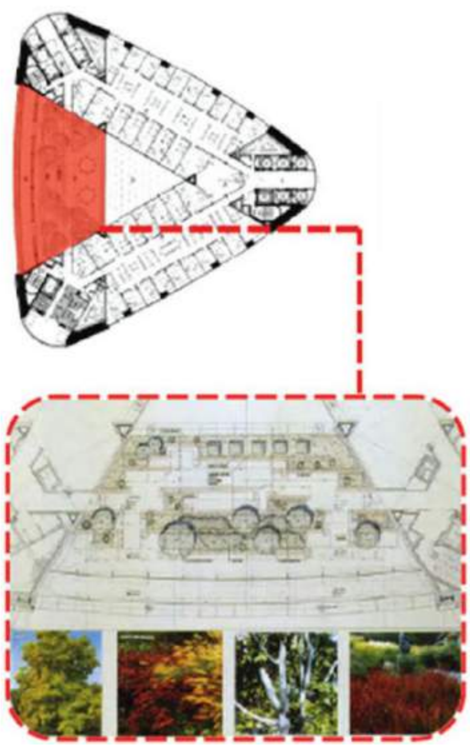


Fig. 322. West Facing Garden Filled with North American Plants

Fig. 323. North American Vegetation

[381] C. Davies, I. Lambot, *Commerzbank Frankfurt-Prototype for an ecological High-rise*, 1997, 278.

The building's double skin facade with low-e coated insulation glazing is designed with operable windows making it possible to the occupants to control natural light penetration and fresh air ventilation to their offices individually.[382] The high rise's intelligent BMS system constantly analyzes the ambient weather conditions and displays a light to show tenants when the operable facade panels could be opened. Switches are located next to the office doors to make the control over light, window and shading louvres possible for the occupants. When the window is open the mechanical ventilation and air conditioning shuts down automatically. The BMS also automatically adjusts the shading louvres in the facade's cavity according to the sun path in order to prevent light penetration and avoid overheating of interior spaces.[383]

The double-skin facade consists of individual modules instead of a continuous vertical facade and the facade's cavity is 0.2-meter (0.66-foot) wide to allow proper air ventilation. The cavity is ventilated separately for each individual facade panel through slots at the top and bottom of the module. Small aerofoil-section strips are installed above and under these slots in order to enhance airflow to the facade's cavity. [384]

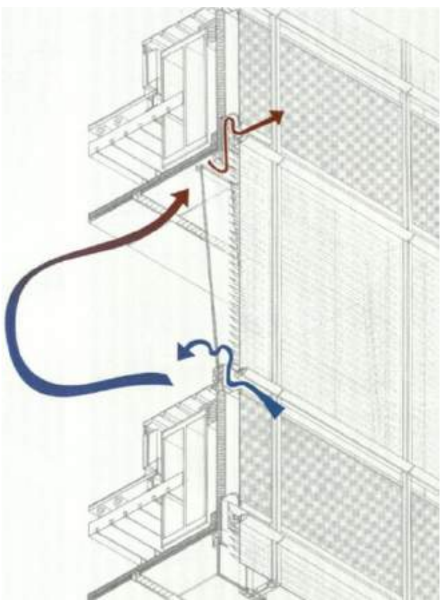


Fig. 324. Airflow Through the Double-Skin Facade

Fig. 325. Window's Lower Ventilation Slot

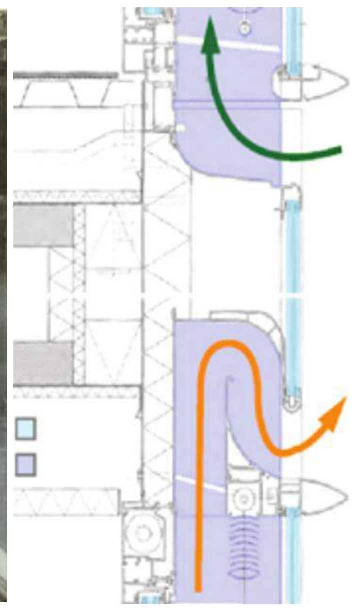


Fig. 326. Window's Air Intake and Exit

Service cores are located on the corners with large eight-story high vierendeel trusses, spanning over 34 meters (112 feet) between them, thus allowing column-free office spaces. There is a huge load concentrated on the 6 massive mega columns on the corners and because of a poor soil quality 111 concrete piles were used as a pile foundation in order to keep the building loads up.[385]

For ecological and financial reasons no hot water was provided for the sinks in the restrooms. To save water, greywater such as water from the cooling towers was used for flushing toilets.[386]

382 Eric Howeler, *Skyscraper-Vertical now*, 2004, 180.

383 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 38.

384 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 35.

385 V. Fischer, H. Grüneis, R. Richter, *Commerzbank, Frankfurt am Main*, 1997, 17.

386 Journal, *Architectural Record 186*, Jan-Mar 1998, 72.

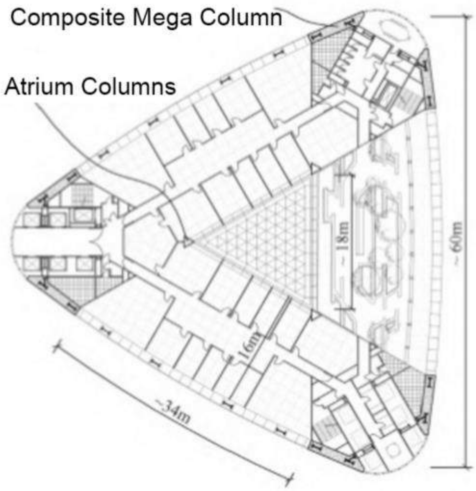


Fig. 327. Floor Plan with Columns

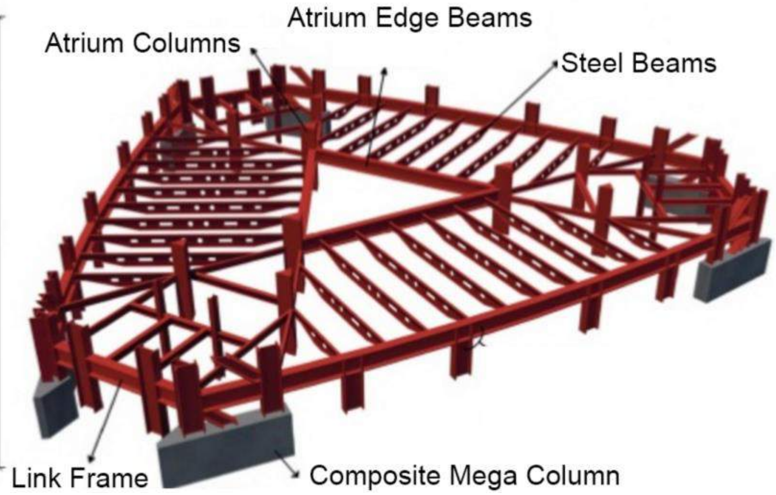


Fig. 328. Structural Axonometrics

A total of 16 lifts are available for the occupants, each suitable for up to 16 people. From these, 5-5 lifts are placed in the north and west core, respectively, whereas an additional 6 express lifts are located in the south core with the highest speed.[387]

The total thermal energy consumption of the building ranges between 105-128 kWh/m2 (33,285-40,576 btu/ft2) which falls below all EnEv 2007 benchmarks that regulate minimum requirements regarding energy use of new and renovated buildings in Germany. It is important to note that this requirement is 135 kWh/m2 (42,795 btu/ft2) for fully naturally ventilated and heated buildings.[388]

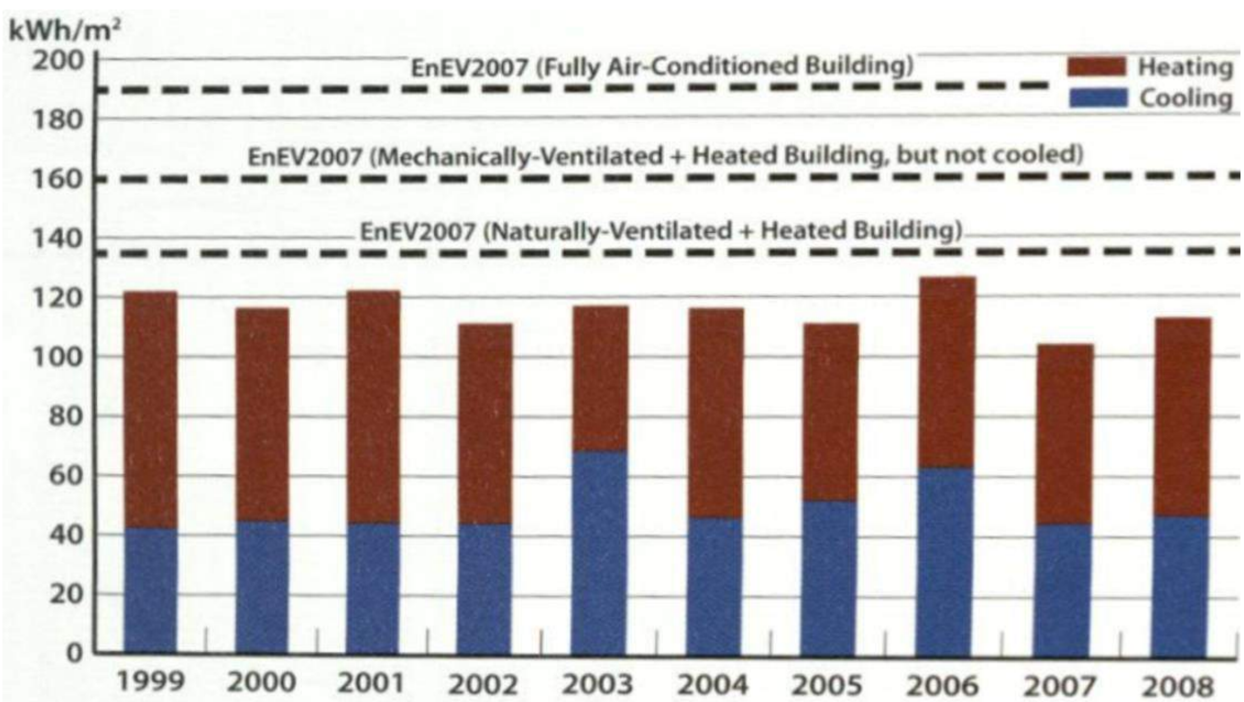


Fig. 329. Average Energy Consumption for Heating and Cooling Between 1999-2008, Compared to EnEV 2007 Energy Conservation Benchmarks

[387] V. Fischer, H. Grüneis, R. Richter, *Commerzbank, Frankfurt am Main*, 1997, 19.
[388] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 39.

5.3.1.2 Pearl River Tower

Location: Guangzhou, China

Year: 2011

Height: 310 m / 1,017 ft

Floor: 71

Use: Office

Designer: SOM

Fig. 330.
Pearl River Tower

The Pearl River Tower in China is one of the most energy-efficient high rises of the world, since energy efficiency was the building's top priority. It was one of the first high rises to be certified with the LEED platinum certification.[389] This tower represents a real symbol of progress for the 21st century. It is environmentally intelligent, and self-sustaining on a high level. The Pearl River Tower was classified as a Supertall Building by the Chinese codes based on its height and aspect ratio (8.4:1).[390] The tower's design philosophy combines both active and passive sustainable measures, as well, in order to decrease the building's impact on the city's electricity grid, reduce CO_2 emissions and provide the most comfortable indoor environment for its tenants.

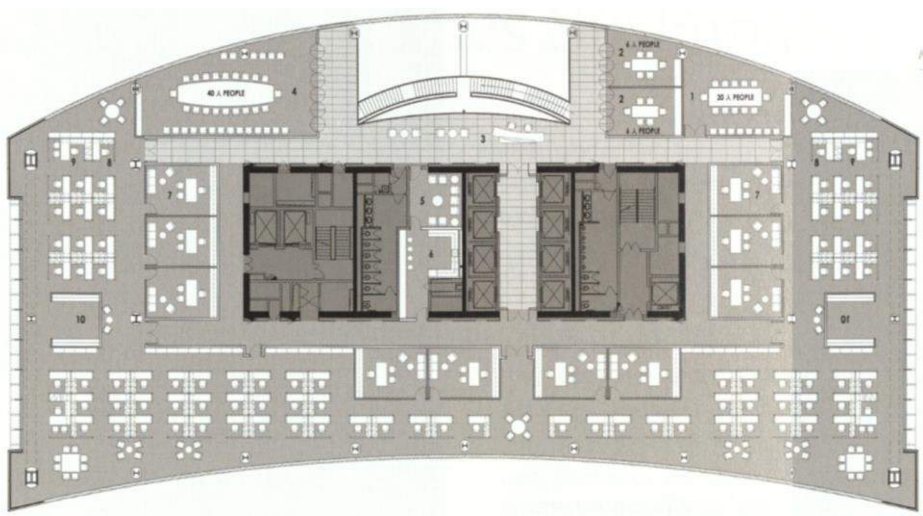


Fig. 331. Office Floor Plan

Fig. 332. Section

The high rise's aerodynamic form was developed through analyzations of prevailing winds and the solar path. The form responds to the local climatic conditions and the design utilizes both sun and wind power to its advantage. The building's floor plate was shifted slightly from the orthogonal grid of the city, thus better capturing solar energy through its location and exploiting prevailing breezes at the highest level.[391]

389 CTBUH, *CTBUH Journal 2014 Issue II, 2014*, 14.
390 CTBUH, *CTBUH Journal 2014 Issue II, 2014*, 13.
391 http://www.som.com/projects/pearl_river_tower__sustainable_design Accessed June 2016

The high rise has effective daylight utilization owing to its floor-to-ceiling-height glass panels and its narrow floor plates. The building uses automatic dimming controls. This system automatically reduces artificial light levels in response to increased available natural light, thus lowering energy costs and contributing to the greatest satisfaction of occupants.[392]

Its sculpted form, which acts as a 75-meters-wide (246-feet-wide) sail, directs wind to openings at the building's mechanical floors, dividing the tower into three villages.[393] There are two of these openings for each mechanical level. The air-intake openings are located at each third of the building's height where vertical-axis wind turbines (2x5 meters / 6.6x16.4 feet) are incorporated in the inlets in order to harness the wind accelaration across the face of the tower. The facade inlets accelerate wind velocity by 2.5 times, leading to more than 8 times the power generation in comparison with a wind turbine in an open field.[394] This power is then converted to electricity and is used by the high rise. The use of these through-building channels greatly contributes to the wind load reduction, thereby enabling a lighter, more efficient building structure. LED lights at the mouth of the air-intake openings change color and intensity at night, to show how much energy is generated by the wind.[395]

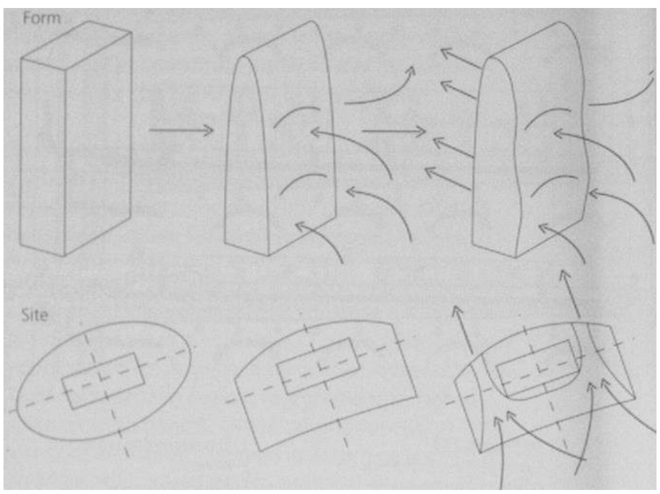


Fig. 333. Concept of the Building Form Influenced by Wind

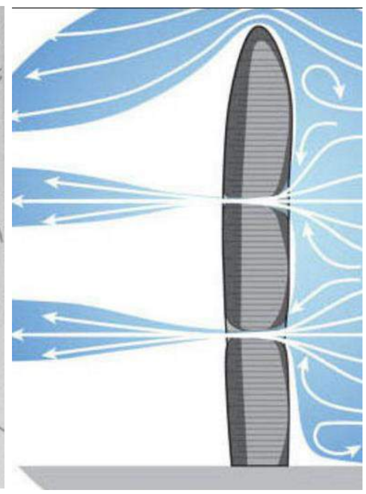


Fig. 334. Wind Flow Through the Building

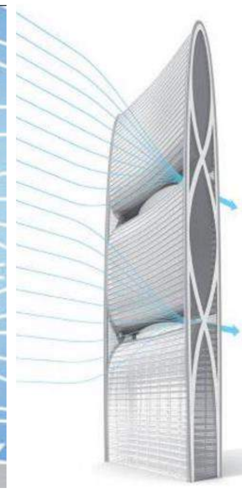


Fig. 335. Air-Intake Openings

While east and west elevations are straight, the north facade is convex, whereas the south facade is concave. Unitized frit glass is used for the east and west facades. The outer layer of the double-skin facade is clear glass with low-e coating, which features the perfect balance between high transparency and low heat gain.[396] The inner glass layer is a single monolithic glazed panel. The warmed-up air rising in the double-skin facade's cavity (0.24 meters / 0.79 feet) is used for dehumidification purposes and to mix with the ventilation air for heat exchange.[397] Rainwater that falls on the building's envelope is collected and used as greywater after its treatment.[398]

392 CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 16.

393 J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 307.

394 CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 15.

395 CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 12.

396 J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 309.

397 CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 14.

398 K. Daniels, R. E. Hammann, *Energy design for tomorrow*, 2009, 222.

Fig. 336. Air-Intake Openings

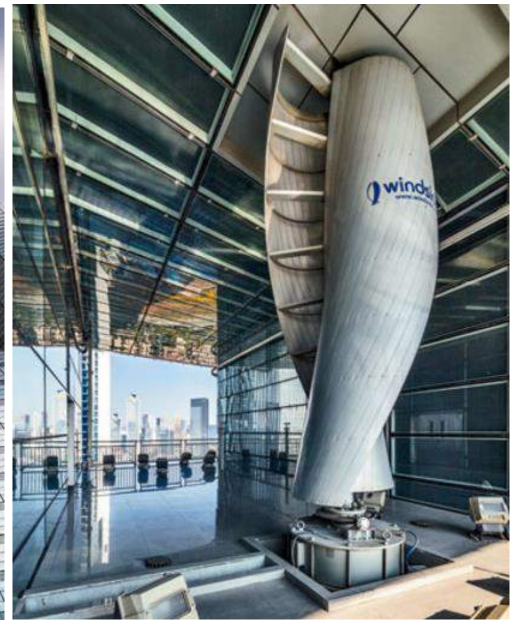


Fig. 337. Vertical-Axis Wind Turbine of the Air-Intake Opening

PV elements are placed on the roof and on the horizontal sun shades of the east and west facades. These PV panels serve dual function, as they protect the building from solar gain and produce energy around 200,000 kWh/year (682,428,327 Btu/year).[399] These facades incorporate automated Venetian blinds, too, thus significantly contributing to the high rise's energy efficiency. The BMS system of the building automatically controls the blind's tilt angle in response to the sun's position and the solar intensity.[400]

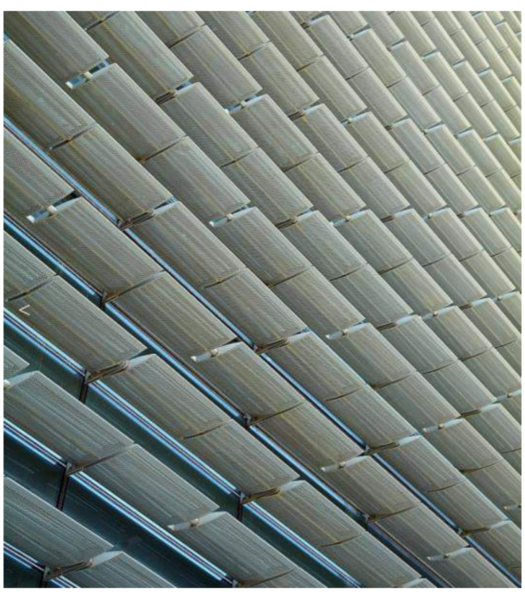


Fig. 338. Horizontal Sun Shades

Fig. 339. Integrated PV System Within the External Shading

[399] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 15.
[400] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 14.

The building's energy use is further lowered by the use of a chilled ceiling system. The use of chilled ceilings leads to a decrease of floor-to-floor height from 4.5 to 3.9 meters (14.8 to 12.8 feet), thus providing an additional 10,000 m2 (107,639 ft2) working space and saving five stories to the high rise within the same square footage of exterior envelope.[401] The radiant ceiling system resulted in a smaller building core owing to reduced air shaft sizes and elimination of on-floor fan rooms.[402]

Fig. 340. PV Panels on the Roof

Fig. 341. Automated Venetian Blinds Within the Double-Skin Facade's Cavity

The floors from 59 to 68 are occupied by the offices of the owner and lower floors are leased to different tenants who want to enjoy great energy savings and who require a prime location. The highest two floors are configured as a club-level amenity.[403] The high rise incorporates double-deck elevators in four zones in order to make circulation more efficient, reduce the size of the core and create more efficient floor plates.[404]

Guangzhou is located in a moderate seismic zone and the tower was designed with an outrigger system with belt trusses to remain elastic during rare earthquake periods.[405] The building structure consists of a composite system, utilizing steel and concrete elements. The shear wall core (thickness ranges from 0.7 to 1.5 meters / 2.3 to 4.9 feet) in the building's center is linked to the exterior columns and mega columns by outriggers and belt trusses at the level of mechanical floors.[406]

[401] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 306.
[402] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 16.
[403] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 12.
[404] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 16.
[405] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 13.
[406] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 14.

Fig. 342. Lateral-Load-Resisting Structural System

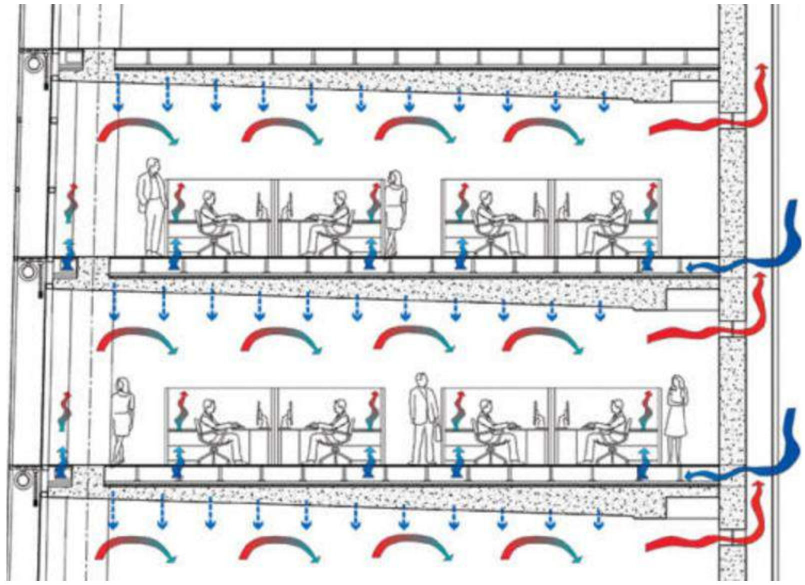


Fig. 343. Cross Section of the Ventilation Concept

The original goal of the designer was to create an NZEB; however, in the final design consideration this was found impossible due to technical economic and legislative reasons.[407] After completion, the high rise uses around 30 percent less energy than a similar building in China and what the Chinese baseline energy code represents.[408]

5.3.1.3 30 St Mary Axe

Location: London, England

Year: 2004

Height: 180 m / 591 ft

Floor: 40

Use: Office

Designer: Foster and Partners

Fig. 344. 30 St Mary Axe

The 30 St Mary Axe, also known as the Swiss Re Tower, is considered London’s first sustainable high rise. The tower features Class A office space, furthermore public spaces and retail amenities on the ground. The high rise was built to serve primarily as the headquarters for Swiss Re, however the company required only the floors between 2 and 15, and thus the floors between 16 and 34 were leased to other companies. The ground floor is open for the public, consisting of a plaza with shops and restaurants.[409]

[407] J. C. S. Goncalves, *The Environmental Performance of Tall Buildings*, 2010, 307.

[408] CTBUH, *CTBUH Journal 2014 Issue II*, 2014, 14.

[409] Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 302.

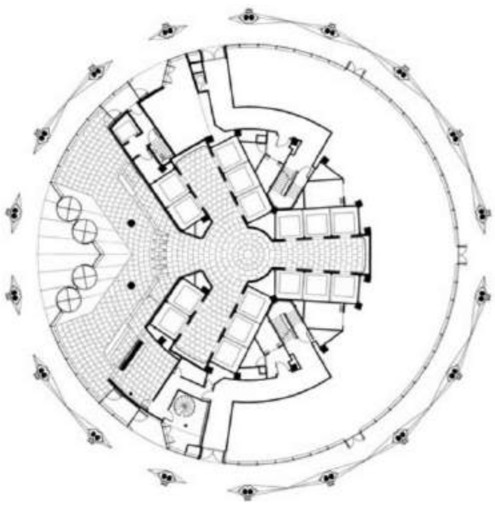


Fig. 345. Ground Floor Plan

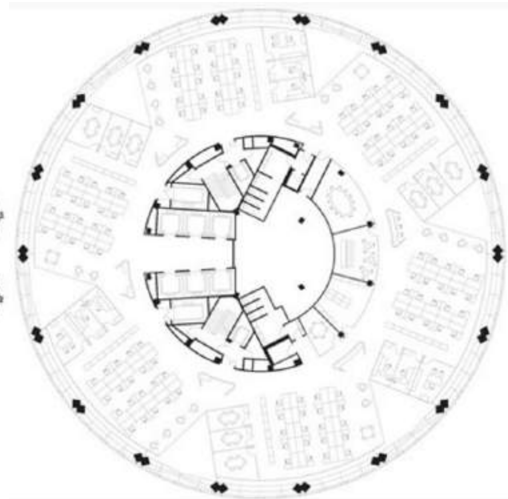


Fig. 346. Office Floor Plan

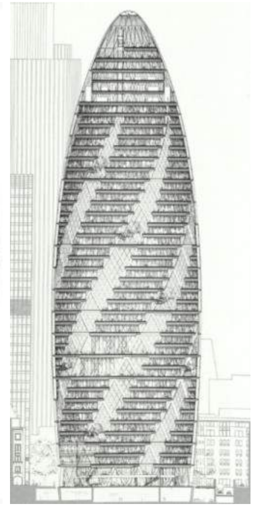


Fig. 347. Section

The cylindrical form of the building contributes to the building's environmental strategy and responds to the constraints of the site. This tapering, circular profile minimizes turbulence around the building and provides an increment in the daylight penetration. Furthermore, the cylindrical form needs 25 percent less external surface than a similar tower with the same size and with a rectilinear form. This contributes to minimize heat loss and heat gain through the building's skin.[410]

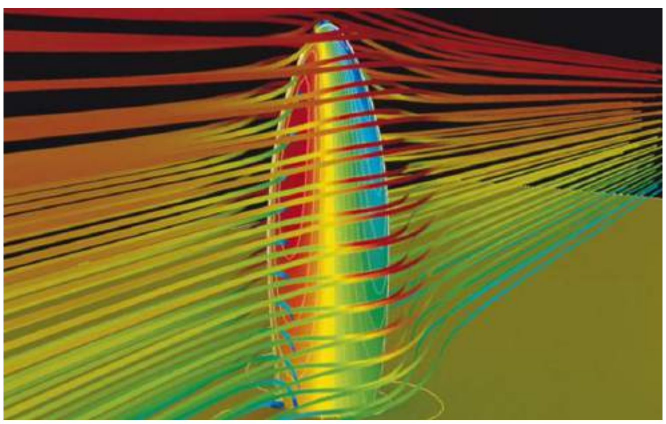


Fig. 348. Wind Flow Diagram

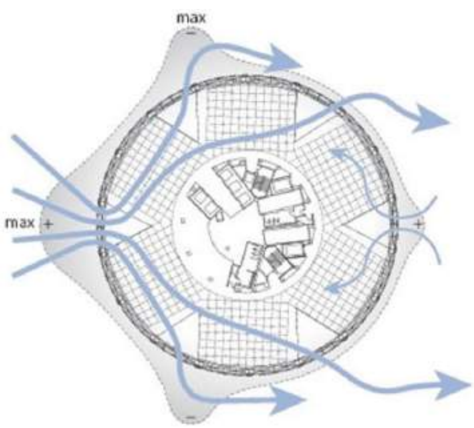


Fig. 349. Pressure Differentials Created Between the Building's Windward and Leeward Sides

The high rise's floor plate sizes vary with height. The first floor has a 50 meters (164 feet) diameter that widens to 57 meters (187 feet) on the middle of the tower and diminishes toward to top. Depending on the size of the floor plate, the distance between the building's perimeter and core varies from 6.4 to 13.1 meters (21 to 43 feet).[411] Each of the floor plates has a 5 degree rotation compared to the floor below. This creates 6 stepped, triangular atria cut into the floor plates, spiraling up the building. Thus 6 rectangular office "fingers" are created. Rectangular office spaces are easier to sub-divide for leasing purposes.[412]

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410 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 90.

411 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 85.

412 Anna B. Frej, *Green office buildings - A practical guide to development*, 2005, 303.

Fig. 350. Atria Spiraling Up the Building

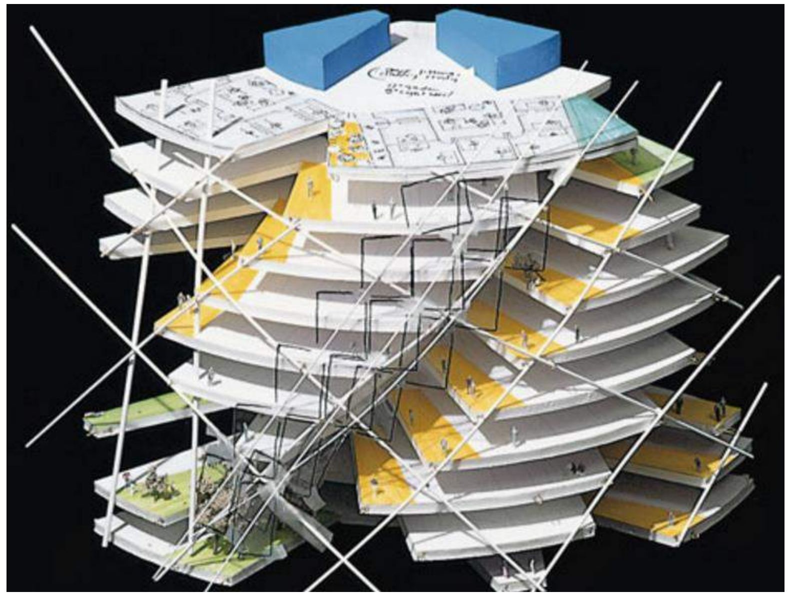


Fig. 351. Detail of Triangular Atria

Owing to the high rise's circular plan, pressure differentials are created between the building's windward and leeward sides thus inducing cross-ventilation. The offices have a natural ventilation strategy where air enters from the windward-facing atria and exits though the leeward-facing atria. Therefore, each office space can be naturally ventilated through the adjacent atria.[413]

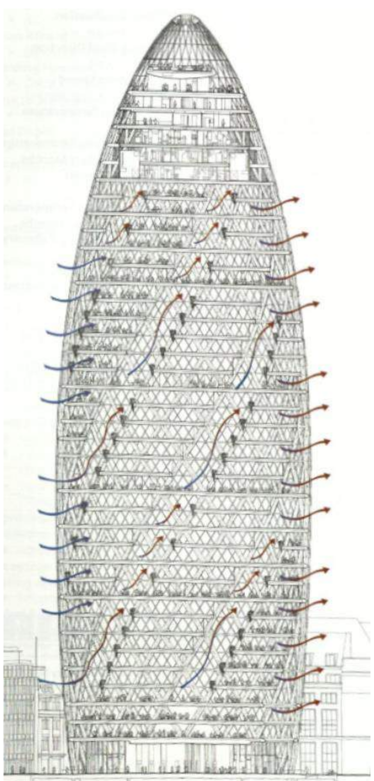


Fig. 352. Natural Ventilation of the Building

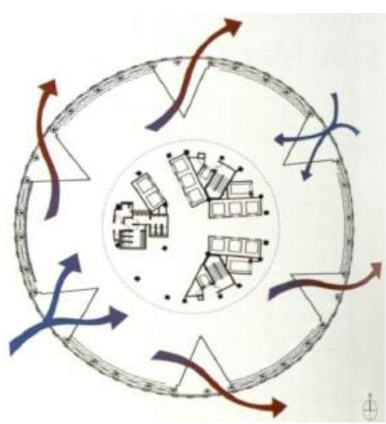


Fig. 353. Natural Ventilation of Atria and Offices

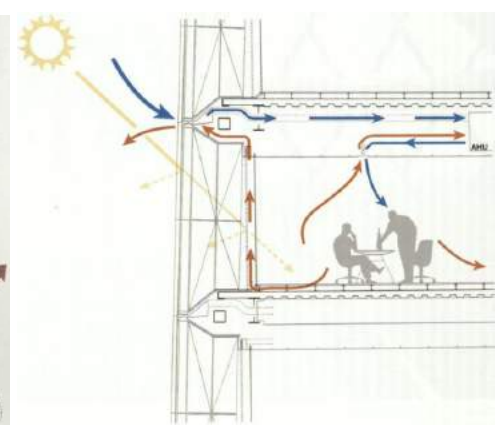


Fig. 354. Mechanical Ventilation Strategy in the Summer

[413] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 87.

The atria are deliberately rotated clockwise along the wind with the predominant winds from the southwest, thereby, enhancing natural ventilation, as well. Every other floor has triangular, motorized windows on the building's envelope which induce fresh air into the atrium where it rises through a stack effect and is tempered before letting it in into the office spaces through their internal, facade enclosing atria. Furthermore this protects the offices from direct winds, too.[414]

Fig. 355. Facade View with Atrium Windows in Open Position

Fig. 356. Opened Windows

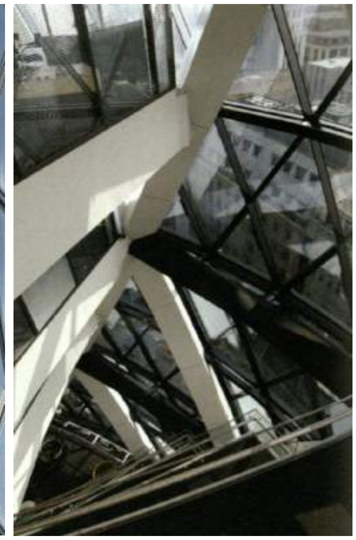


Fig. 357. Atrium as Lightwell

The atria not only bring daylight and natural ventilation deep into the building, thus reducing artificial lighting and mechanical ventilation loads, but they also enhance external views and visual communication between office spaces. Tinted glass was installed in the spiraling atria in order to reduce glare and solar gain. Although this later gave the building its unique appearance that inspired its official logo too.[415]

Fig. 358. Tinted Glass of the Spiraling Atrium

Fig. 359. Views from the Atrium

Fig. 360. Tower's Logo

414 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 87.

415 K. Powell, G. Smith, *30 ST Mary Axe A tower for London*, 2006, 83.

The extracted air from the office spaces is led into the facade's cavity in order to provide ventilation. This air has about the same temperature the entire year, cooler than the outside air temperature in the summer and warmer than the outside air temperature in the winter. The cavity of the double-skin facade incorporates automated venetian blinds in order to decrease solar heat gain and glare. The building's BMS permanently monitors the external weather conditions and controls the opening of exterior windows and the angle of the facade integrated blinds accordingly.[416]

The building is naturally ventilated for about 40-50 percent of the year. Although, when weather conditions don't allow natural ventilation, the building is sealed and mechanical air conditioning is activated. During the operation of mechanical ventilation, external fresh air is drawn in through narrow slits which are installed at floor levels between the glazing panels. However, these slits are not part of the natural ventilation system and they are used only during mechanical ventilation. Each office space has a slit for air intake as well as one for air exhaust. After the air gets into the ceiling, it is conditioned before being introduced into the office space.[417]

Diagonally braced steel diagrid wraps around the tower as the building's exterior structure which allows column-free interior spaces.[418] The diagrid structure consists of two-story-high A-frames that are installed end-to-end in order to form a diamond pattern.[419] Almost 8,500 tons of steel were used for the diagrid structure which means 20 percent savings in structural materials. Steel was used for the building's structure and floors, concrete for floors and foundation such as aluminum for external finishes and glass for the double-skin facade.[420]

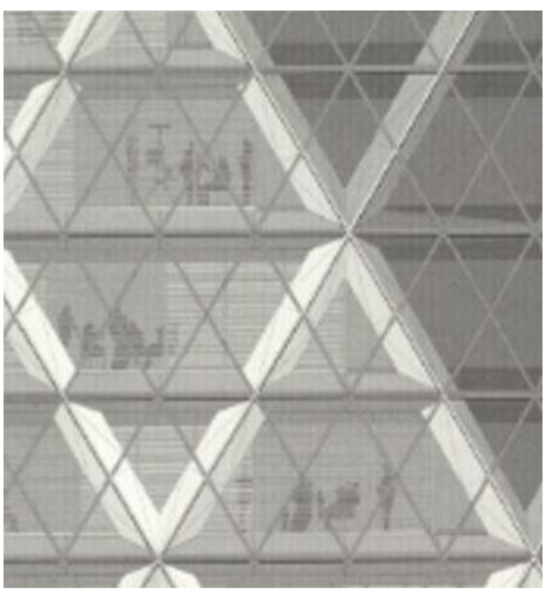


Fig. 361. Diagrid Structure

Fig. 362. Diagrid Structure with Spiraling Atria

Fig. 363. Two-Story-High A-Frame

416 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 87.
417 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 89.
418 Kheir Al-Kodmany, *Green Towers and Iconic Design: Cases from Three Continents*, 2014, 18.
419 K. Powell, G. Smith, *30 ST Mary Axe A tower for London*, 2006, 84.
420 D. Trabucco, *An analysis of the relatiosnip between service cores and the embodied, running energy of tall buildings*, 2008, 943.

On the high rise top, there is a steel-frame dome consisted of three floors (i.e., 38-40 floors), sitting on the diagrid structure as the crown of the high rise. The dome offers magnificent panoramic views across London and it contains a restaurant, a series of private dining-rooms and a bar which is floating above the restaurant.[421]

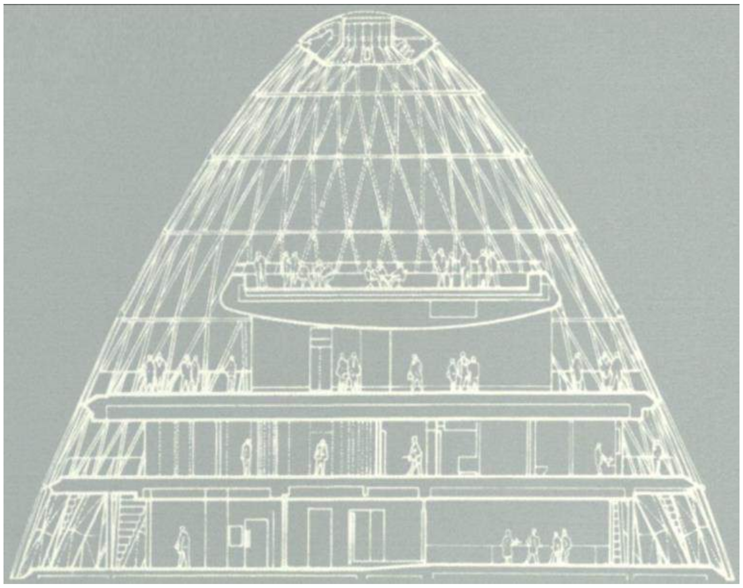


Fig. 364. Top of the Building with the Dome

Fig. 365. View from the Dome

The 30 St Mary Axe became an instantly recognizable feature of London and it is one of the best examples of an ecological, sustainable high rise in contemporary architecture. Through its natural ventilation strategy along with other sustainable measures, the high rise uses only half of the energy that is used by a traditionally air-conditioned office building.[422]

5.3.1.4 Manitoba Hydro Place

Location: Winnipeg, Canada

Year: 2009

Height: 115 m / 377 ft

Floor: 22

Use: Office

Designer: Bruce Kubawara

Fig. 366. Manitoba Hydro Place

[421] K. Powell, G. Smith, *30 ST Mary Axe A tower for London*, 2006, 154.

[422] http://www.fosterandpartners.com/projects/30-st-mary-axe/ Accessed June 2016

The Manitoba Hydro Place in Winnipeg, Canada is one of the most energy-efficient high rises in North America and represents a new generation of bioclimatic architecture. The tower's sustainable efficiency was realized in an extreme challenging climate that falls into the very cold category Zone 7 by ASHRAE.[423]

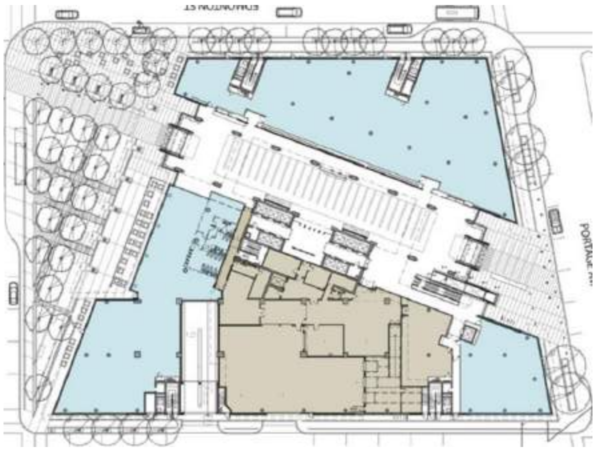


Fig. 367. Ground Floor Plan

Fig. 368. Office Floor Plan

The building optimizes passive free energy for the entire year in Winnipeg where the fluctuation of temperature ranges between -35 °C (-31 °F) and +34 °C (93.2 °F). In fact, this is achieved by no restrictions to the design quality and human comfort and the tower provides a healthy workplace environment for all of its 2000 employees. The building is filled with fresh air the entire year.[424]

The design team realized through analysis of climate conditions, that Winnipeg is an ideal location to employ passive solar heating and daylighting strategies. Thus the orientation and form of the building was designed to harness the solar potential of the site and to enhance natural ventilation within the building through prevailing breezes. As a result, the complex comprises two office towers facing west and northeast, which are set on a podium of three stories. The towers splay open to the south in order to catch southerly winds, that are characteristic to Winnipeg, and to receive maximum solar exposure.[425]

The building's floor plate depth was kept narrow by placing the office spaces into two separate towers and by the introduction of multi-floor stacked atria. These, along with the floor-to-ceiling windows, provide access to great views throughout as well as natural daylight penetration deep into the interior.[426] Thereby the building occupants have abundant sunlight in the winter. Every occupant has access to one of the building facades and enjoys natural daylight during 80 percent while being in the office. No tenant sits more than 9 meters (60 feet) away from the window.[427]

423 http://manitobahydroplace.com/Consortium/About/ Accessed June 2016

424 http://manitobahydroplace.com/Consortium/About/ Accessed June 2016

425 A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 356.

426 A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 356.

427 David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 386.

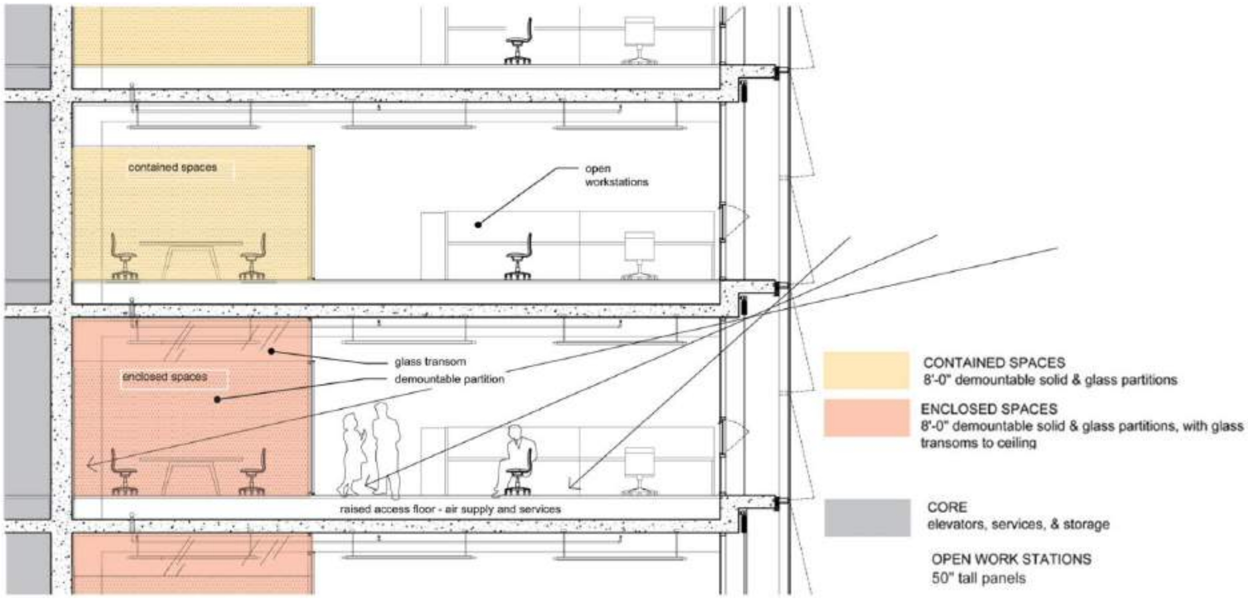


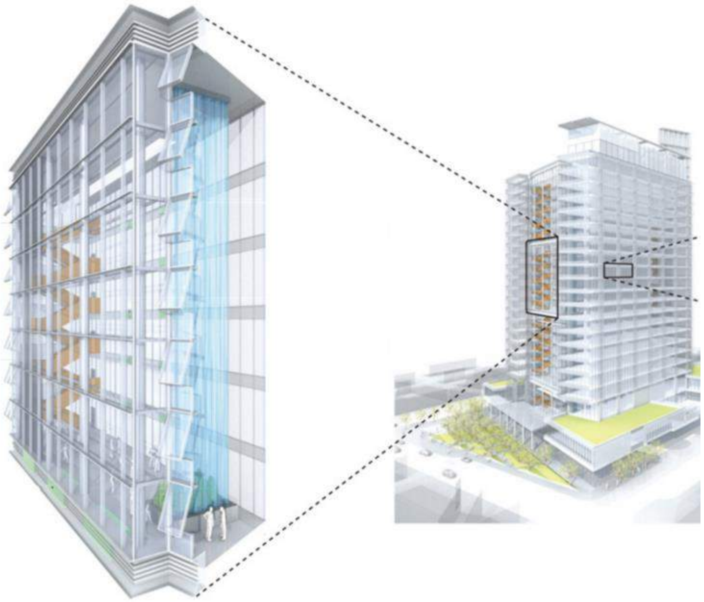
Fig. 369. Section Illustrating the Winter and Summer Daylighting Conditions within the Office Spaces

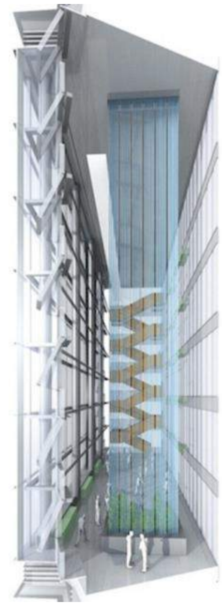
The choice of a glass tower in this extreme climate works remarkably efficiently, since even when it is very cold outside, it is still sunny which allows ideal solar gain for the building. This effect is further exploited by the double-skin facade's cavity serving as a buffer zone, that significantly reduces the building's heating and cooling loads by tempering the extreme outdoor temperatures.[428]

The double-skin facade features a 0.9 meter (3 feet) cavity between its two layers. The facade's outer skin consists of insulated glazing with low-iron and low-e coatings in order to maintain high thermal resistance and maximize the transmission of daylight at the same time. The inner layer is a single-pane glazing with low emissivity as well. In the inner and outer layers of the double-skin facade, operable windows allow natural ventilation at appropriate times of the year. Horizontal shading is integrated into the facade's cavity and is controlled automatically. These elements are perforated thus allowing some transparency and diffused daylight entrance even when fully extended.[429]

On the south side of the tower, there are three six-story high skygardens incorporated that are stacked above each other. Each of these skygardens has a 23 meters (76 feet) tall, water curtain wall from 280 Mylar ribbons that conditions the air through evaporation before it enters the interior space. Dry winter air is humidified by warm water and chilled water dehumidifies humid exterior air in the summer.[430] Concrete floor slabs in the gardens absorb solar radiation and release it to preheat the intake air. Six, three-story atria capture return air from the offices at the tower's north end and channel it into the solar chimney.[431]

[428] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 355.
[429] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 355.
[430] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 385.
[431] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 355.





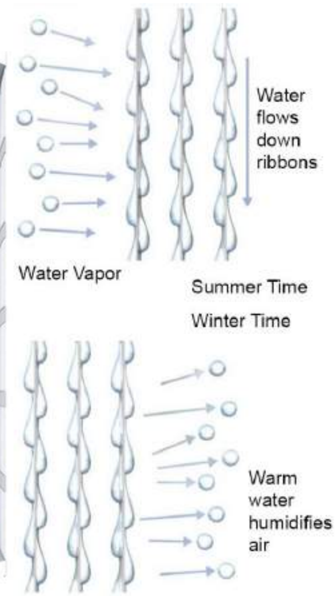


Fig. 370. Waterfall and South Atrium Detail **Fig. 371.** Water Curtain Wall **Fig. 372.** Mylar Ribbons

The north end of the tower consist a 115 meters (377 feet) tall, fully glazed solar chimney which gives an instantly recognizable appearance to the building. This chimney plays a crucial role in the high rise's passive ventilation system, relying on the stack effect sucking air out from the building's interior spaces. Skygardens work in combination with the solar chimney, serving as the lungs of the high rise and providing fresh air during the whole day, in the entire year.[432]

Fig. 373. South Atrium Waterfall

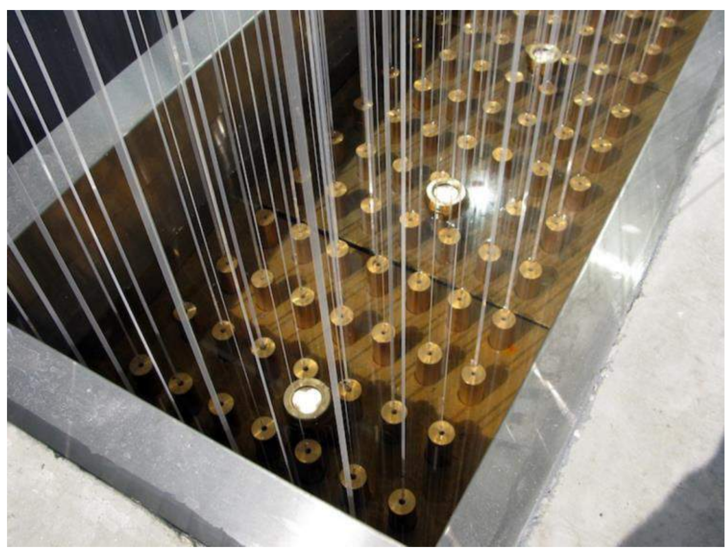


Fig. 374. Waterfall Collection Pool

Exhaust air from office spaces is returned back by fans in the winter, rather than letting it in into the chimney to rise and get out at the top. Heat is extracted from this air by the heat recovery system and it is sent to fan-coil units for preheating purposes in order to be distributed to the

[432] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 385.

public ground floor spaces.[433] During the summer, the chimney top is heated by the sun that enhances the air buoyancy pulling air upward. There are sand-filled pipes installed at the chimney top which are able to absorb solar radiation at daytime and release the resulting heat at night in order to heat the air in the chimney when the temperature falls down.[434]

Fig. 375. Sustainable Design Strategies Incorporated in the Tower

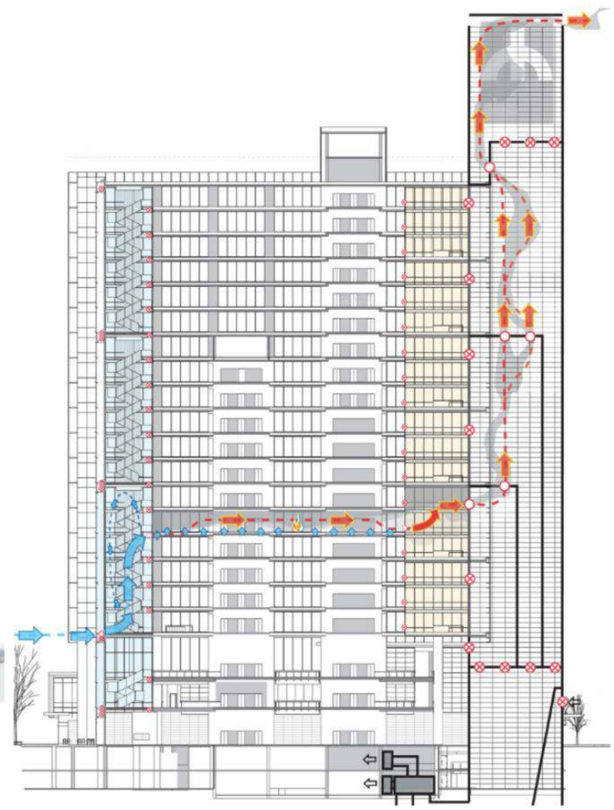


Fig. 376. Section Showing Air Flow Through the Building

The building's BMS with numerous observation points enables the tenants to receive feedback and to have control over thermal comfort, lighting, ventilation and solar shading. When not under tenant's control, the shading system and the electric lighting automatically responds to the changing daylight conditions by the BMS. Furthermore, it controls the operable windows of the facade's outer layer, while inner layer windows are operated manually by tenants.[435]

The thermal mass of the building is high and the concrete floor slabs incorporate a radiant heating and cooling system, circulating water in it. These exposed radiant ceiling slabs maintain a 20 °C (68 °F) temperature in the whole year. The high rise's geothermal system heats the radiant ceiling and thereby the office spaces. The geothermal energy benefits from consistent ground temperatures in the entire year, whereas heat captured during the summer is stored by thermal energy storage and used later in the wintertime. The geothermal system with closed loop provides 60 percent of the building's heating needs.[436]

[433] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 356.
[434] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 354.
[435] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 386.
[436] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 356.

The high rise incorporates low-flow fixtures as well as waterless urinals, thus minimizing the building's water demand.[437] In addition, a green floor covers the building's three-story podium and thereby protects the roof membrane underneath from UV degradation and performs as a thermal insulation.[438]

Fig. 377. Green Roofs in Plan

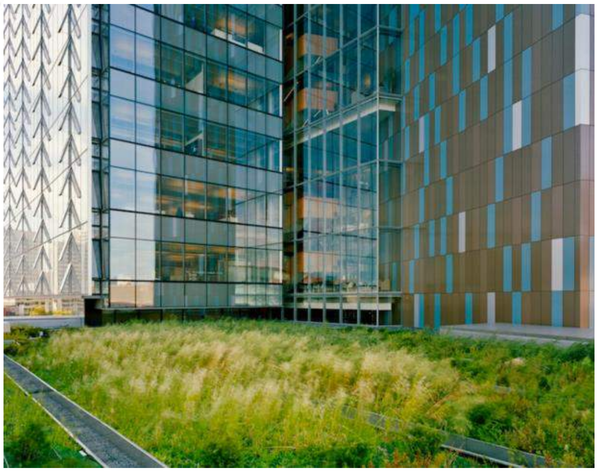


Fig 378. Green Roof of the North Facade

Manitoba Hydro Place is a highly energy efficient high rise, taking advantage of the local climate. The towers's greatness was awarded by the CTBUH as the Best Tall Building Americas in the year of its completion.[439] The high rise is 66 percent more efficient then the Model National Energy Code for Buildings and it has an annual energy consumption of only 88 kWh/m2 (27,896 Btu/ft2) and was certified with the LEED platinum certification.[440]

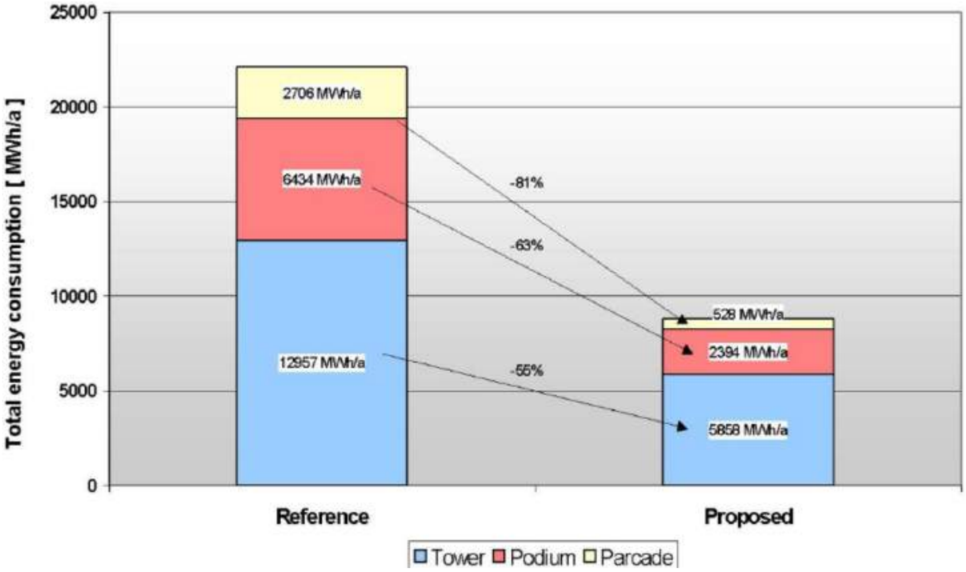


Fig. 379. Total Energy Savings of Manitoba Hydro Place

[437] David Parker, Antony Wood, *The Tall Buildings Reference Book*, 2013, 386.

[438] A. G. Kwok, W. T. Grondzik, *The green Studio Handbook: Environmental strategies for schematic designs*, 2006, 356.

[439] http://skyscrapercenter.com/building/id/9086 Accessed June 2016

[440] http://www.manitobahydroplace.com/Post-Occupancy-Performance/Performance/Detail/?rid=42 Accessed June 2016

5.3.1.5 Menara UMNO

Location: Penang, Malaysia

Year: 1998

Height: 93.5 m / 170 ft

Floor: 21

Use: Office

Designer: Ken Yeang

Fig. 380. Manitoba Hydro Place

The Menara UMNO in Malaysia was a breakthrough for being a naturally ventilated, energy efficient tower. Its form was configured by the geometry of the site as well as by considering the local climate. The high rise incorporates office spaces above a 7-story podium.[441] The service core was located on the building's southeast facade, thereby shading the interior spaces from the morning sun. Thus, the lift and other core uses can be naturally ventilated and receive natural daylight. The narrow floor plates allow office spaces to be within 6 meters of the facade; hence, every occupant has natural daylight access. When exterior weather conditions are appropriate, all office floors can be fully naturally ventilated.[442]

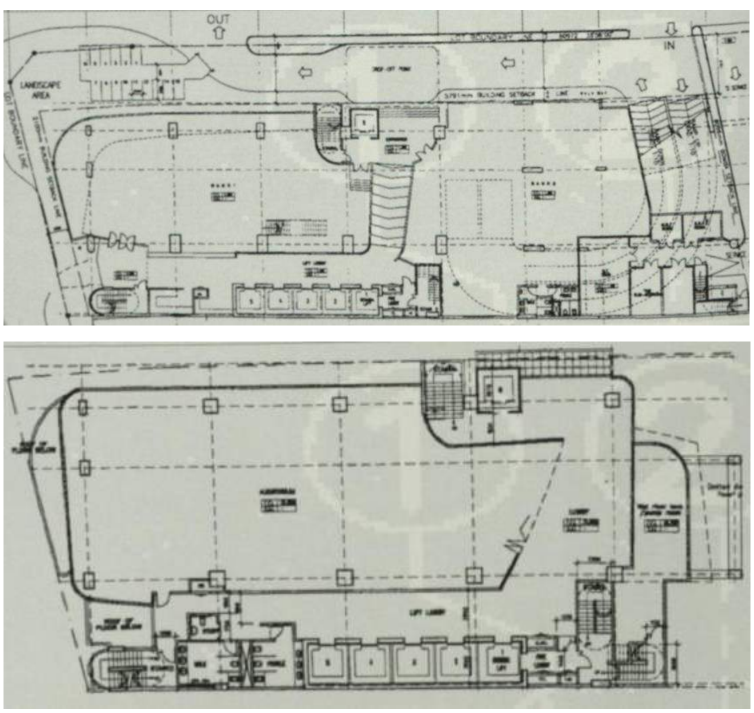


Fig. 381. Ground Floor Plan (Top) Office Floor Plan (Bottom)

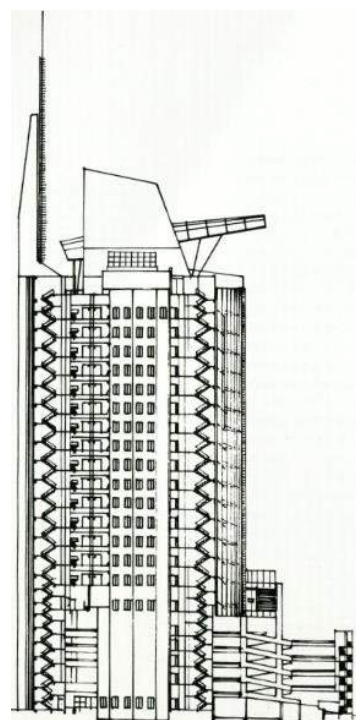


Fig. 382. Section

[441] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 51.

[442] Eric Howeler, *Skyscraper-Vertical now*, 2004, 182.

The high rise could not be entirely oriented to capture prevailing winds and, thus, wing walls were planned on the building's facade. These are basically protruding vertical walls, rising the full height of the building, which were established to channel wind into the interior. Wind walls also create pressure differences that further increase airflow into the office spaces and create natural ventilation.[443]

At the design stage, the effectiveness of the wing wall was analyzed by simulations and it turned out that natural comfort ventilation could not be achieved without the use of them.[444] Even so, Menara UMNO was the first high rise office building to incorporate a wing wall system in its design. The wing walls run up the building height on the south, southwest and northeast elevations.[445]

Fig. 383. Wing Walls

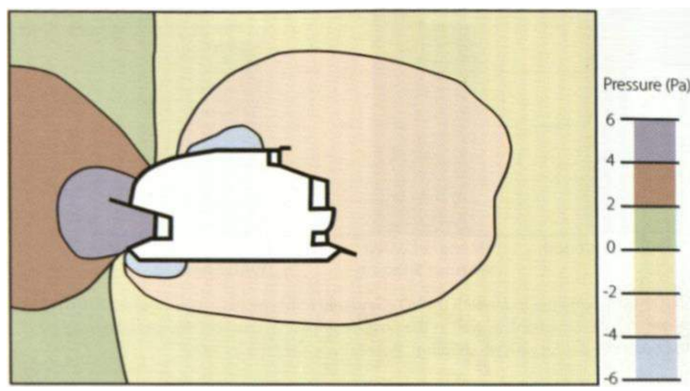


Fig. 384. Wind Pressure Analyzis

Balconies on the facade provide a perfect place for the tenants to meet up and enjoy the cooling breezes of the location as well as they provide shading for the tower. From the building's windward side, the air is channeled to a zone with special balconies, called airlocks, serving as pockets.[446] These pockets are provided with manually openable and adjustable windows and doors in order to control the natural ventilation's degree in the interior space. These balcony doors and windows are placed on the northeast and southwest sides of the building, inducing cross-ventilation.[447]

The building's southwest and northwest facades are protected from the sun not only by balconies and skycourts but also by perforated, horizontal screens of aluminum, serving as solar shading. These shading screens get more transparent toward the north. Placement of the sunscreens plays an aesthetic function and their location is determined by the solar orientation. The building's rooftop, which is highly exposed to the sun at this latitude, is shaded to withstand solar heat gain, too. It is protected not only by the upward extension of the service core, but it also has a large curved roof canopy.[448]

[443] H. Meyer, D. Zandbelt, *High-rise and the sustainable city*, 2012, 172.
[444] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 55.
[445] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 53.
[446] Ken Yeang, *Eco Skyscrapers*, 1998, 117.
[447] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 53.
[448] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 55.

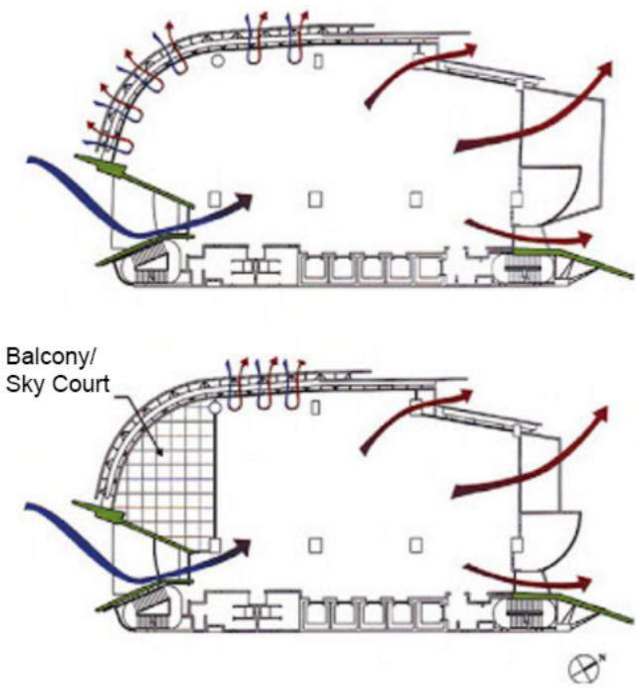


Fig. 385. Plans of Cross-Ventilation

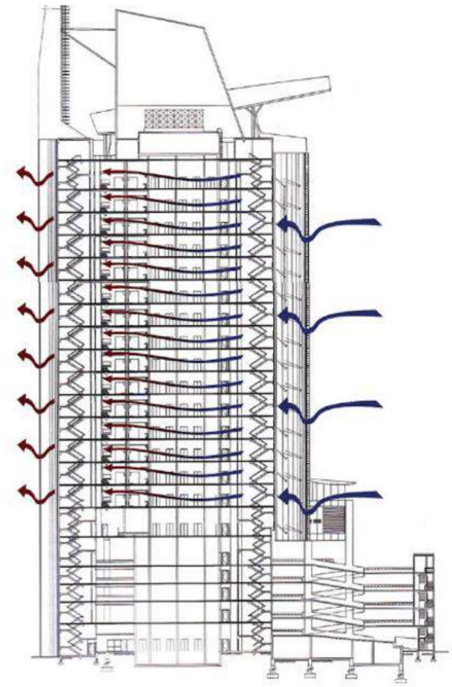


Fig. 386. Section of Cross-Ventilation

The high rise does not have any BMS, which would control the windows' operation or the amount of airflow into the interior spaces. Although, the tenants can choose between active or passive systems in the building thus deciding, for instance, whether the space should be naturally or mechanically ventilated.[449]

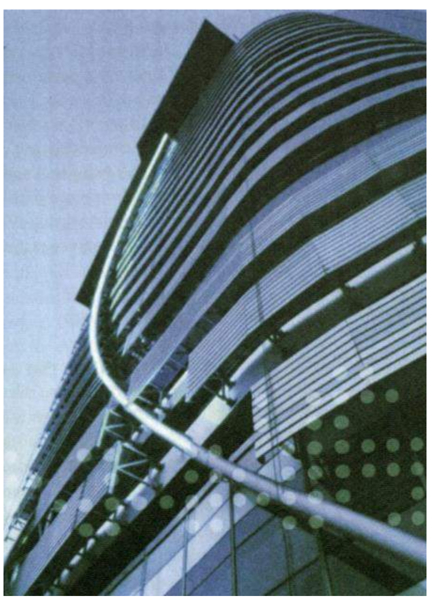


Fig. 387. Aluminum Shading Screens

Fig. 388. Shading Screens at Ground Level

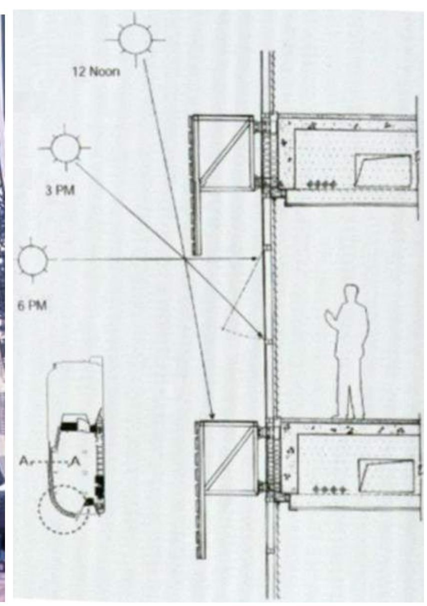
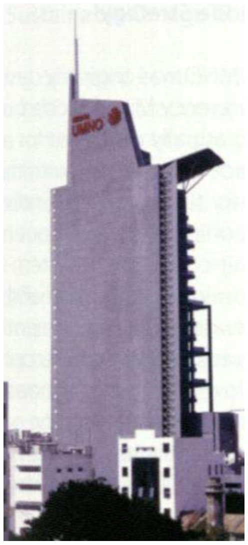


Fig. 389. Shading Screen During the Day

[449] Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 54.



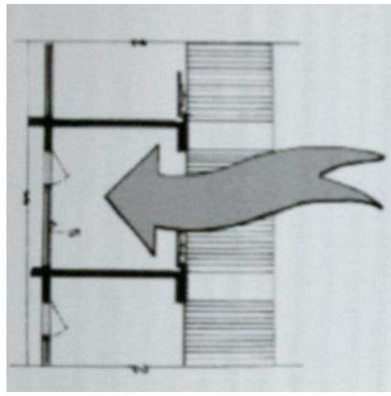


Fig. 390. Service Core on the Southeast Facade **Fig. 391.** View from a Shaded Balcony **Fig. 392.** Adjustable Doors and Windows for Ventilation

Fig. 393. shows the comparison between the energy use of Menara UMNO and a typical air-conditioned building in the same region where Meanara UMNO has a 25 percent energy reduction over the typical air-conditioned building. It also presents the positive impact of the tower's shading devices, which has a 7 percent energy reduction over the same design without shading.[450] This tower is a perfect example of Ken Yeang's ecological, sustainable and innovative design that takes advantage of the ambient environment.

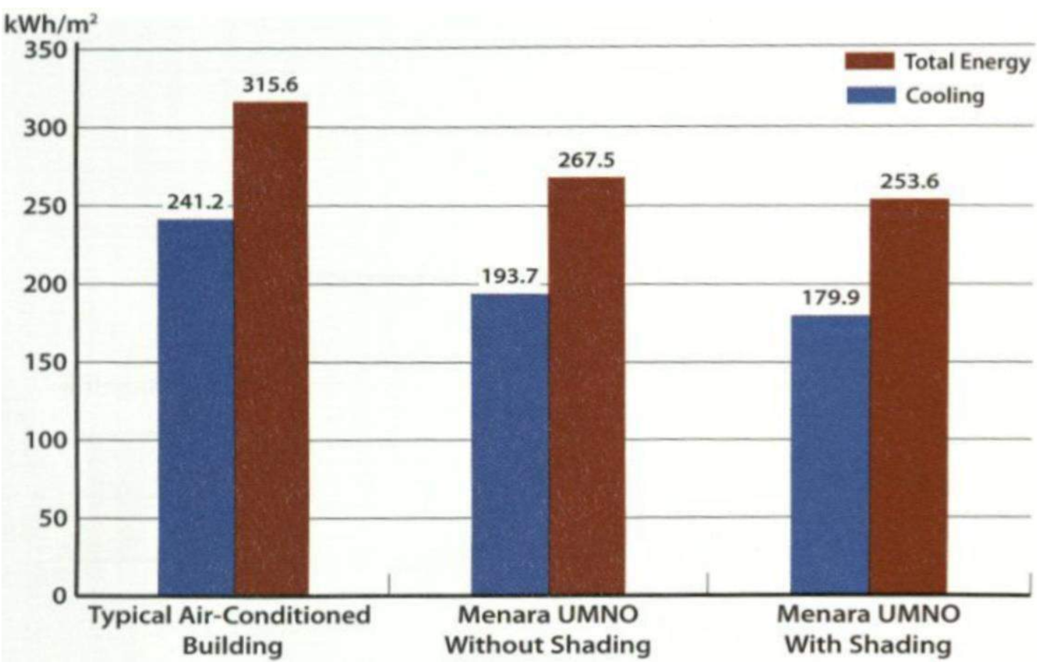
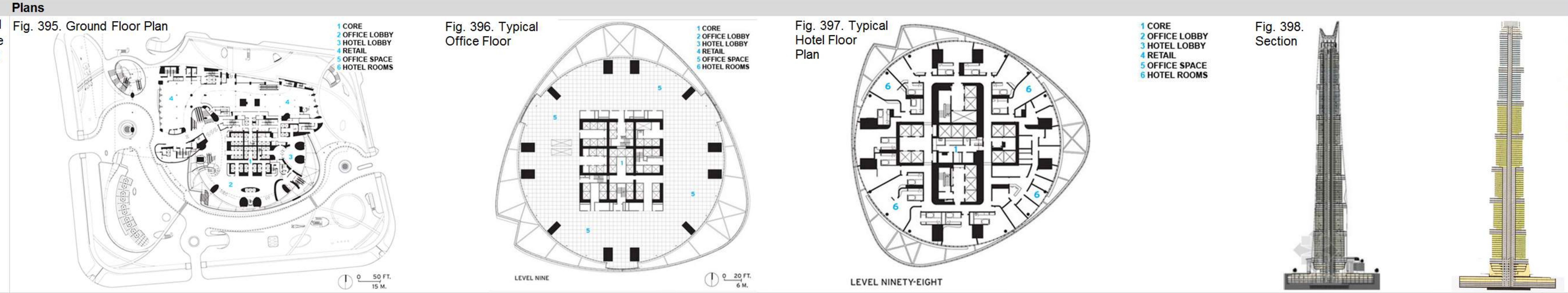
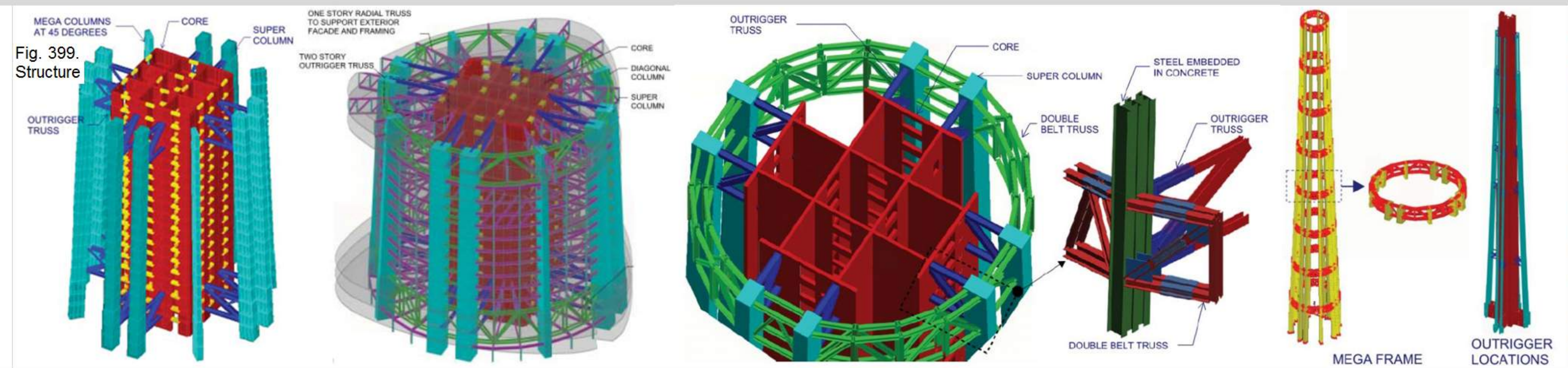
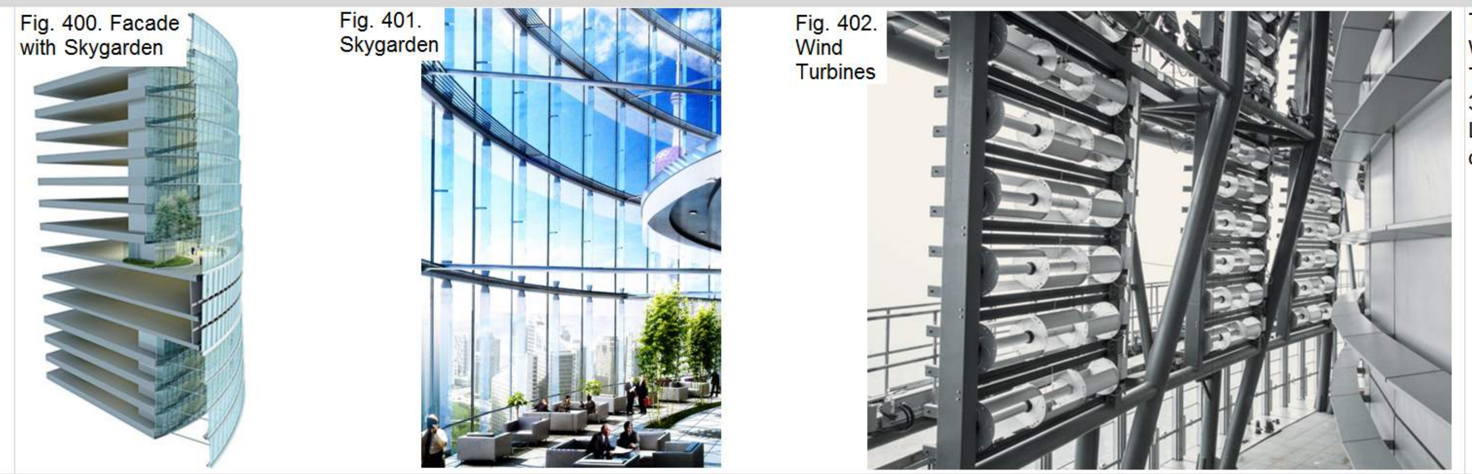
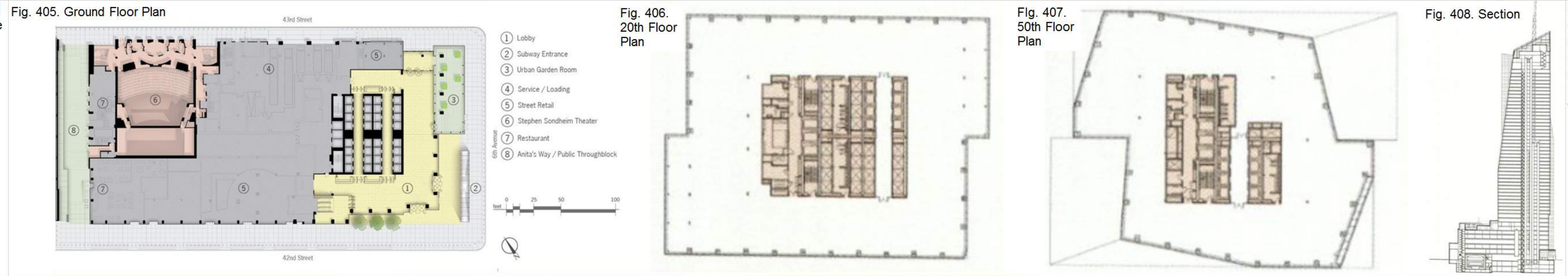
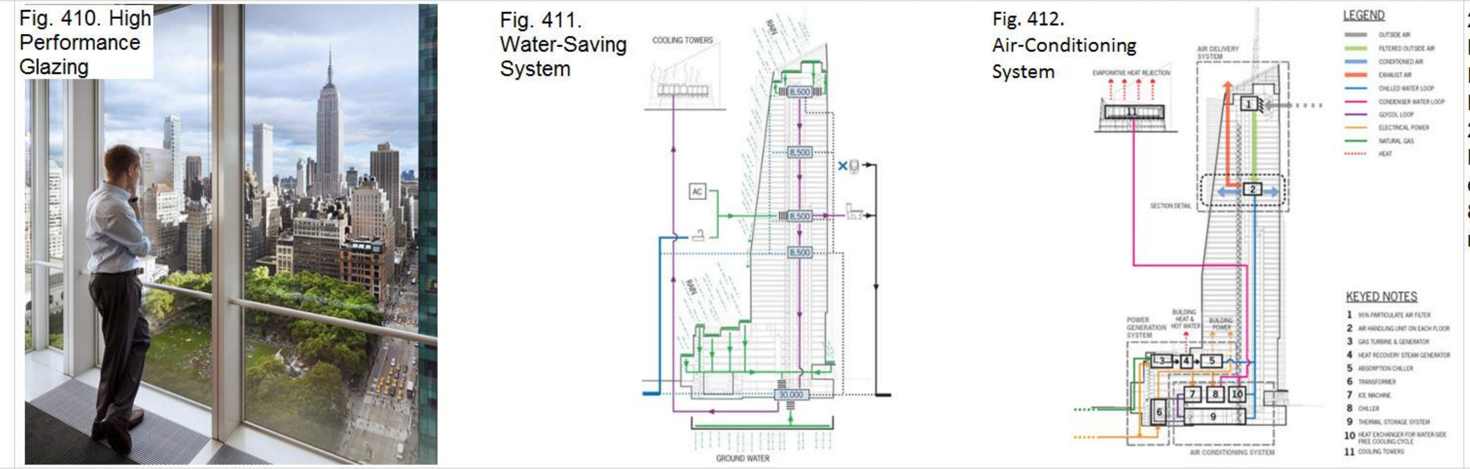
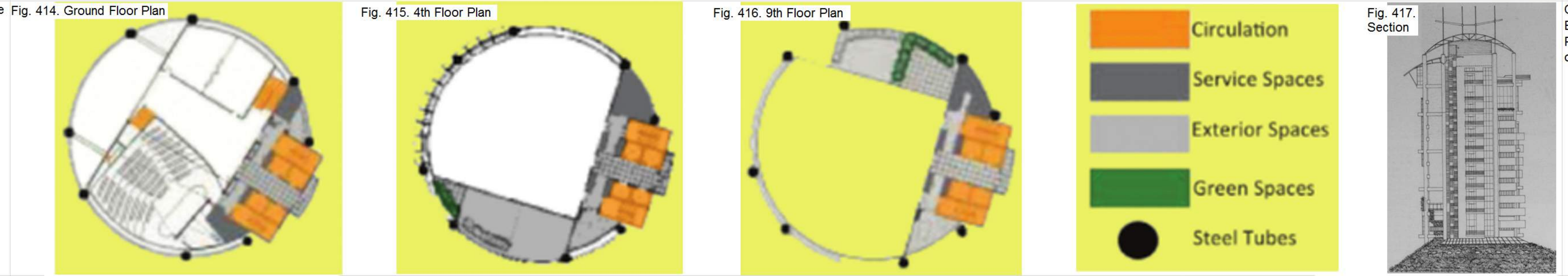
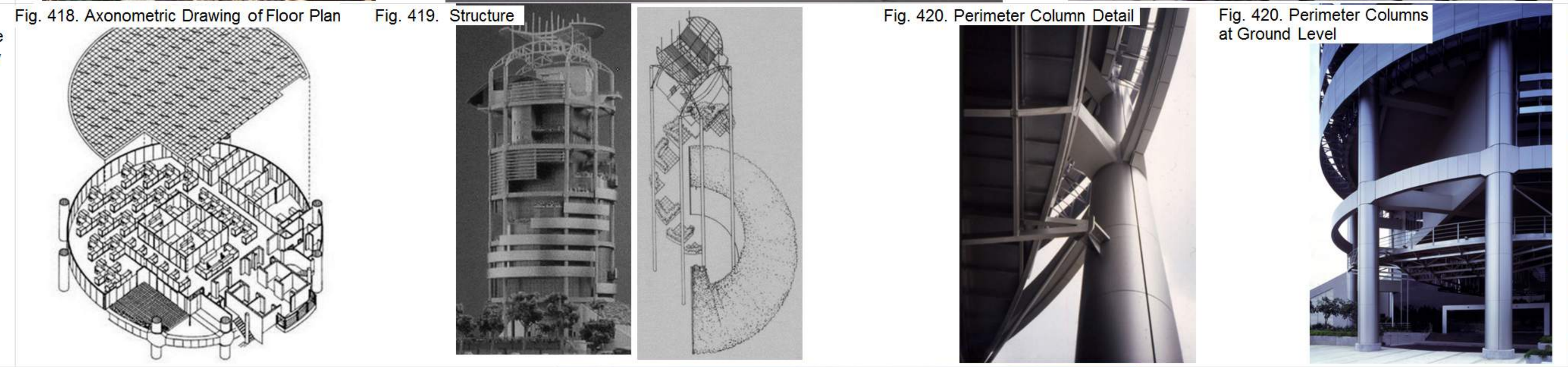
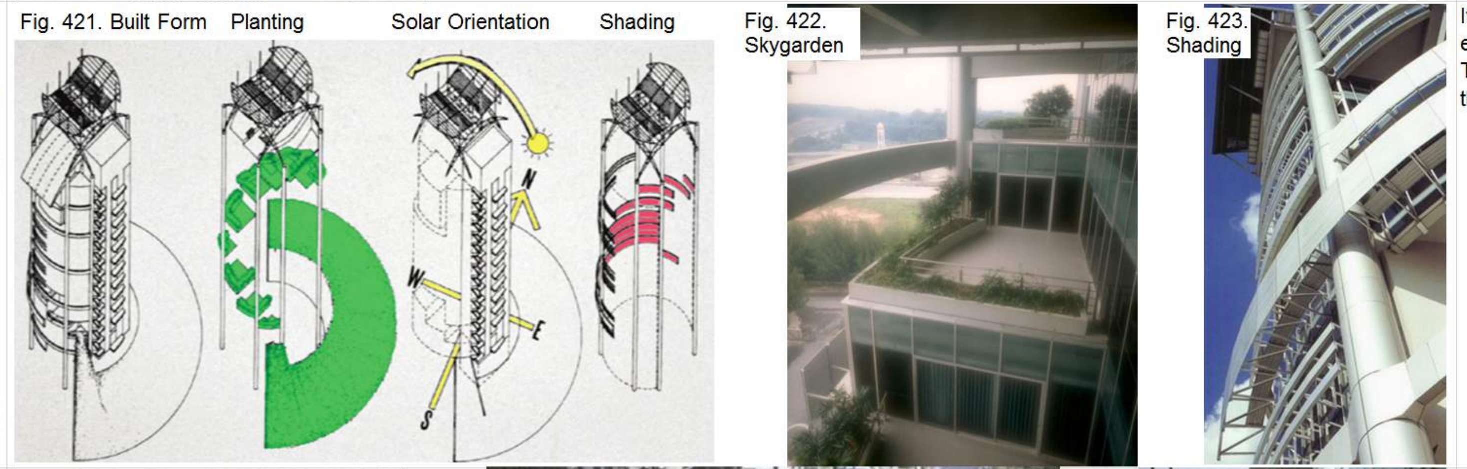
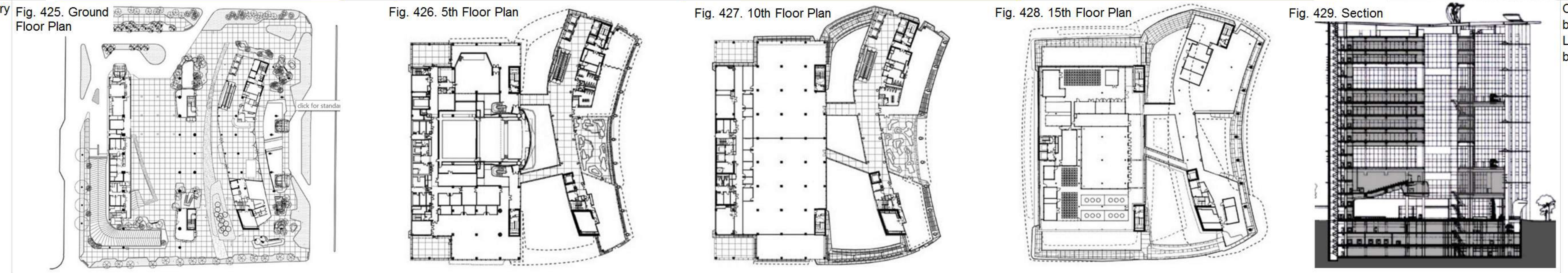


Fig. 393. Comparison of Energy Use in Menara UMNO Compared to a Typical Air-Conditioned Building In the Region

450 Antony Wood, *Natural Ventilation in High Rise Office Buildings*, 2012, 56.

5.3.2 Table of Sustainable High Rises

Photo	Building	Place	Year	Story / Height	Climate	Use	Plans	Structure		Sustainable Techniques		Other Features
	Shanghai Tower Fig. 394. Shanghai Tower	Shanghai China	2015	128 stories 632 meters 1,016 feet	Tropical	Retail Office Hotel	Fig. 395. Ground Floor Plan Fig. 396. Typical Office Floor Fig. 397. Typical Hotel Floor Plan Fig. 398. Section 	Outrigger system with megacolumns Concrete square core (30 m/ 98 ft wide) Steel outriggers and belt trusses Composite megacolumns with concrete encased steel 2 megacolumns at each side of the core Diagonal megacolumns at the core corners[385]	Fig. 399. Structure 	*Wind Load Reduction* - The twisting, assymetrical form reduces wind load by 24 percent,thus reducing the building's structural load. *Rainwater Collection* - The building's spiraling parapet collects rainwater, that is used for the building's heating and air conditioning systems.[386] *Wind Turbines* - Wind turbines located beneath the parapet produce electric power. Furthermore, wind turbines on the building's top power the exterior lighting. *Double-Skin Facade* - The building indorporates two independent curtain walls with low-e coating. Fritted glass on the outer wall provides additional sun-shading. *Skygardens* - Nine cylindrical atria encircle the nine vertical building zones stacked one atop the other. The spaces between the building's two facade layers create these nine atrium sky gardens. Used indoor air is circulated through skygardens in order to temper the air temperature. This keeps the heat out during summer and the building's heat in during winter. *Natural Daylight* - The transparent inner and outer skins allow maximum daylight penetration. This is further enhanced by the floor-to-ceiling glazing of the office and hotel floors. *BMS* - The BMS monitors and controls systems such as heating, cooling, lighting, ventilation and energy generation. This significantly lowers the building energy costs. *Geothermal Energy* - Geothermal energy is used to cool and heat the building.[387]	Fig. 400. Facade with Skygarden Fig. 401. Skygarden Fig. 402. Wind Turbines 	Tallest building in China and second in the world World's highest non-enclosed observation deck Tallest single-lift elevator in the world 33 percent of the site is green space Locally sourced materials with high recycled content were used[388]
	Bank of Amerika Tower Fig. 404. Bank of America Tower	New York City United States	2009	55 stories 366 meters 1200 feet	Temperate	Retail Office	Fig. 405. Ground Floor Plan Fig. 406. 20th Floor Plan Fig. 407. 50th Floor Plan Fig. 408. Section 	Structural steel core encased in reinforced concrete shear walls with reinforced concrete slabs and beams framing the interior space Floors are concrete on metal deck permanent shuttering, framed by structural steel Perimeter moment-resisting frames complete the lateral structural system[389]	Fig. 409. Construction 	*Air Filtering System* - The high rise acts as a giant air filter with its two-way air filtering system. About 95 percent of the dirt, dust and particulates are filtered from the entering air. Exhaust air leaving the building may actually be cleaner than the outside air.[390] *Cogeneration Plant* - The building has an on-site cogeneration plant that generates two-thirds of the high rise's energy needs.[391] *Ice Battery* - It creates ice at night and releases the coolness during the day as the ice melts.[392] *Water-Saving System* - The tower has an extensive greywater and water-saving system with waterless urinals that save 11.4 million liters (3 million gallons) of water a year. The tower captures rainwater and uses groundwater from sump pumps. *Glazing* - The high rise is enclosed in high-performance low-iron and low-e coated glazing with fritting. This allows visible light to pass though whereas it reflects UV rays. Office spaces have high floor-to-ceiling heights that optimizes the access to natural light.[393] *Transport* - The high rise sits atop nearly a dozen subway lines and close to three of the largest intermodal transportation hubs in North America. The building has no underground parking garage so employees must use public tranportation to get to work. *Geothermal Energy* - Geothermal energy is used to cool and heat the building. Wastewater from this system is collected and it is used for toilet flushing purposes.[394]	Fig. 410. High Performance Glazing Fig. 411. Water-Saving System Fig. 412. Air-Conditioning System 	2010 Best Tall Building Americas by the CTBUH[396] First high rise office tower to be certified LEED Platinum by the US Green Building Council[397] Locally sourced materials were used for more than 20 percent of the construction More than a third of all materials used in construction were recycled 85 percent of the resulting construction debris was recycled[398]
	Menara Mesiniaga Fig. 413. Menara Mesiniaga	Subang Jaya Malaysia	1992	15 stories 63 meters 207 feet	Tropical	Office	Fig. 414. Ground Floor Plan Fig. 415. 4th Floor Plan Fig. 416. 9th Floor Plan Circulation Service Spaces Exterior Spaces Green Spaces Steel Tubes Fig. 417. Section 	Concrete core on the building east side Eight steel columns on the building envelope Perimeter columns allow maximum flexibility on the interior[399]	Fig. 418. Axonometric Drawing of Floor Plan Fig. 419. Structure Fig. 420. Perimeter Column Detail Fig. 420. Perimeter Columns at Ground Level 	*Orientation* - The orientation of the building was determined by the sun and wind. *Core Position* - The core of the high rise is placed on the building's east side in order to shield to building from the direct hot sun. The core provides thermal insulation and reradiates absorbed heat during the day into interior spaces at night. The core relies on natural ventilation and natural lighting.[400] *Shading* - Windows facing east and west are recessed and contain external aluminium louvres to reduce solar heat gain. Skygardens on the east and west facades provide additional shades and they also contribute to natural ventilation of the building.[401] *Operable Openings* - Operable openings are implicated on the north and south facades. These provide natural light and natural ventilation to internal spaces. *Vertical Landscaping* - The planting spirals upwards across the face of the building. The vegetation cools the building and connects the workers with nature.[402] *Rainwater Collection* - Rain water is channeled from the top garden terraces to the lower terraces. *Rooftop Pool* - The roof is inhabitable and it contains a pool and a gym. The pool insulates the rooftop and reflects sun rays. It stores thermal energy during the day and releases heat at night. The roof is crowned with a steel trellis that provides shade.[403]	Fig. 421. Built Form Planting Solar Orientation Shading Fig. 422. Skygarden Fig. 423. Shading 	It is one of the most famous projects of the ecoarchitect Ken Yeang The first floor of the building incorporates a theater[404]
	Singapore National Library Fig. 424. Singapore National Library	Singapore Malaysia	2005	16 stories 103 meters 338 feet	Tropical	Library	Fig. 425. Ground Floor Plan Fig. 426. 5th Floor Plan Fig. 427. 10th Floor Plan Fig. 428. 15th Floor Plan Fig. 429. Section 	Concrete cores are positioned on the building north-west and south-west facades Large steel columns are placed on the building's perimeter[405]	Fig. 430. Structure Fig. 431. Perimeter Columns Fig. 432. Interior View of Perimeter Column and Shading Louvres 	*Orientation* - The building is oriented in relation to the sun path and prevailing winds. *Core Position* - Core positions on the building's north-west and south-west facades serve as thermal buffers and reduce solar heat gain.[406] *Atrium* - The building consists of two blocks which are separated by a large atrium in the middle. The central atrium creates a cool microclimate zone and provides natural daylight to the building's interior. Bridges connect the upper levels in the atrium. *Skycourts* - Skycourts provide a relaxing environment for the library users while enhancing biodiversity. They provide fresh air and dalight to the users. The north-east facade contains two skycourts that are 40 meters (130 feet) heigh each and incorporate 12 meters (39 feet) heigh trees. *Windbreaker* - The skycourts are protected by windbreakers from outside. The windbreakers break the wind into smaller eddies before they enter the skycourts.[407] *Color* - The building incorporates very light colors on its envelope as well as in the interior spaces in order to reflect solar radiation and diffuse sun rays in the building's interior.[408] *Shading* - Wide sunshades limit direct sunlight and glare as well as they serve as light shelves to deflect natural light into the inner parts of the library. *Roof Canopy* - The building incorporates an extensive roof canopy for shading.[409]	Fig. 433. Skycourt Fig. 434. Shading Fig. 435. Windbreakers 	The building incorporates over 6,300 m2 (68,000 ft2) green space in the form of skycourts 60 percent of the building's footprint is devoted to green spaces[410]

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List of Figures

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Fig. 48. Eric Howeler, *Skyscraper-Vertical now*, 2004, 40.

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