Thermal Comfort in Tropical High-Rise Buildings: A review of published research

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Abstract

The concept of high-rise buildings continues to provide a meaningful solution for land conservation in cities. Highrise buildings stand out for many good reasons. A challenge with them however, is that they demand huge amounts of energy to build and operate compared to low and medium-rise buildings. Studies show that this is largely due to the heating and/or cooling load required to sustain human activities at such great altitudes, amongst other factors. The concept of bioclimatic skyscrapers popularized by Ken Yeang is undoubtedly a good approach to tackling this challenge as it helps to save conventional energy, protect the environment and improve indoor thermal comfort. Some questions however still remain unresolved like; "What are the optimal design conditions for achieving bio-climatism in tall buildings? Should height be arbitrary? Does it bear significant influence on thermal comfort and energy use? If so, What is the nature of this influence? and How can developers use this knowledge to their advantage when planning highrise buildings?

Recent studies reveal that building energy use increases as height increases but very little is yet known about the empirical nature of this increase. This paper reviews existing literature related to the relationship between height, occupants' thermal comfort and building energy use in tropical high-rise dwellings. The authors examine research gaps related to bioclimatic skyscrapers with specific attention to the influence of height as a major design parameter. It concludes that there is a need for further scientific investigations in the light of existing research gaps.

Keywords: thermal comfort, building height, energy-use, high-rise, tropical

1.0 Introduction

The concept of building tall is attractive and interesting. In fact, the concept of high-rise building or the vertical city typology provides a meaningful solution for the conservation of land and resources (Le Corbusier, 1946). A building is regarded as "high-rise" when it exceeds twelve (12) suspended floors. The Council For Tall Buildings and Urban Habitat CTBUH, through her official partner for high-rise buildings database, EMPORIS, defines a high-rise building as a structure whose height is between thirty-five (35) and a hundred (100) meters (Emporis, 2000).

The condition of human comfort in high-rise buildings has been a subject of debate in academic and professional circles. Ethical and health concerns have been expressed regarding ventilation conditions at higher levels of dwellings and work. This paper examines the current state of knowledge on the subject of thermal comfort and energy use in high-rise buildings with a focus on the tropical climatic region.

1.1 Aims of the research

The aim of this research is to analyze the existing literature on thermal comfort and energy use in high-rise buildings with a view to identify recent trends and possible gaps in the literature. The key theoretical concepts guiding this review are "building height", "thermal comfort" and "high-rise building". This review assumes a hypothetical position based on the idea that the height of a building may hold potential relationship with thermal comfort of its users and if so, that there must be a threshold beyond which it becomes impractical to apply passive cooling techniques for tall buildings. The paper identifies existing approaches adopted to investigate the optimal height or height threshold $(h_x...h_n)$ for energy efficiency and thermal comfort in high-rise residential buildings in the tropics. The Objectives of the study are:

a) To examine the literature related to energy efficiency and thermal satisfaction in high-rise residential buildings in the tropical environments.

b) To find out the trends related to research in energy efficiency and thermal satisfaction in high-rise residential buildings in the tropical environments.

c) To predict future research direction for studies related to energy efficiency and thermal satisfaction in high-rise buildings.

1.2 Background to the Study

1.2.1 Historical development of high-rise buildings

According to the Council For Tall Buildings and Urban Habitat; CTBUH (Buildings, 2013), a building can be described as being tall, based on three main criteria. They are:

1. It's height relative to its context,
2. It's proportions with respect to its footprint and/or slenderness and
3. Whether it embraces technologies that are typical with tall buildings such as vertical transport systems and structural wind bracings.

Based on these criteria, buildings may be classified as being tall, up to 50m above the ground level, super-tall if up to 300m, or mega-tall if up to 600m above the ground level (CTBUH, 2010).

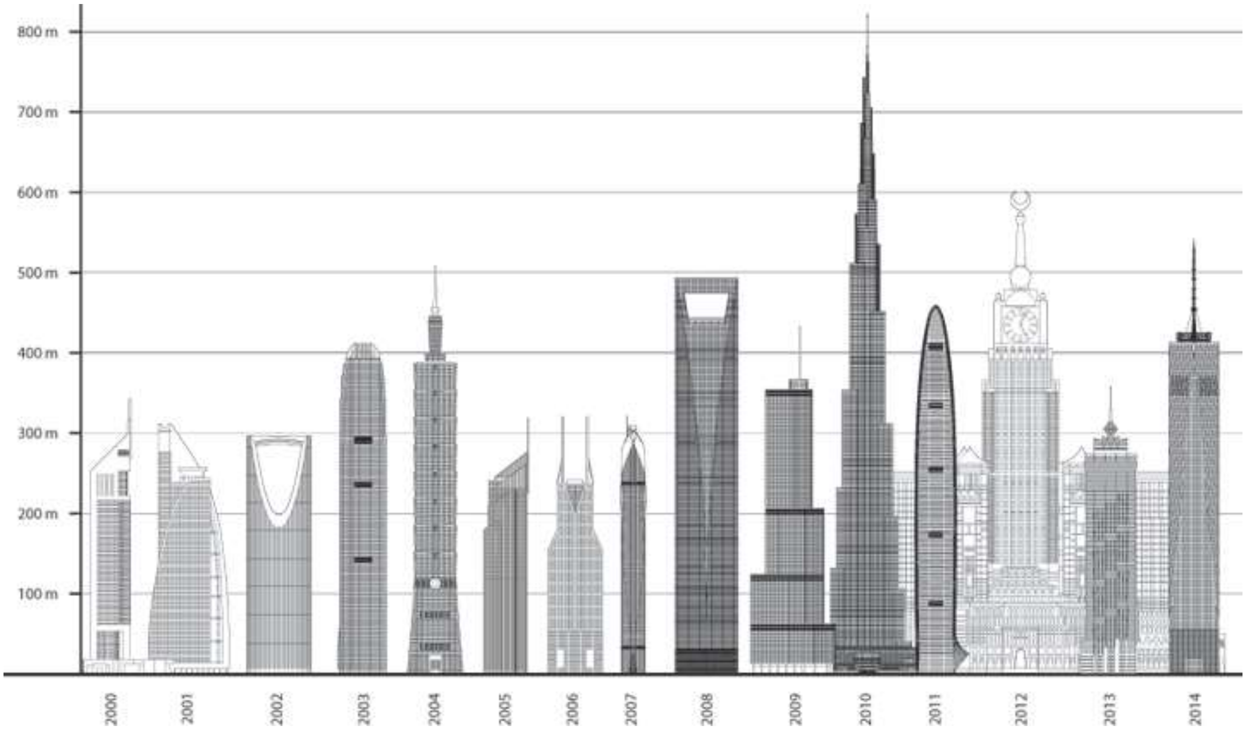


Fig. 01: Tall buildings by height and year of completion
Source: www.skyscrapercenter.com

The figure above shows a cross-section of some of the world's tallest buildings with their constructed heights. The tallest building, Burj Khalifa, stands out clearly at 828m height and a total of 163 floors. It would appear however that the most accepted definition of a high-rise building is taken primarily with respect to the influence its height may have on available fire-fighting equipment. According to Craighead (2009), generally, a high-rise structure is considered to be one that extends higher than the maximum reach of available fire-fighting equipment. The Council For Tall Buildings and Urban Habitat CTBUH, through their official partner for high-rise buildings database, Emporis, defines a high-rise building as a structure whose architectural height is between 35 and 100 meters (*high-rise building | Emporis Standards | EMPORIS*, no date)

While vertical stacking of multiple floors helps us maximize land and expand the financial yield, a number of concerns about life and conditions of living and working at such heights above the ground level exists. A study by CTBUH (Carter and Stangl, 2012) reveals that very tall buildings could be more exposed to heavy wind outbursts, surface exposure to rainfall, snow and solar heat gain. To compound the matter, people continues to build taller buildings that tower into the skies leaving Nature far below with all its freshness and beauty.

From a historical perspective, dating back from the 18th century, architects started exploring vertical urbanization as a viable alternative to horizontal spreading (*High-rise building - Wikipedia*, no date). The earliest tall buildings appeared in Chicago, Illinois. After the great fire of 1871, which consumed about one-third (1/3) of the city, it had to be rebuilt and the population was eager to make Chicago better than before the disaster. However, the high cost of land and the new building materials of iron and steel, coupled with the invention of the electric elevator pushed the architects and engineers to stack more floors vertically (Hollister, 2013)

The high-rise buildings that followed were heavy masonry blocks with walls having thicknesses of 8-foot; in some cases for example, the seventeen (17) storey Monadnock building (1884-91) (Bennett, 1995). Gradually, these were replaced by even taller high-rise buildings of the twentieth century which were made of light, cost-effective steel skeletons and sometimes a combination of steel and masonry structures; for example, the Home Insurance Building (1885) by William Le Baron Jenney is generally credited to be the first fireproof, iron-frame skyscraper. The building construction combined masonry-reinforced frames with masonry bearing walls (Saliga,1990)

Moving on, Louis H. Sullivan who is seen as the architectural father of the skyscraper, in his book; The Tall Office Building Artistically Considered (1896) posited that; "The form of a tall building must follow the function". He divided skyscrapers into three parts: the base (shops and entrance), the core (an x-number of office floors) and the top (installations and framework). This model became the basis for the high-rise buildings afterwards. Frank Lloyd Wright (1867-1959) is an important architect identified in this early movement of high-rise buildings. In the European, African and Asian contexts, tall buildings have been described as a viable alternative to horizontally spreading living, work and business (Ali and Al-Kodmany, 2012) largely due to the scarcity of urban land and advancement in technological innovations (Hollister, 2013).

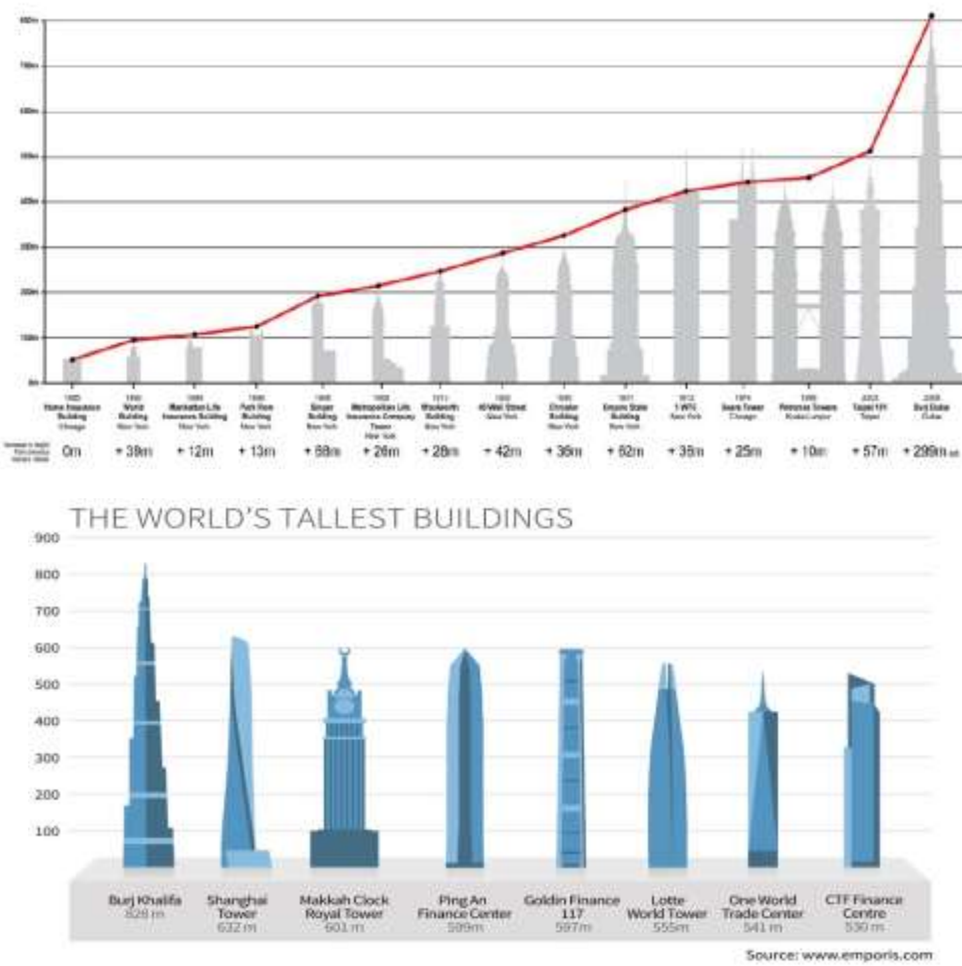


Fig. 02: Trend of continuous height increment of buildings over time.
Source: (EMPORIS 2021)

The figures attached show the continuous increment in height of different buildings in different locations globally as curated by Emporis, the world leading authority on documentation of tall building statistics. It clearly shows that over the years, developers have continually reached for higher heights irrespective of the numerous challenges associated with high-rise building design, construction and operation (Emporis 2021).

2.0 Research Method

This study is based on a review of journal articles published or in press between the years 2000–2021, accessed through searches of the Scopus database. The search terms were central concepts identified in research on thermal comfort in high-rise office buildings in the tropical environment. Various relevant combinations of search terms including the terms (thermal comfort) OR (high-rise buildings) OR (tropical) OR (building height) And OR (influence) were used. The titles, abstracts and keywords of the identified articles were screened for relevance. After sorting out publications that considered thermal comfort in high-rise buildings, ninety-nine (99) articles were retrieved. These were independently read in full and then jointly categorized and analyzed in terms of :

- Author(s) name(s)
- Year of publication (chronological)
- Title of the study
- Geographic/climatic region wherein the work was focused
- Building typology investigated
- Research objectives identified
- Research methods adopted
- Key findings; Results

Further statistical analysis of the retrieved articles was carried out to show the distribution of articles according to date of publication:

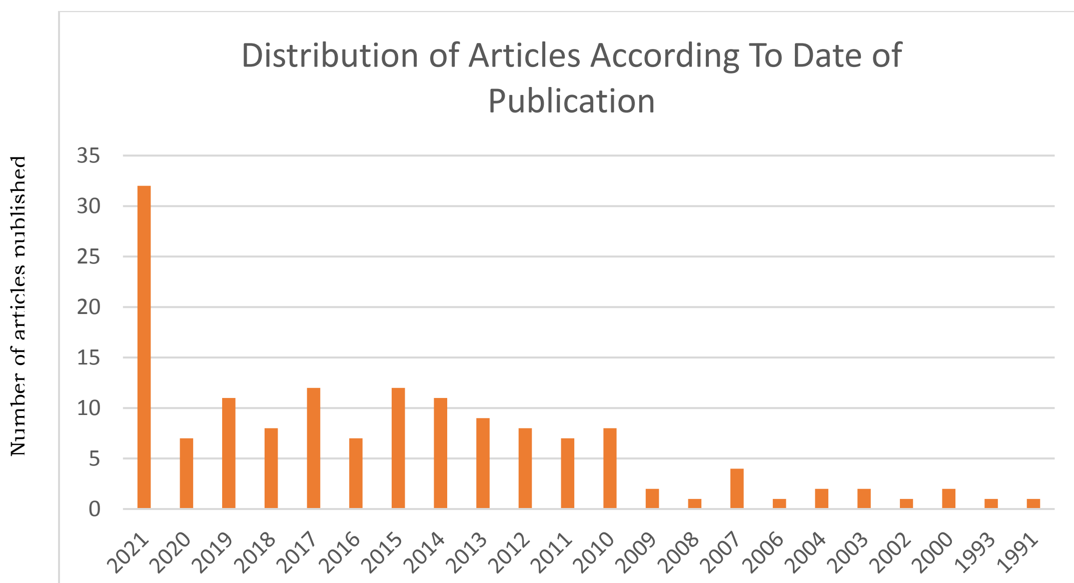


Fig. 03: Distribution of articles according to date of publication.
Source: Author

3.0 Published research reviewed

3.1 Benefits associated with high-rise buildings

Fig. 04: Apartment building-Chennai, Marina One-Singapore and Chrysler building- New York.
Source: Wikipedia

High-rise buildings provide huge land saving benefits. (Ahmad, Aibinu and Thaheem, 2017) Mixed-use advantages bring cheaper tenancy costs due to the shared facilities. (Vijayasree, 2019) It stands as a symbol of political, economic and technological advancement of a people (Ibrahim, 2007). High-rise developments provide more free space for green plantations, leaving the land free for parks and public spaces (Ibrahim, 2007). It improves the social and economic value of surrounding properties (Giyasov and Giyasova, 2018) and less noise at uppermost floors (Ng, 2017). Occupants enjoy unobstructed scenic views from higher floors and enjoy a feel of exclusive living (Ng, 2017).

3.2 Challenges Associated with High-rise Buildings

Tall buildings are resource-intensive due to the excessive scale and complexity of design (Cook, Browning, & Garvin, 2013). They require heavy energy and heat or cooling supply to maintain habitation at such heights far away from natural supply. Fig. 04 shows the average energy consumption of a typical high-rise office building calculated across sixteen (16) United States cities in various climates by the US department of Energy. Heating and cooling energy are shown to consume approximately 33% of the total building energy consumption with equipment, lighting, fans and water systems consuming 31%, 29%, 6% and 1% respectively (Wood and Ruba, 2013).

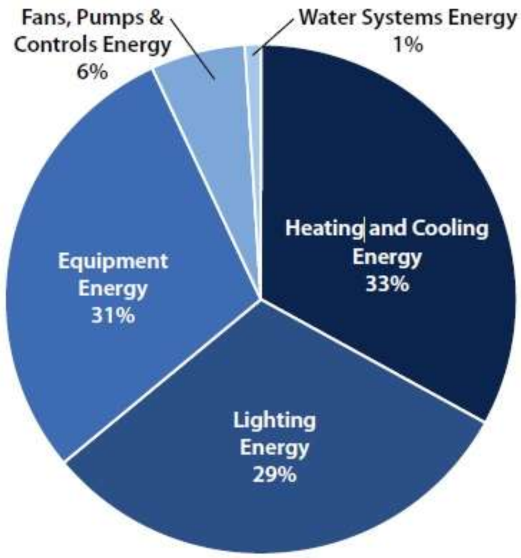


Fig. 05: Average energy consumption of a typical high-rise office building. (Source: Interpreted from the US Department of Energy's reference building energy models for existing large commercial buildings built after 1980, across 16 US cities, in various climates.) (Wood and Ruba, 2013)

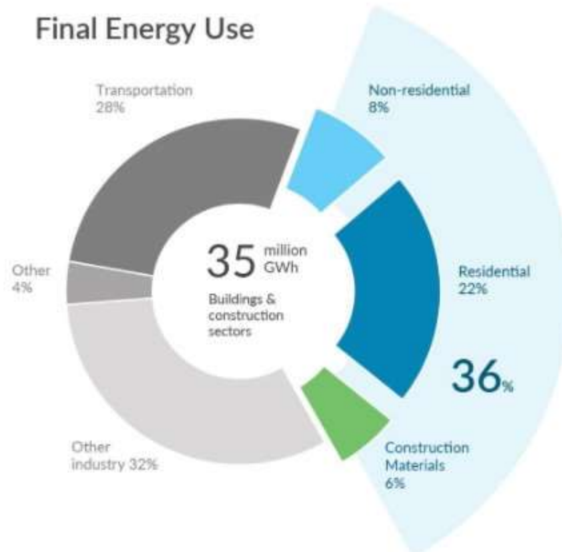


Fig. 06: Global Energy Use; Source: (Abergel, Dean and Dulac, 2017)

According to the United Nations Global Status Report, 2017, (Abergel, Dean and Dulac, 2017), the construction and operation of buildings consume 36% of the world energy consumption and generate 39% of the world's GHG footprint (Fig. 06). Buildings used 36% of the global energy use in 2018, with a majority of it being used in the residential sector. Energy consumption in buildings is projected to grow by 37% by 2035 - UN 2018. Ninety Six percent of this growth is projected to occur in developing countries – (UN, 2018).

Further challenges associated with high-rise buildings include structural impact of unstable wind pressures at higher altitudes (Tembhare and Budhalani, 2008). There are over-arching concerns about the safety of human life at such heights. The International Conference on Fire Safety in High-Rise Buildings defined a high-rise as "any structure where the height can have a serious impact on evacuation; (Murat Saatcioglu,2016). The reliance on technology for fire safety of occupants in high-rise buildings remains a subject of concern. The design and construction of high-rise buildings requires highly skilled experts as any wrong design strategy can lead to life threatening hazards (Teger 2012). (*Simulated Construction Management of a High-Rise Building | Ari Teger - Academia.edu*, no date)

3.3 Energy Efficiency in High-rise Buildings

Energy efficiency is defined by the European Union broadly as the ratio of output of performance, service, goods or energy, to input of energy (Erbach and EPRS | European Parliamentary Research Service, 2015). The central philosophy behind sustainability is the judicious use of resources in a manner that provides for Man's needs today without jeopardizing the ability of the future generation to fulfill their own energy needs (Liu, 2017). Every building requires some form of energy to function, either electrical or mechanical. The cost of energy generation is consistently on the increase with the ever-increasing price of oil. As well known, Oil is non-renewable. The United States Green Building Council, USGBC, defines green building as "the planning, design, construction, and operations of buildings with several central, foremost considerations: energy use, water use, indoor environmental quality, material selection and the building's effects on its site" (USGBC 2014). If we are going to continue building tall, we must figure out how to keep the energy consumption of such buildings within environmentally and economically sustainable limits.

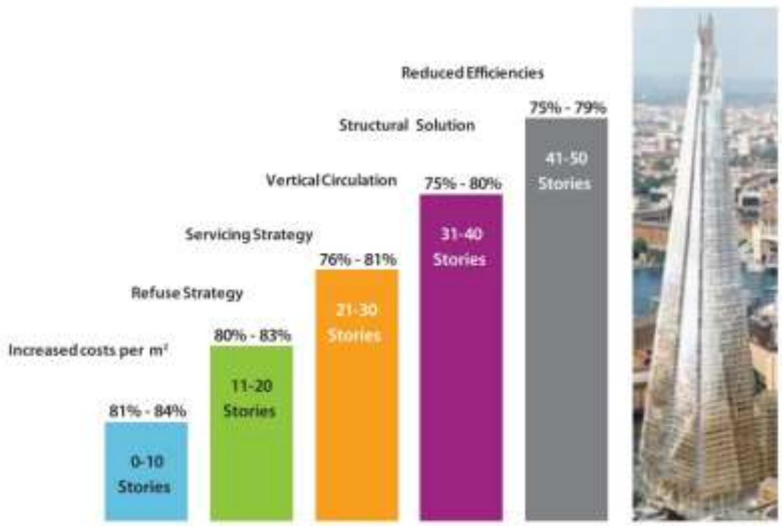


Fig. 07: Decreasing building efficiency with increase in building height. © AECOM Davis Langdon
Source: (Barton and Watts, 2013)

Fig. 07 shows the graphic summary of a study by Barton & Watts (2013). With every ten (10) storey increment in the building height, the efficiency in various aspects was seen to drop by an average of 10%. Reflecting on this, several critical questions immediately spring up such as;

- To what extent an increase in height affects energy use and how may this relate to thermal comfort of building occupants?
- It is seen that the large part of energy consumed goes to cater for heating/cooling. Is this influence is the same across different climatic regions?
- Is it the same for high-rise residential versus high-rise commercial buildings? What are the design implications for the future of high-rise buildings?

CTBUH summarizes this as the "sustainability threshold" in her publication titled; "Natural ventilation in High-rise Office Buildings" (Wood and Ruba, 2013). According to CTBUH, this threshold would be:

> *"..that height or floor count figure beyond which additional height would not make sense on sustainable grounds (and likely cost grounds as well)."* (Wood and Ruba, 2013)

The big question here is: Should a building's height be arbitrary?

Yeang (1992), in his book; "The Skyscraper: Bio-climatically Considered" summarizes the guiding principles for designing a truly tropical high-rise building. However, there seems to be yet missing a definite statement or at least identification of a given range of building heights within which Yeang's principles remain effective. Put it another way, is Yeang's principle of bio-climatism applicable to infinite building heights? Or is there a threshold beyond which skyscrapers may cease to be energy efficient should the building grow taller?

3.4 Thermal Comfort

The thermal experience of a building's users are evaluated in terms of the thermal comfort. Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55 - 2004). It is the psychophysical satisfaction of an individual immersed in a thermal environment (Shaw, 1972). As described in the EN ISO 7730:2005 standard, Thermal comfort is influenced by six factors which are; air temperature, relative humidity, air velocity, mean radiant temperature, body metabolic activity and clothing. Academic studies on thermal comfort are performed on the assumption of steady rates for these factors allowing only limited temperature variations (Salamone *et al.*, 2018).

When discussing thermal comfort, there are two main models that can be employed namely: Fanger's predicted mean vote (PMV) model; an index that predicts the mean vote of a group of people voting on how comfortable they are in an environment and the adaptive model which was developed based on the idea that occupants dynamically interact with their environment and control their thermal environment by means of clothing, operable windows, fans, personal heaters, and sun shades (Van Hoof, Mazej and Hensen, 2010). The Centre for the Built Environment CBE, in an attempt to unify the significance of all variables that affect thermal comfort, into one simple and readily applicable formula, developed a simple tool for calculating thermal comfort. By providing input values for each of the variables, a user can determine not only the predicted mean vote, but also can find where those conditions fall within the comfort range. (*CBE Thermal Comfort Tool - Center for the Built Environment*, no date)

Fig. 08: CBE Thermal Comfort Tool.
Source: CBE Thermal Comfort Tool - Center for the Built Environment, no date

Pau and Pao (2013) had made a case for integrating Fangers's PMV model with the adaptive model. In doing this, they arrived at a new integrated thermal comfort model that in their argument best applies to the tropical environment. The new model widens the range of thermal comfort originally accepted by the PMV model to a new range stating from + or - 1.0% to + or – 1.17% for 80% thermal comfort in a building.

This wider range is due to the fact that people living in the tropical climates have higher tolerance for thermal environment than those in other climates (Pau and Pao, 2013).

In addition to this innovative measurement model, the Rocky Mountain Institute RMI – an independent non-profit organization founded in 1982 raises the argument for an early consideration of the six variables that affect thermal comfort during the design process (Rawal *et al.*, 2019). Their study posits that such early consideration pushes for more efficient solutions to thermal comfort and energy savings. This rather practical concept was experimented in the design of their Innovation Center in Basalt, Colo. Where the design team adopted the "integrated Design Approach" from the onset, making sure that each variable was considered and provided for from design stage.

In practice, buildings are made for human beings and human beings actually feels and interprets thermal sensations differently. It is a personal experience dependent on a number of criteria and can largely vary from one person to another within the same space. Because of this, (De Dear, 2004) concludes that the use of the adaptive model for evaluating thermal comfort makes more sense especially for situations where occupants interact with their immediate spaces in response to changing thermal sensations for example in naturally ventilated buildings. Vernon concluded that 18.94°C (66.1°F) in summer and 16.72°C (62.1°F) in winter were ideal temperatures with air movement of 50 fpm or less. while according to Markham, 15.55°C (60°F) to 24.44°C (76°F) is the ideal range with relative humidity at noon between 40 to 70%. According to ASHRAE Standard 55-2004, a range of 24°C and 30°C is ideal for thermal comfort. The Health and Safety Executive (HSE) suggests that an environment can be said to achieve 'reasonable comfort' when at least 80% of its occupants are thermally comfortable.(*Thermal comfort in buildings - Designing Buildings*, no date)

3.5 Thermal Comfort in Low-rise Buildings Vs. High-rise Buildings

Different Building characteristics such as form, orientation, *building height*, façade (or envelope) material and plan configuration bear significant impact on the thermal experience of building users (Zhang *et al.*, 2021) especially in tall buildings. Even though, the mechanisms for ventilation of low-rise buildings are similar to those for ventilation of the high-rise typology (Etheridge and Ford, 2008); an experiment by (Aflaki *et al.*, 2014), confirmed that there was a significant difference between the thermal experience recorded in the lower floors of a high-rise residential apartment in Kuala-Lumpur when compared to the thermal experience recorded in higher floors of the same building. Another study by (Chen *et al.*, 2020) further posits that building height and building density had impact on surface block temperature of the buildings studied under simulated scenarios using ENVI-met. In a similar study conducted by (Chow and Chow, 2010), it was found that air movement induced by stack effect through leakages in an 800 m tall building can give 1.2 times higher the air intake rate than in a room at ground level of the same building. It also noted that the airflow rate could be three times the value in a room at 800 m high.

3.6 Thermal comfort in high-rise residential buildings Vs. high-rise office buildings

Buildings perform differently according to design and purpose which are both influenced by environmental factors (Kwon, Remøy and van den Bogaard, 2019). When it comes to high-rise buildings, the fundamental measures that determine their viability are time, cost and floor area efficiencies (Barton and Watts, 2013). These three affect every high-rise building irrespective of the building use.

Remarkable differences exists however between the residential, commercial and office typologies with respect to the fire-fighting techniques, the vertical connectivity arrangement, the HVAC mode, floor plan configuration, envelope design etc. The common practice has been to combine vertical accommodation for these three building uses in one compact product (the mixed-use typology) in order to maximize cost, save land and reduce energy consumption (Ali and Al-Kodmany, 2012).

Shell & Core elements	Typ. residential tower ($£/ft^2$ GIA)	Typ. office tower ($£/ft^2$ GIA)
Substructure	8	20
Superstructure	33	45
Façades	60	52
Internal walls, finishes & fittings	11	23
MEP services	21	42
Vertical transportation	5	18
Contractor's preliminaries, profit, contingencies	37	50
Sub-total: shell & core costs	175	250
Fit-out costs (developer's standard)	120	27
Total including developer's fit-out	295	277

Table 01: Comparison between a typical high-rise office vs. residential building in London (both shell- and-core and fit-out). © AECOM Davis Langdon

Table 01 above shows a comparative analysis of construction cost of a typical London high-rise office building vs a residential one; for both shell-and-core and fit-out. From the information shown, one is able to deduce that the mechanical, electrical and plumbing (MEP) services in a typical high-rise residential building (in London) cost about half that of the office typology (Barton and Watts, 2013). One cannot help but imagine that this sharp difference may stem from the fact that high-rise office buildings, feature more heating, cooling and ventilation load than the residential typology based on the sheer fact that it caters to more users who are actively performing work compared to the residential scenario where the occupants may be in mostly sedentary states. The high-rise office building has peak operational time as against the residential one which may or may not be in use all day. This difference points to a varying degree of requirement for indoor thermal comfort. There is however not enough data to support or describe the nature of the difference between the thermal experience(s) of occupants in both cases.

3.7 Thermal comfort in tropical high-rise buildings; The peculiar condition in the tropics

According to the Koppen climate classification system, the tropical climatic region which comes under the first class (A) is characterized by constant high temperatures (at sea level and low elevations); all twelve(12) months of the year with average temperatures of 18 °C (64.4 °F) or higher; and generally high annual rainfall. (*Table 2 Overview of the Köppen-Geiger climate classes including the defining criteria.*, no date) It is sub divided into three sub-regions which include the tropical rainforest (Af), the tropical monsoon (Am) and the tropical savanna (Aw).

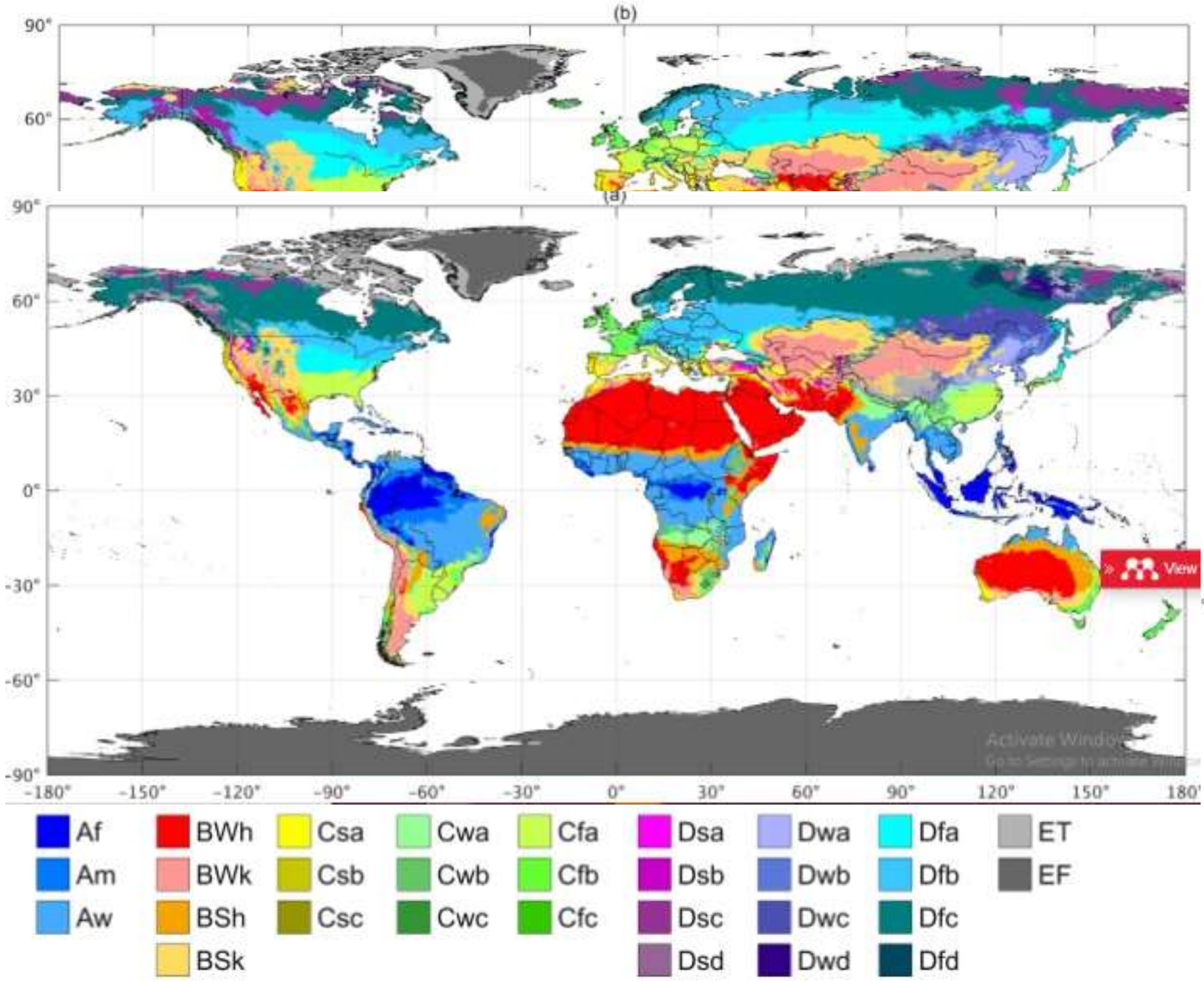


Fig. 09: Countries under the Koppen Climate Classification;
Source: Scientific Data (Sci Data) ISSN 2052-4463 (online)

The maps above show in color-code, the different climatic regions according to the Koppen climate classification. According to Pasquay (2004), it is possible to achieve a completely naturally ventilated high-rise building in Germany if some days with inside temperatures close to the outside temperature are accepted. He however admits that this possibility may not necessarily apply to high-rise buildings in the hot-humid tropical areas.

When it comes to the issue of high-rise buildings in the tropics, of notable significance is the work by Asian Architect Ken Yeang, who is renowned for his interests in ecological architecture and the climate of the tropics. His particular involvement in the commercial high-rise building typology has afforded him the opportunity to gather great experience on the subject, which he has crystallized and published as a set of guiding principles with which he designs tall buildings, globally.

His work, Solaris, located in Singapore, exemplifies how a high-rise building can go up literally with the local flora of the site thus providing the occupants at the higher floors with fresh air and a cooling effect made possible through the interaction between plants and the building occupants.

Yeang (1996) argues that the idea of the tropical high-rise should be a tall building whose built forms design and planning have responses to and take advantage of the climatic and ecological factors of the locality. He summarizes the guiding principles for designing a truly tropical high-rise building to include the following.

- The presence of open to air-ground floor areas,
- The use of multi-storey atria that are open or semi open at the top or corners,
- The adoption of the building core at the East and West sides of the buildings,
- Placement of curtain walls on the North and South faces, and
- The use of recessed sun spaces and
- The use of environmentally interactive walls.

However, there seems to be a missing definite statement or at least identification of a given range of building heights within which Yeang's principles will be effective. One wonders therefore whether these principles of bioclimatic skyscrapers for the tropics may cease to be effective, should the building grow taller beyond a certain height.

4.0 Discussion

4.1 The Summary of Research Methods

This study employed Field measurement CFD simulation, Energy modelling using Energy Plus, literature review and statistical analysis. The table below summarizes the articles according to the research methods employed.

Table 02 The distribution of research methods

RESEARCH METHODOLGY	ARTICLES	OCCURENCE
field measurement only + statistical analysis	Onur Kaplan et al 2021, Helen Stopps et al 2020, Muhammad Hafeez et al 2020, Isabelle Y.S. Chan et al 2018, Lokman Hakim Ismail 2016,Wahyu Sujatmiko et al 2015,Wei Yanga et al 2015,Ardalan Aflaki et al 2014,Mohammad Rahim et al 2014,Doris Hooi Chyee Toe et al 2013,J. S. Pau ET AL 2013, Simons Barbara et at 2012,Mohammad Kotbi et al 2012,Liu, Tianqi et al 2011,Oluwafemi K. Akande et al 2010,Nooriati Taib 2010,Till Pasquay 2004,Kenneth Ip 2000,ABDULMALIK BIN ABDULSHUKOR 1993,Ardalan Aflaki et al 2014,Sara Omrania et al 2017,Wahyu Sujatmikoa et al 2014,	**22**
Questionnaire survey + statistical analysis	Mishan Shrestha et al 2021, KADIRI, D.S.2015,Achoru Afam Mike 2015,Chengri Ding 2013,Robert Gifford 2007,Oldfield,P. et al 2014,Thibaut Abergel et al 2017,	**7**
Field measurement + questionnaire survey + statistical analysis	Huan Zhang et al 2020, Zhongjun Zhang et al 2019,M Rajapaksha et al 2015,Babak Raji et al 2014,Daniel Godoy-Shimizu 2018,Christopher Drew et al 2015,CTBUH 2013,Helen Stopps 2020,M Rajapaksha et al 2015,Lokman Hakim Ismail 2016,	**10**

field measurement + questionnaire survey + CFD Simulation + statistical analysis	Francesco Salamone et al 2018,Xiangyu Zheng et al 2016,Paige Wenbin Tien et al 2019,Tianqui liu et al 2021,	**3**
CFD Simulation only	Lan Chen et al 2021, RODRIGO MORA et al 2018,Pimolsiri Prajongsan 2012,Tahir Ayata et al 2009,Yim, S. H. L. et al 2009,Sam Pournazeri et al 2009,	**6**
Energy use modelling using EnergyPlus, Design builder, IES VE, ENVI-MET, APACHE, RADIANCE or other	Joanna Ferdyn-Grygierek et al 2021, N H Roslan 2021,Yunhao Chen et al 2020, Usamah Derwaish et al 2019, Jing Li et al 2017,Jaberansari et al 2016,Nobuo Mishima et al 2010,Kenneth Ip 2000,Jing Li et al 2019,Kwang Ho Lee et al 2014,Mostafa M. Saad et al 2021,Sundus Shareef 2021,Yingbao Yang et al 2017,Ahmad Sanusi et al 2015,Jaberansari et al 2016,Saba Alnusairat et al 2015,	**16**
CFD + Energy modelling	Meseret T. Kahsay 2021,Jian Hang et al 2012,	**2**
Literature Review only	Nurul Hidayah Roslan et al 2018, Mustapha Adamu Kaita et al 2017,Seyedehzahra Mirrahimi et al 2015, Saba Alnusairat et al 2015,Anthony Nkem Ede 2014,Joanna Pietrzak 2013,Antony Wood 2008,Eldemery Ibrahim 2007,Imaah, Napoleon Ono,Seyedehzahra Mirrahimi et al 2016,Nurul Hidayah et al 2018,Raji, Babak et al 2014, Tatjana Anholts 2012,	**12**
Scaled model with experimental iteration, eg: wind tunnel testing or other, observation and inferences	Junliang Cao et al 2017, Lan Chen 2017,Prata, Alessandra 2005,ISHWAR CHAND et al 1991,Chris McClurg 2016,Yaik-Wah Lim et al 2013,	**6**
Qualitative approach, Design proposal, theoretical evaluation	Paige Wenbin Tien et al 2019,Ahmad Sanusi Hassan et al 2015,M. Sijanec Zavrl et al 2015,Peter Simmonds et al 2013,Antony Wood et al 2012,Dr. Akram Farouk 2011,Jianlei Niu 2003,CTBUH 2020,David Etheridge et al 2008,CTBUH 2012,	**10**
GIS / Remote Sensing	Usamah Derwaish et al 2019,	**1**

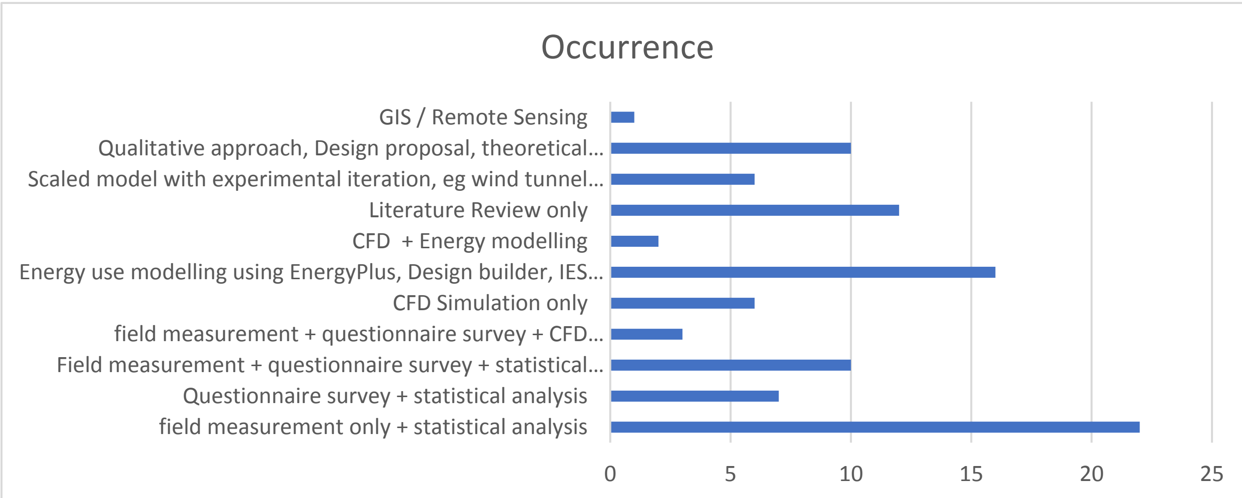


Fig. 10: Frequency of Occurrence of research methodologies
Source: Author

The review identified eleven (11) broad methodologies. The most commonly used methodologies were the field measurement and statistical analysis and Energy-use modelling using a variety of simulation software. GIS/Remote sensing technique was the least commonly used method.

4.2 Distribution of Articles According to Climatic Regions

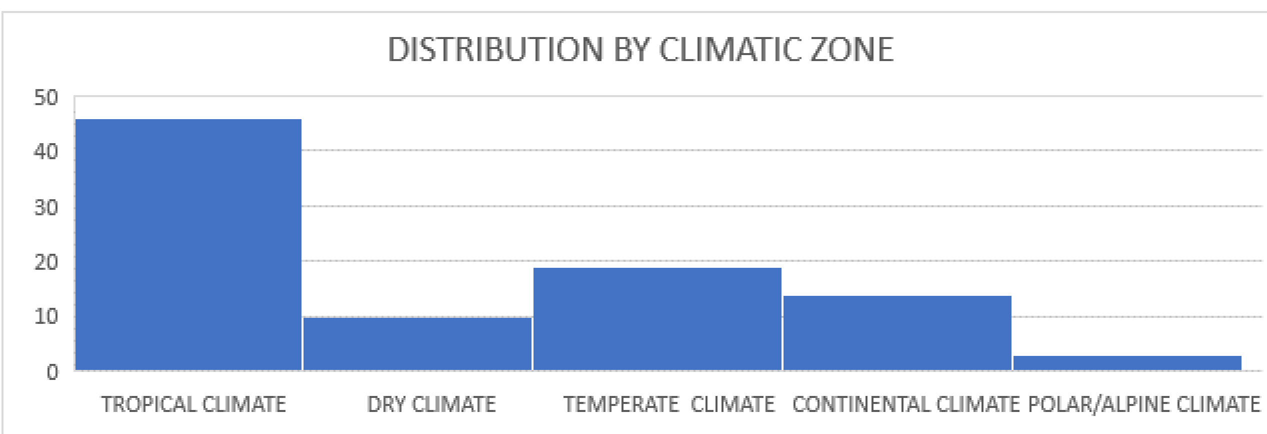


Fig. 11: Distribution of reviewed articles according to climatic zone where the study was conducted.
Source: Author

The results reveal that the tropical climate zone has seen a higher number of publications in the field of thermal comfort, energy use and building height followed by the temperate climate, continental, dry and polar climates in order of decreasing occurrence. There appears to be a more rigorous research activity related to the issue of thermal comfort and energy conservation for high-rise buildings in the tropical climatic zones possibly due to the hot-humid nature of the weather in those areas.

4.4 Distribution of Articles According to Building Use

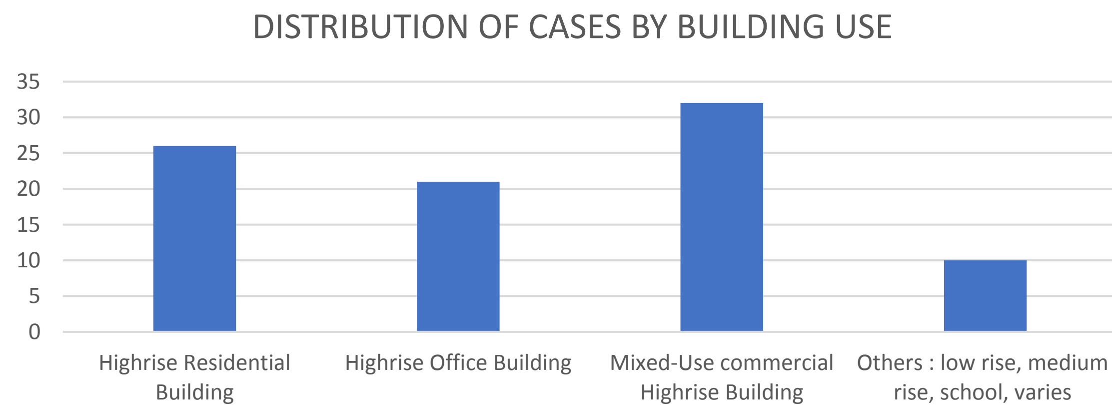


Fig. 12: Distribution of studied cases by building use
Source: Author

The results of the statistical sorting reveal that the majority of research studies were carried out on the mixed-use type of high-rise buildings followed by the residential types. The low rise, medium rise and varied types have been less frequently examined.

4.3 Summary of Research Objectives

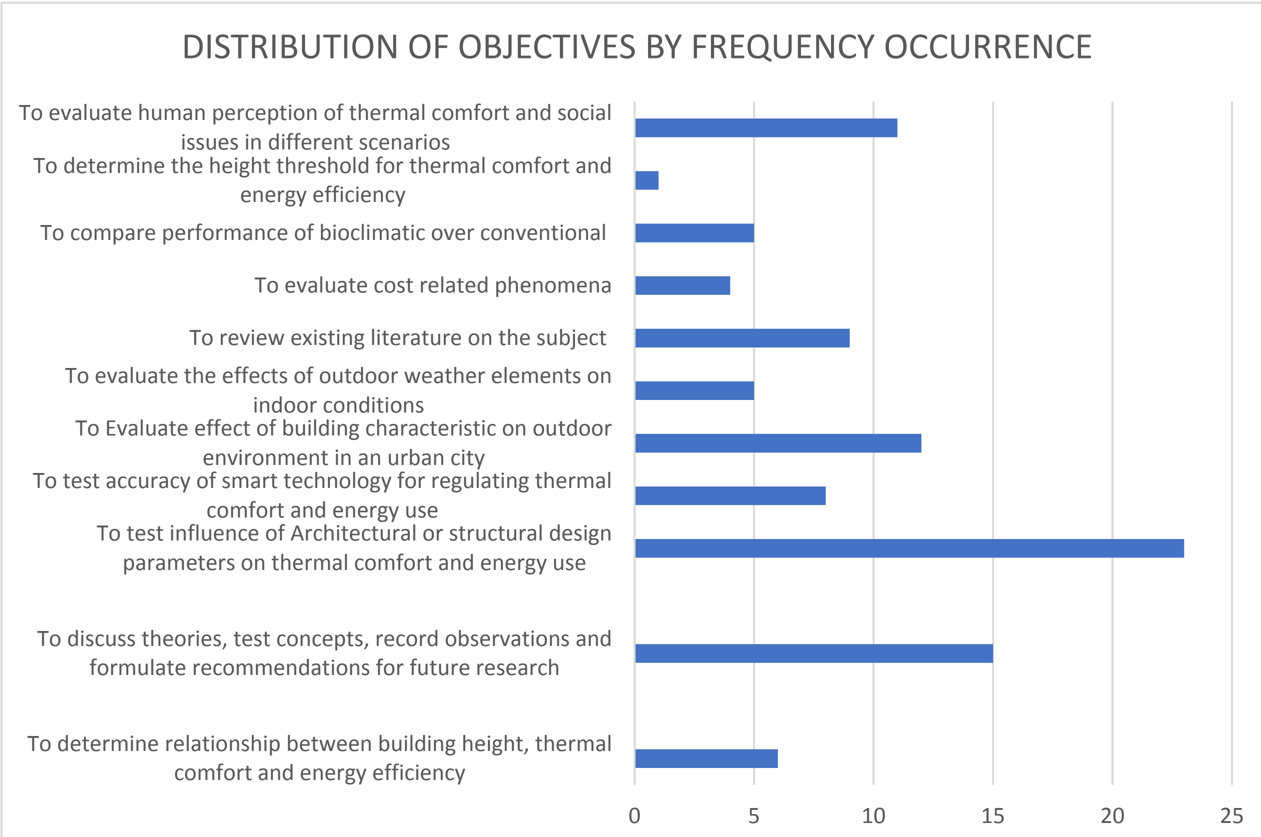
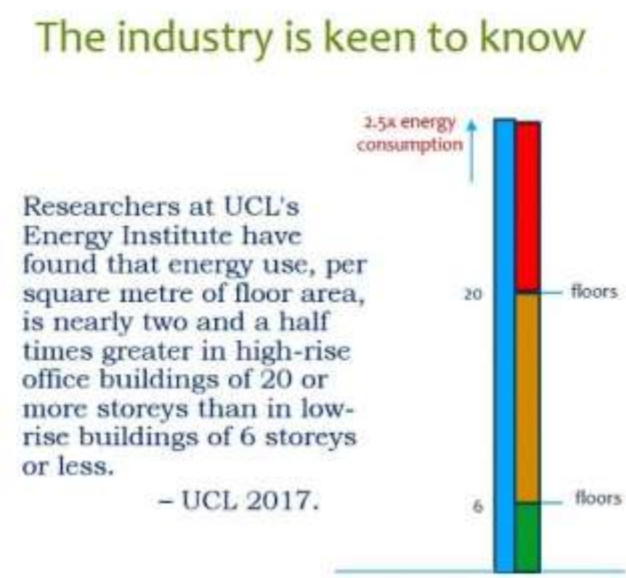


Fig. 13: Distribution of research objectives by frequency of occurrence.
Source: Author

Studies focused on testing the influence of architectural or structural design parameters such as height, form, orientation, facade material etc. on thermal comfort and energy use was found to have the highest frequency of occurrence followed by studies aimed at discussing theories, testing concepts, recording observations and formulating recommendations for future research.

4.5 Gaps in Literature

A study by the Council for Tall Building and Urban Habitat CTBUH stood out as it set out to identify and prioritize a roadmap for future research on needs of tall buildings. After a series of sorting and elimination, a list of five topics made it to the top of the CTBUH research topic priority index (Oldfield, Trabucco and Wood, 2014). Topic number two identified the need to ascertain the optimum height for building efficiency as a priority research area. Researchers at the University College London, UCL's Energy Institute found that energy use, per square meter of floor area, is nearly two and a half times greater in high-rise office buildings of twenty (20) or more stories than in low-rise buildings of stories storeys or less (Godoy-Shimizu *et al.*, 2018). This has to be tested for residential high-rise buildings in the tropics.



This may lead to the discovery of a definite height threshold for energy efficiency and thermal comfort for residential high-rise buildings. This will clearly provide information on the nature of such relationship. Whether this influence is same across different climatic regions and whether it is the same for high-rise residential versus high-rise commercial buildings needs to be? The paucity of research publications on high-rise buildings emanating from Africa may be an indicator of the fact that there are fewer high-rise buildings in the continent.

Fig. 14: Illustration of UCL's research finding.
Source: (Godoy-Shimizu *et al.*, 2018)

5.0 Conclusions and Recommendations

The illustration shown in Fig. 15 shows the `authors' conceptualization of how energy consumption is related to the use of HVAC equipment, which emanates from the need to maintain a comfortable indoor environment for occupants of high-rise buildings in terms of indoor air quality and thermal comfort. The arrows indicate the two-way relationship between the sections implying that any change in either of the sections bears significance on the others.

Fig. 15: Cause and effect relationship between energy efficiency and design factors.
Source: Author

The authors argue that for energy consumption to reduce, passive design strategies must be employed to provide alternative sources of natural ventilation and thermal comfort. Such design strategies may include but are not limited to: design issues affecting building height, form, and orientation.

In conclusion, the task of building performance evaluation is a collective responsibility of every member of the building industry. If we fail to examine how our existing high-rise building stock is performing with respect to concerns about energy efficiency, then we miss out on vital information relevant to improving the future of high-rise developments. The graphical representations will help the scholars to understand the direction and position of such a relationship.

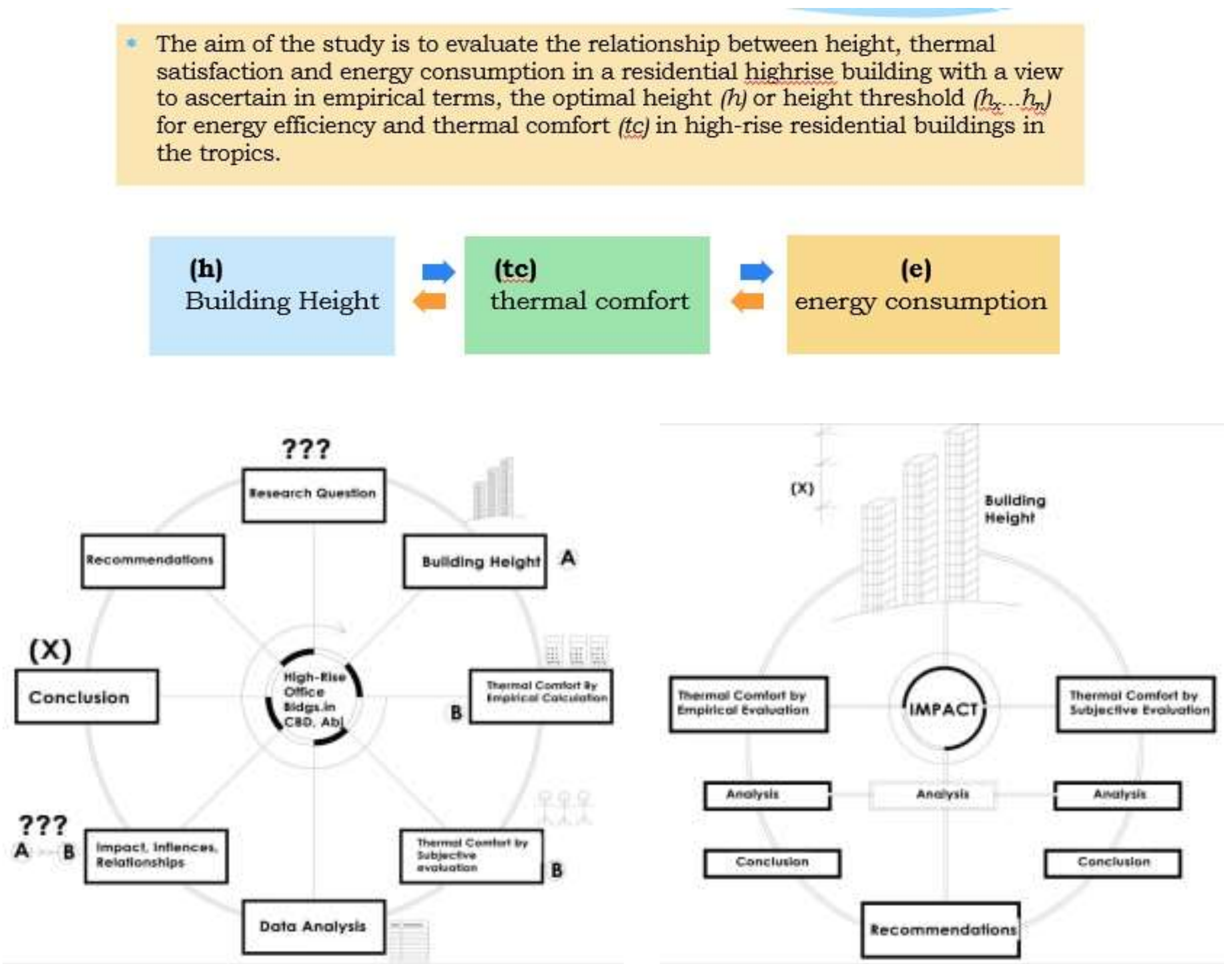


Fig. 17: Conceptual Framework for the impact of building height on thermal comfort in high-rise office buildings.
Source: Author

It is expected that a definitive mathematically expressible, relationship exists between energy consumption *(e)*, thermal comfort *(tc)*, and floor height*(h)* that may be established. If this is found to be true, the expression of this relationship in mathematical form can become a reliable piece of information which developers can take advantage of, while planning design, construction and operation of high-rise residential buildings in the tropical environment. The findings would have important implications for policy-makers, especially in congested cities where urban land is a scarce commodity, and the only way to build is upwards.

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