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High rise buildings in Europe from energy performance perspective

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Abstract. The United States is well known for the birthplace of tall buildings in the world since the nineteenth century. The trend continued across all continents and in 1940, Europe developed its first tall building of over 100 meters in Genoa, Italy. Building codes, technological development, energy crisis, etc. have all influenced the built environment in different ways, a very visible sign of such impacts can be seen in high rise buildings not only on their architectural style but also on their performance. Different studies worldwide investigate energy performance of modern high-rise buildings; however, evolution of such buildings is rarely considered; energy performance of different high-rise buildings' generations is seldom investigated and compared. To close a gap this study aims to make a closer look of how technological developments and energy crisis affected high-rise buildings in Europe with a focus on their energy performance.

Keywords: high rise buildings, generations, energy performance, Europe.

Introduction

Since 1998, there has been a significant growth in the number of high rise buildings in Europe and the tallest reached 373 meters in height with a mixed-use function (Federation Tower, Moscow). European cities that have historically built tall buildings to protect their valuable heritage (e.g. London, Paris, Frankfurt, Amsterdam, Moscow, and Warsaw) have resumed constructing tall buildings. By 2013 skyscrapers had been constructed in over 100 European cities located in 30 different countries and the expansion of high-rise construction continues (Pietrzak, 2014). If Europe had only two above 250 m tall buildings before the 21st century, by 2020 it is expected that 23 buildings will be built in this height category (Al-Kodmany, 2018).

Most buildings between 100–150 meters' height built in Europe are residential, between 150–250 m are offices and above 250 m are mixed use (Viñoly et al., 2013; CTBUH, 2013) (see Figure 1 for individual building heights and trends until present). Since 1940, the typology of tall building in Europe has been influenced by numerous technological and regulatory changes. Developments such as strengthening the building codes for lower U-Values, the usage of curtain wall systems and the world's energy crises in 1970s have all affected the design and construction of tall buildings not only in the continent but also in the world, such events also affected the performance of tall buildings in various ways.

The importance of looking at tall buildings performance as large consumers lies on the fact that in European Union, buildings are responsible for almost 40% of overall energy consumption and 36% on carbon emissions (Hajdukiewicz & Goggins, 2014). In light of this, continuous effort is being made to reduce the overall energy demand from buildings and so it is stimulating to look back and examine how tall buildings, as one of the largest consumers in the urban environment, in particular have responded to environmental concerns over time. Moreover, as noted by Oldfield, Trabucco, and Wood (2008, 2009), "it is also interesting, and necessary, to look back at the energy consumption characteristics of tall buildings throughout history; to examine how and why these changed and to learn possible lessons for the future".

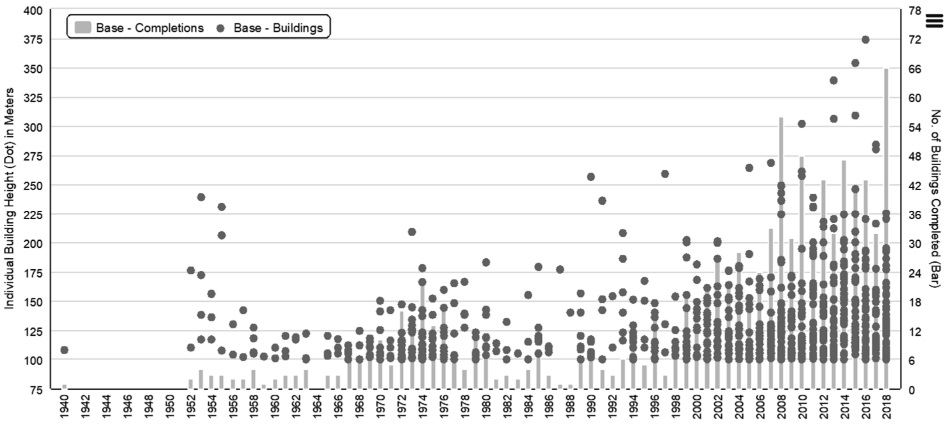

Figure 1. Individual building heights and trends until present (data source CTBUH, 2019)

High rise buildings dominate energy use because of their scale and purpose and so they are the focus for sustainability and energy standard. ASHRAE standard for the Design of High-Performance Green Buildings (189.1) (IGCC, 2017), suggests the requirements to design the high performance green buildings can be met by reduction in emissions, building user health and comfort enhancement, water resource, local biodiversity and ecosystem conservation, promotion of recyclable materials and by developing targets without compromising the needs of future generations. Most of the EU building codes also consider the site context, use of materials, energy consumption, use of water and ecological balance as critical design factors to decide the overall performance of a building. Furthermore, Mir and Armstrong (2008) describe a high performance tall building as those that "achieve peak efficiency of building functions while meeting the requirements of optimum performance employing green technologies".

Since 1830, building technology has improved from monolithic structures to glass-enclosed frames. This shift has become more noticeable since 1940 with advancement in electrical, mechanical and plumbing systems (Bachman, 2003). The impact of industrial revolution was on using more durable and higher quality materials and on standardization of building components which were mass produced by machines (Mir & Armstrong, 2008). Recent developments in robotics, micro generation and more advanced technologies for prefabrication and intelligent managing systems has also influenced the built environment. Currently, with the growing concerns of climate change, it is important to have an overview of energy consumption characteristics of tall buildings in Europe and how these have changed to respond to human's needs and challenges.

Literature on energy performance of different high rise buildings' generations is very limited. The most extensive study in this field was performed by Oldfield et al. (2008, 2009), who distinguished five energy generations of tall buildings in the North America. None such studies were performed for the European context. This study is organized as follows. In Section 2 changes of high-rise buildings' performance are categorized into three distinct periods of from birth to when curtain walls become widely popular across Europe and from curtain wall system popularity to the world's environmental awareness and from environmental awareness to the development of improved building standards. In Section 3 simplified (steady-state) heat loss comparison is performed. Summary on findings and comparisons among different generations of buildings with a focus on energy performance is provided in Section 4. Section 5 concludes the study and provides insights for future research.

Three generations of high rise buildings

First generation from birth to the development of glazed curtain wall

Steel structure development, invention of elevator and inspirations from first tall buildings in North America led to the birth of tall buildings in Europe. The first high rise buildings in continental Europe were the 26-story *Boerentoren*, built in 1932, in Antwerp, Belgium, and the 31-story *Torre Piacentini*, built in 1940 in Genoa, Italy.

The first generation of tall buildings in Europe like other parts of the world required limited amount of energy to operate since the technologies like air conditioning did not exist. Natural ventilation was provided through windows and inefficient lighting widely used for offices. Therefore, the quality and rentability of office space depended on large windows and high ceilings, windows occupied some 20%–40% of the façade (Oldfield et al., 2009).

Even though the first generation of tall building benefited from structural development but the envelope was largely relied on masonry and traditional methods of construction. This was the case until 1959 when curtain walling has become widely used in buildings. Small windows, no insulation, poor air tightness and high level of thermal mass can be categorized as their main energy consumption characteristics. In terms of shape, the tall buildings had compact forms with boxy shapes. These characteristics of compact and boxy shape were best reflected in *Torre Velasca* and *Torre de Madrid* (see Figure 2). There is no reliable data available to suggest the U-Value of the external envelope for the tall buildings built in this period, building standards started to improve in 1970 in East part of Europe and mostly in the UK.

Figure 2. From left to right: *Torre Piacentini*, Genova, 1940; *Torre de Madrid*, Madrid; 1957;
Torre Velasca, Milan 1958 (Images from CTBUH, 2019)

Second generation from curtain wall system innovation to environmental awareness

Even though Mies van der Rohe arguably revolutionized the design of tall buildings in 1921 with fully glazed system for *Friedrichestrasse* tower in Berlin, however such typology did not become popular until after the Second World War. After the Second World War, technological innovations dramatically changed the high-rise typology (Oldfield et al., 2008). The second generation of tall building has significantly higher ratio of glass in their envelope compared to the previous generation. The *Torre Galfa* in Milan, *Millbank Tower* in London and *Tour Logica* were the leading samples of tall buildings over 100 m with curtain wall system in their façade (see Figure 3).

The façades used in second generation were single glazed with inferior thermal performance compared to the heavy weight façade that was common before them. Significantly low U-Vale because of a very thin envelope caused considerable heat loss and overheating issues in summer. The comfort level inside was heavily relied on the air conditioning system and therefore significantly higher energy was required to respond to such need.

Towers in this generation constructed very similar to the first generation in terms of shape. Deep plans for offices restricted ventilation and day lighting performance. The considerable shift from masonry construction as envelope to a poor performance glazed system had considerable negative impact on their energy consumption.

Figure 3. From left to right: *Torre Galfa*, Milan, 1959; *Millbank Tower*, London, 1962;
Tour Logica, Courbevoie, 1971 (Images from CTBUH, 2019)

Third generation from environmental awareness to building standards improvement

Energy crisis in 1973 and 1979, increasing number of tall buildings with environmentally relatively poor performance and technological advances has created a shift toward more environmentally sustainable and higher performance buildings from 1973. The energy consumption has become an issue, building codes became stronger on insulation requirement and architects started to design more environmentally friendly towers. The usage of double glazing with argon filled cavities also reduced the U-Values and heat loss. In comparison, second generation buildings had façade U-values in the range of 3.0–4.2 W/m^{2}K, the use of double glazing, low-e coatings and argon-filled cavities reduced these figures to 1.0–1.5 W/m^{2}K (Oldfield et al., 2009).

The shape of the tall buildings has also started to change in this era from boxy shape to more creative and free form shapes thanks to improvement in construction methods with environmentally and functionality driven thinking (see Figure 4). Dark color towers became increasingly unpopular because of their overheating issues and users started to see towers with sustainability ideas. Central atrium for natural ventilation (in e.g., *Deutsche Post Tower*, Bonn, 2002; *'Swiss Re' Tower*, London, 2004) and light, sky gardens, double skin façades and renewables became a mainstream in most towers.

Furthermore, the introduction of stricter building standards like Passive house standard in 1998 has caused a shift toward lower U-Values and air tightness, more efficient usage of Heating, Ventilation, and Air Conditioning (HVAC) systems and construction detailing to minimize heat loss through thermal bridge. The standard has spread around the world and recently the world's tallest building made by Passivhaus standard is built in Bilbao, Spain in 2018 claiming to have the air tightness of 0.3 m^3/(m^2·h) @50 Pa and a U-Value of 0.1 for the envelope and consume only 7 kWh/m^2 per year (Passive House Institute, 2008).

Figure 4. From left to right: *La Grande Arche*, Puteaux, 1989; *Turning Torso*, Malmo, 2005; *Strata Tower*, London, 2010 (Images from CTBUH, 2019)

New designs and some completed projects all over the world utilise technologies such as building augmented photovoltaic cells, wind turbines, co-generation and tri-generation systems, fuel cells and ground-source heat pumps to reduce primary energy consumption (Oldfield et al., 2009).

Moreover, nZEB-directive in Europe was introduced aiming to reduce the CO_2 emissions of all new buildings to nearly zero by 2020. Reductions can be realized by shifting the focus on the materiality of construction to wood (Hafner, 2014; Hildebrandt, Hagemann, & Thrän, 2017). Wooden skyscrapers are estimated to be around a quarter of the weight of an equivalent reinforced-concrete structure as well as reducing the building carbon footprint by 60–75%.

Figure 5. From left to right: *Mjøsa Tower*, Brumunddal; *HAUT*, Amsterdam; *HoHo*, Viena, 2018 (Images from CTBUH, 2019)

Several wooden skyscrapers already have been designed and built in the world, with the tallest the *Brock Commons*, an 18-story wooden dormitory at the University of British Columbia in Canada. A number of high profile architects and engineers are trying to recast wood as a material fit for the 21st Century and Europe is not an exception in this case. Examples include 18-story, 80-meter-tall-plus building in Brumunddal, Norway known as the *Mjøsa Tower*, 21-storey (73 m high) *HAUT* building in Amsterdam, Netherlands to be completed in 2019 and 24-storey (84 m high) *HoHo* building in Vienna, Austria, completed in 2018 (see Figure 5). Other, even more ambitious projects include the 40-floor *Trätoppen* ("Treetop") in Stockholm, Sweden and the 300 m high *Oakwood Timber Tower*, proposed by PLP Architects for London.

Simplified (steady-state) heat loss comparison

On the basis of building codes development in Europe, it can be assumed the U-Vale for second generation is likely to be 1.7 W/m^2K and for the third generation to be the maximum of 0.3 W/m^2K. There is no data available to confirm the first generation but it can be assumed as around 3 considering the masonry materials used with no insulation in place. Therefore, a simplified heat loss through a 1 m^2 given surface can be calculated using the following equation, where U – U-value (W/m^2K), thermal transmittance, A – Area of surface (m^2), dT – temperature difference:

$$\text{Heat loss} = U \times A \times dT. \quad (1)$$

Figure 6 demonstrates the likely heat loss per square meter of a typical each generation only through the wall in occasions where 5 °C, 10 °C, 15 °C and 20 °C dT applies. It can be observed the significant difference between each generation in terms of envelope performance. Heating and cooling energy use can also be calculated using the following equations (where QNH is the monthly heating demand, SCop is coefficient of performance, QNC is the monthly cooling demand and SEER is System Energy Efficiency Ratio of HVAC system) (Wang, Mathew, & Pang, 2012):

$$\text{EHeating} = \text{QNH/SCop}; \quad (2)$$

$$\text{ECooling} = \text{QNC/SEER}. \quad (3)$$

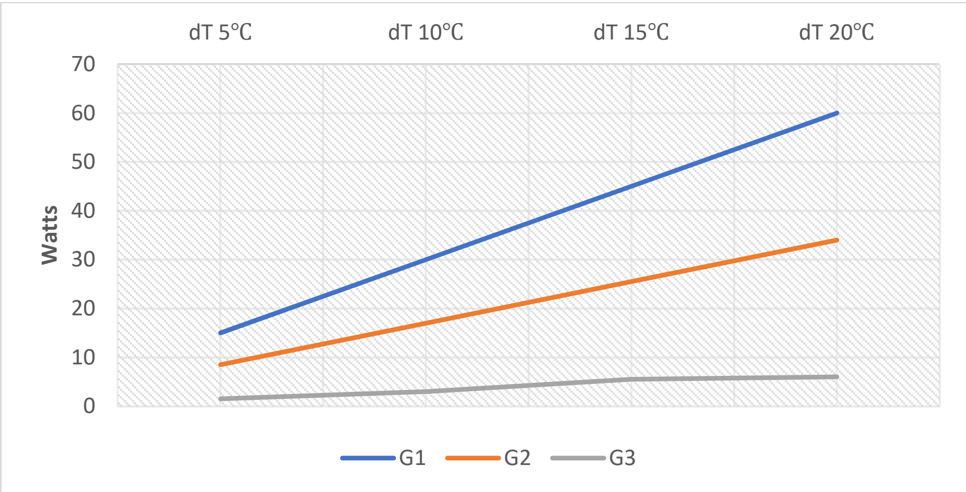

Figure 6. Heat loss comparison with 5 °C, 10 °C, 15 °C and 20 °C in a typical fabric U-Value of each generation

Due to complexity of the HVAC systems and unavailability of the data, it is not possible to quantify the heating and cooling loads for each generation and almost all the first-generation tall buildings are equipped with updated systems. The most commonly used HVAC system in the new built and refurbished ones are recorded as Variable Air Volume System (VAV) and constant Air Volume (CAV). VAV is generally an air system which varies the supply air volume rate but keep a supply air temperature remain constant, CAV system keeps the air volume flow rate constant but varies the supply air temperature. The VAV system in comparison with the CAV has higher efficiency (Korolija, Zhang, Marjanovic-Halburd, & Hanby, 2009).

Summary of findings

A review on each tall building generation shows for certain period these buildings has distinct characteristics in their performance. Table 1 summaries the inclusive findings of this study.

Table 1. Summary of findings

Indicator	1st Generation	2nd Generation	3rd Generation
Thermal mass level	High	Low	Varies
Shape	Compact	Compact	Compact and free form
Slenderness ratio (the base width to the height of the tower)	*Torre Piacentini*, Genova 1:15	*Torre Galfa*, 1:19	Various shapes, up to 1:24 (Riad, 2016)
Façade transparency	Low	High	High
Energy consumption characteristics (from Oldfield et al., 2008)	Heating and elevators main consumers of energy	Mechanical conditioning main consumer of energy	Natural ventilation, on site energy generation
Envelope material	Masonry	Glass, Concrete, Steel	Glass, Aluminum, Steel, Concrete, Wood
Envelope U-Value	Information unavailable, likely to be around 3	Likely to be around 1.5–2.0	0.3–0.1
Glazing type	Single glazed	Single glazed	Double glazed, triple glazed
Ventilation strategies	Natural ventilation	Natural ventilation	Natural and mixed mode ventilation
HVAC system	None	Boiler/Chiller less VAV system compared to CAV (Winiarski, Jian, & Halverson, 2006)	Boiler/Chiller more VAV system compared to CAV (Winiarski, Jian, & Halverson, 2006)
Heat loss	Significant	Moderate	Controlled
Use of renewable energy resources	No	No	Yes

Conclusions

This study distinguished three periods to classify tall buildings in Europe chronologically and on the basis of their energy consumption features. In the first generation of tall buildings, energy mostly consumed for heating spaces and the elevators, however the high level of thermal mass and compact shape influenced the performance in a positive way. The second generation becomes slenderer but the single glazing and low U-Value as a result caused considerable heat loss in winter. However, towers with low slenderness ratios tend to have better performance in terms of daylighting and ventilation since the distance from the envelope to the core of the building is moderately short. The third generation benefited from double glazing, lower U-Values and technological improvement to also make them work as power stations by using renewables. Better ventilation and daylighting as well as improvement in HVAC systems significantly reduced the energy consumption in these towers. Wooden high rise buildings recently becoming the most sustainable buildings, their energy performance will be investigated in future research.

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