Skyscrapers and the city: How tall buildings interact with their users and urban environment

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Abstract. Tall buildings have become a prevalent typology around the world. They carry benefits for the entrepreneur (profits) and the local authority (municipal taxes), the architect and the tenants (prestige). Yet little is known about the actual needs of the building itself, the fact that its different levels are exposed to different climatic conditions, thus have different energy needs, or the contingencies involved in living high up in, or down around them. This paper presents results of ongoing research, including tall buildings' microclimatic peculiarities with height and ensuant energy needs; building envelope design and energy efficiency; microclimatic peculiarities created on the pedestrian level; and environmental quality. Specific modules results have been published in several papers, while additional work is ongoing, since this building prototype and its implications are still mostly poorly understood. Such work ties into climate change and the built environment, public health, survivability and resilience under extreme environmental events, which seem to become the norm. Results of parts of this research certainly tie into Covid-related contingencies and the need for usable public open spaces, efficient building ventilation to ensure good Indoor Air Quality (IAQ), and a whole array of other issues.

1 Introduction

Population growth and intense urbanization push for mass housing solutions. Half of the world population is already urban, a figure anticipated to rise to over 60% by 2030 [1]. Big cities, e.g., Hong Kong and Mumbai, are already exceeding 20,000 people/km^2 [2]. Such processes make the dense city unavoidable, and many claim the skyscraper is the most appropriate solution [3]. Yet little has been investigated about this building type, and much is not well understood yet. For example, how tall is still reasonable and sustainable. How does living and working at heights of 100, 200, 500m and more above ground affect people, and how such buildings interact with their environment (or is the environment changing with altitude?), energy needs and usage, urban infrastructures, and the city at large?

To tackle this very broad and multifaceted issue, this multidisciplinary team has embarked on a latitudinal study of such questions which so far has yielded several papers documenting different modules of this study. Coming from different disciplines (architecture, urban planning, civil and environmental engineering, remote sensing, public health), the team's aim is to study the skyscraper phenomenon holistically. This paper is a brief summary of work accomplished so far, parts of it published in peer reviewed journals and presented at previous scientific conferences. The focus has been the city of Tel Aviv, on the Mediterranean coast of Israel, which is undergoing rapid densification, boasts over 30 buildings over 150m tall, some well over 200m, and has already promoted a master plan for skyward development. As such, this work is of relevance to many cities in the Middle East and the Mediterranean basin, which are undergoing similar processes.

2 Skyscrapers and climate

The Köppen-Geiger classification of Tel Aviv's climate is Csa, a hot summer Mediterranean climate. It has a cool rain season roughly running from October to April, and a dry one between May and September. The average annual temperature is approximately 20.5°C, minimal and maximal temperatures range annually between 10-31°C, and the annual rainfall average is 413mm. Relative humidity monthly average is appr. 70%, and the prevailing wind is the westerly Mediterranean breeze

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blowing from the sea inland. Having said that, it has become apparent that climate change is raising both temperature and relative humidity [4], extending the hours of thermal discomfort, especially at night [5].

When discussing skyscrapers, otherwise named tall (<300m), supertall (300-600m), and megatall (>600m) buildings depending on their height [6], it needs to be noted that air temperature drops with altitude above ground, while wind velocity rises. This affects differently the energy needs of tenants on different levels above ground, as well as their ability to ventilate by operating windows, or to use balconies.

A first study on the different energy needs of two 100m tall reference models – residential and office - per altitude change showed significant differences of cooling and heating needs between the two [7]. Using EneryPlus as the main simulation engine, and Ecotect Analysis for the design of optimum shading devices, different envelope scenarios were analysed for four major orientations of residential units – SE, SW, NW, NE – and an open plan for the office building. Energy needs were then extended and simulated for 100, 200, 300 and 400m above ground, based on indoor thermal comfort as defined by Fanger's Predicted Mean Vote (PMV) – 20-23°C in winter, 23-26°C in summer. Figure 1 shows the heating and cooling needs at different heights for each one of the two building types.

common in office towers, yet recently becoming common in the design of residential buildings as well. Internal loads have also been assumed to comply with the models' different function (e.g., building users per floor area, equipment).

3 Skyscrapers and energy

To lower the energy needs, a study of the skyscraper envelope was undertaken already in the previous module, including parametric studies of minimal and improved insulation, double glazing with and without Low-E coating, incorporation of balconies, external fixed and operable shading devices on the windows. In current practice most such buildings do have double glazing curtain walls, yet such do not seem to be adequate in either lowering the substantial cooling needs demonstrated in the previous module or addressing glare and indoor radiant heat from the façade panels.

Thus, studies were conducted to assess the impact of double skin façades (DSF) on the energy needs of skyscrapers, considering both fixed and dynamic DSFs. Façade configurations simulated included in the first stage: clear single glazing; Low-E double glazing, Low-E double glazing, external shading; double skin façade. The second stage focused on the following DSF

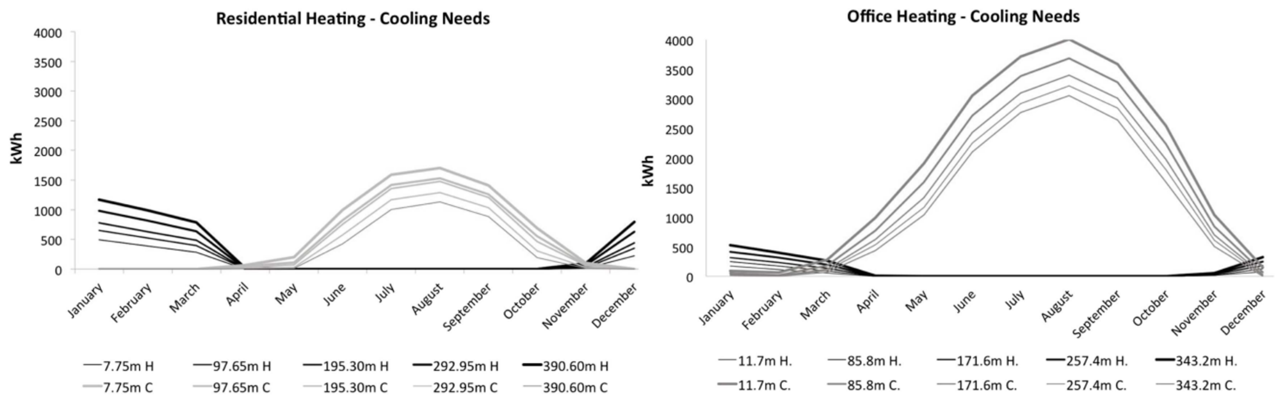

Fig. 1. Comparison of heating and cooling needs between optimal residential and office scenarios [7].

In the case of Tel Aviv studies showed that cooling loads were significantly higher in the office building, yet in both models cooling needs dropped with altitude above ground. Both models have a floor area of 460m^2 per floor, and were detailed so that they comply with the relevant Israeli standards for building insulation and energy rating of buildings. It should also be noted that whereas the office building is assumed to be a fully glazed one, the residential model is detailed so that it has both opaque and glazed façade components, as stipulated by the relevant green building standards, defining optimal window-to-wall (WWR: N,E,S≤15%, W≤10%) or window-to-floor (WFR: N,E,S ≤23%, W≤18%) ratio for residential and office use respectively, depending on orientation and the country's climatic zones. Such differences are of cardinal importance, not least because of the common practice of designing skyscraper façades as fully glazed curtain walls, a practice originally

configurations: Single glass panel out, Double clear panel in; Double clear panel out, Single panel in; Single panel out, Double Low-E in; Double Low-E out, Single in. Different air cavity depths (0.2, 0.5, 1.0, 2.0m) were simulated, as were different operation modes, including dynamic operation of intake and outlet dampers based on thermostat settings. All such simulations were performed with EnergyPlus 8.8, using its integrated HVAC system (Ideal Loads Air System), specifically focusing on the Airflow Network (AFN) method to assess the impact of both natural and mechanical ventilation methods [8-10].

Results showed that a DSF with exterior layer with Low-E employing selective ventilation reduced cooling loads by 15% on average compared to conventional DSF design with the Low-E on the interior layer of the DSF, and lowered cooling needs by an average of 50% compared to the single skin envelope with Low-E. Operation scenarios showed that changing the DSF air cavity function from airtight to open space between 08:00-20:00 allowing cavity ventilation during peak load hours reduced cooling loads by 50% percent. Some of these results are illustrated in Table 1 and Figure 2.

Table 1. Heating (H) and cooling (C) loads of three envelope scenarios: DoubleLowE and Shading (SH.), a DSF (single_doubleLowE), and a DSF (doubleLowE_single). U-values of wall and windows ratio according to Israel's Green Building Standard [8].

Curtain wall composition	Hgt. above gnd. (m)	8.7 m	81.9 m	167 m	235 m	339 m
	kWh/m^2/yr					
Dbl. LowE + Sh.	H	0.9	1.38	1.9	2.52	3.06
	C	**49.3**	**43.8**	**39.7**	**36.1**	**35.8**
DSF Sgl._ DLowE	H	0.2	0.4	0.7	1.03	1.37
	C	**53.2**	**46.5**	**41.6**	**38.3**	**36.0**
DSF DLowE_ Sgl.	H	0.3	0.7	1.4	2.0	3.12
	C	**48.4**	**39.3**	**33.2**	**32.2**	**28.6**

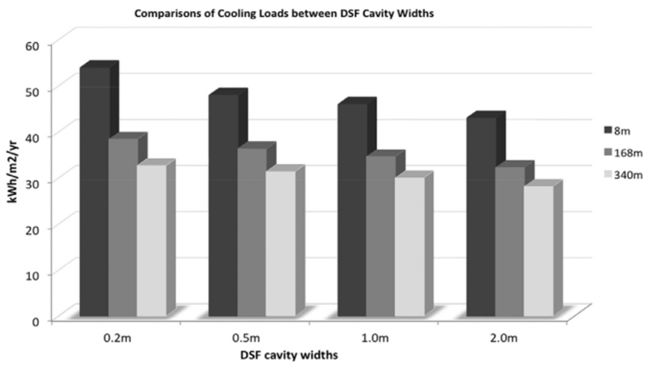

Fig. 2. Comparisons of cooling loads between DSF cavity widths per height above ground [9].

These are significant results since office buildings in general, and office skyscrapers in particular, tend to have substantial cooling loads even in winter, due to their envelope design which turns them into greenhouses, as well as their internal loads.

4 Skyscrapers and the microclimate at their base

When the urban fabric is uniform more or less, the wind regime within it may be anticipated to a rather high degree of certainty. When buildings of significant volume are introduced in this fabric, though, their impact on the microclimate on the pedestrian level can be detrimental, not least since this level is often designated for leisure, shopping, restaurants and cafés. Not only can the mass of skyscrapers divert the incident wind downwards creating unpleasant conditions, thus compromising the proper operation of whatever services are housed there; it can even create such extreme wind conditions which may well endanger pedestrians.

To better understand such urban climate specificities, two office towers (165m tall) and two neighbouring residential ones (120m tall) were chosen, located appr. 3km inland (westward, downwind) from the coast, with a relatively uniform urban fabric of low and medium height buildings both windward and leeward. Spot measurements were conducted (using hand-held LUTRON LM-8192), microclimatic conditions were monitored (by stationary HOBO USB Microstations H-21), and a survey was conducted administering randomly semi-structured questionnaires to pedestrians around the base of the towers. Microclimatic data were recorded for four days in February 2020 (cold period) and beginning of October 2020 (representative of hot period with ambient temperature reaching 30°C), while two 24-hour periods were selected for the surveys, with most of the questionnaires covering the periods with the highest numbers of pedestrians (office workers, local residents, services providers, suppliers) between 06:00-20:00. A total of 256 questionnaires were collected, 124 for the hot period, 132 for the cold one, which should be considered satisfactory under Covid-19 restrictions of the period, mainly during time restrictions were partially eased. They included demographic data on the interviewees, their thermal experience and activity levels prior to the interview, and thermal sensation and satisfaction with the microclimatic conditions. A 7-point Likert scale was used for this, in accordance with the ASHRAE TSV scale [11,12]. Weather data from local meteorological stations, including the Tel Aviv station at the beach, were also collected, and coupled with the local ones to identify trends and discrepancies specific to the towers' vicinity.

Indicative measurements undertaken over several days pointed to a wide diversity of wind and gust velocities common around the base of the towers at a height of 1.5m above ground, with the highest value recorded between the two taller towers reaching 9.3m/sec. This should not come as a surprise since the massive facades of the two office towers and the narrow passage between them create a funnel inducing a Venturi effect (Figure 3) [13].

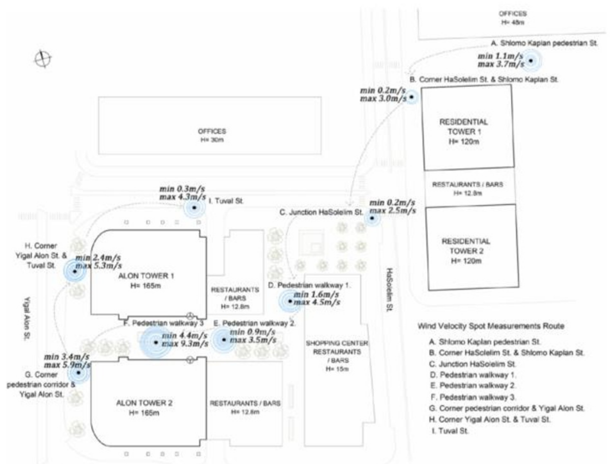

Fig. 3. Visual representation of spot measurements. Concentric circles represent wind velocity and intensity. Min./max. gust velocity values - Feb.26, 2020, representative day for highest values recorded [13].

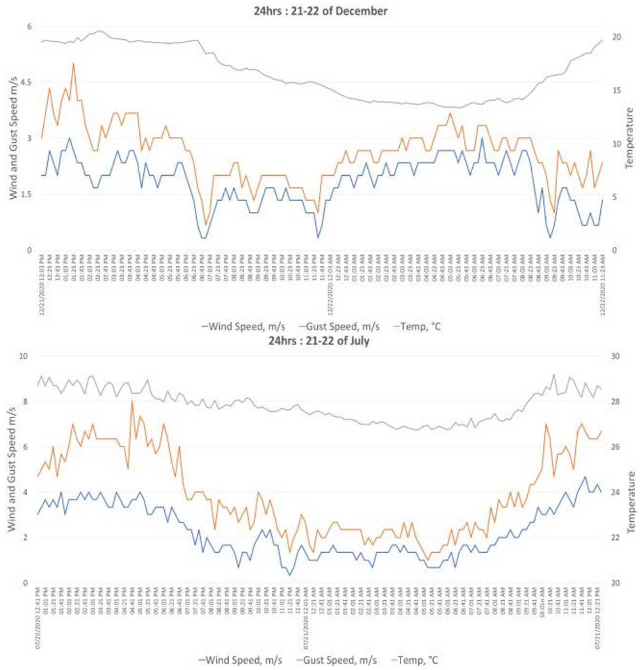

Fig. 4. 24hrs recordings of air temperature (°C), wind and gust velocities in summer (up) and winter (down) [13].

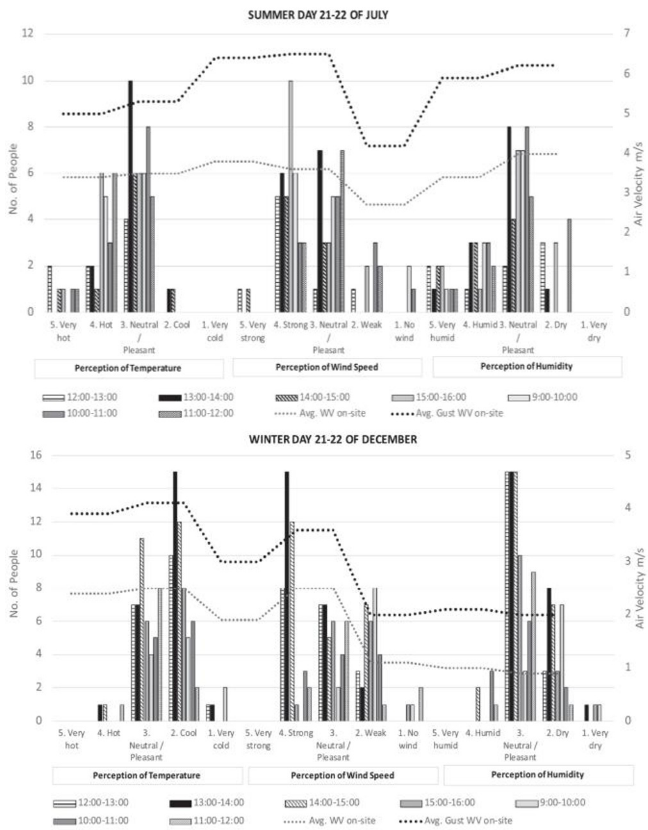

Fig. 5. Graphic interpretation of temperature, wind velocity and humidity compared to measured wind and gust velocities in summer (up) and winter (down) [13].

Monitored air temperatures, wind and gust velocities were recorded and indicated locus specific conditions significantly different from those registered by the Tel Aviv beach and other meteorological stations, formatted by the almost constantly shaded area in the vicinity of the towers due to their height and volume, and the wind patterns created by these. Figure 4 depicts such data over two 24-hour periods – Dec.21-22; July 21-22.

Under such conditions clothing was assumed to be 0.5 clo in the hot period and 1.0 clo in the cold one. However, in several cases the attire of individuals was observed to divert significantly, e.g., long and even heavy clothing in summer (14% of the interviewees) and light clothing in winter (20% of the interviewees), which can be attributed to personal preferences (e.g., men vs. women), but not least on the indoor conditions – open space offices with centrally controlled air conditioning systems the thermostat of which is set at too low a temperature in summer, and a too high one in winter.

Questionnaire analysis shows rather clear preferences in the two seasons, with summer perception votes mostly “neutral” regarding temperature and humidity, yet “strong” regarding wind. In winter perception votes run mostly “neutral” regarding humidity, but “strong” regarding wind and “cool” regarding temperature. It can thus be deduced that the local wind regime is the predominant factor in shaping thermal sensation, whereas the shadows cast by the towers between and around the towers’ base improve almost constantly local microclimate in summer but exacerbate it significantly in winter. This module’s results are illustrated in Figure 5.

5 Skyscrapers, wind and air quality

Ongoing work includes several modules ranging from the urban and infrastructural domain, land values and gentrification, as well as an array of technical and socio-behavioural issues. Two of the more advanced ongoing modules are the wind in altitude (monitored by HOBO USB Microstations H-21) and the air quality (NOx monitored by 42C NOeNO2eNOx Monitor Labs 9841A; PM2.5 and PM10 in µg/m3 monitored by Continuous Ambient Particulate TEOM™ Monitor 1400ab, and Dylos PM1700; Campbell meteorological stations), as these are affected and shaped by the specific buildings discussed in the previous module. Though still working on data analysis and interpretation it can be said with a great degree of confidence that wind along the height of skyscrapers changes significantly both in altitude and in relative position around the building’s perimeter, esp. relative to adjoining towers. The wind profile created along the towers’ height raises many questions regarding the usability of balconies, which add to the price of the real estate during purchase or rent, as well as in terms of municipal taxes. From a certain height upwards comfort on and the use of balconies in general are questionable, and in specific cases balcony use becomes dangerous.

As for air quality, three spots have been monitored including the open space at the base of the towers in discussion, a low-rise residential area in the leeward direction, and a major traffic (vehicular and rail) artery in the windward direction. Trends indicate similarities in PM10 and PM2.5 concentrations between the towers and over the heavy traffic artery. Here again local monitoring results are compared with data from additional monitoring stations in the vicinity, operated by the municipality, the ministry of environmental protection and other institutions. Currently NOx and SOx data are being collected. As in previous modules of this study, the location, morphology, dimensions of such buildings are shown to significantly affect the local conditions, among them microclimate, air quality and mere usability of the urban space around them.

Following are some additional topics which are being considered within separate modules of this study, among them public health, safety and security.

6 Skyscrapers and other considerations

The above observations raise several additional issues regarding the appropriateness of this building type, certainly under Covid-19 related concerns, among them the vital need to efficiently ventilate indoor spaces to ensure good indoor air quality by exhausting pathogens and supplying clean air, provided such is available. It is also important to remember that adjacent open spaces on the pedestrian level may be of vital need in times of an epidemic or pandemic which may again subject people to quarantine and movement restrictions. For such spaces to function as needed and intended, reasonable microclimatic conditions must be ensured. However, as was shown above, the specific building type in its current detailing creates unpleasant conditions around its base. Thus, appropriate detailing needs to be developed to ensure wind, air temperature and solar access/shading control.

Safety and security are certainly of cardinal importance regarding skyscrapers. Their behaviour in extreme events, e.g., earthquakes and fires, needs to be carefully considered. Cases of fire are not uncommon and have occurred time and again [e.g., 14]. One of the more extensively documented and analysed fire cases was that of Grenfell Tower in Kensington, London (2017), where 72 people perished. In this and other cases combustible cladding was the main problem, in the Grenfell Tower case having been used despite standards and regulations. However, one of the reasons given for the deaths of so many tenants was the inadequate length of the firefighters' ladders being too short to allow access to and evacuation of tenants. The haunting images of people jumping to their death from the burning World Trade Center (2001) should be kept in mind when security and safety in tall buildings are considered.

Yet one need not go that far – to death cases. Suffice to mention the Walkie Talkie building in London, branded also the Torching Tower. Due to its concave south façade, the building concentrates reflected radiation almost to a single point, unfortunately on the other side of the street, causing exceptional glare and damaging cars parked there [15]. Freakishly weird as this may sound, this is not the first such case and work has been undertaken to assess the dangers and propose appropriate strategies to avoid and mitigate such [16].

Spontaneous glass breakage is a well-known phenomenon, caused by NiS presence at a rate of 1 in every 500 glass panels, with a fracture rate of 0.8%. Even though safety standards demand in many countries that glass panels incorporated in the curtain walls of skyscrapers are layered ones preventing collapse of the glass in any case of damage, spontaneous or otherwise, the concern cannot be overlooked that the danger exists that shards and splinters may be a potential hazard. Of even higher concern is the potential disconnection and fall of whole glass panels spontaneously, under extreme wind conditions, or during earthquakes, which may well cause death among the pedestrians around skyscrapers. It is enough that a small percentage of such panels fall for consequences to be grave, certainly when considering the number of glass panels on 100, 250 or taller fully glazed façade buildings.

7 Conclusions

Since this is ongoing research, conclusions can only cover part of the issues mentioned. What can be said with certainty is that the larger the building volume, the taller it is, the bigger the problems it creates, certainly when its peculiarities and specificities are not carefully considered. Following are some interim conclusions.

The **changing climate in altitude** needs to be taken into consideration when designing a skyscraper. It was clearly demonstrated here that cooling and heating needs change significantly due to the **changing air temperature**, as well as **wind velocity**. This calls for a tailor-made façade detailing per altitude, and affects both **infiltration** and the **potential for ventilation** to achieve thermal comfort and structural cooling, as well as to exhaust pathogens and allergens, and to improve **Indoor Air Quality** (IAQ), which in work environments may have significant impact on productivity. However, the changing wind velocity with altitude also affects the **usability of balconies**, whose design and detailing should address such issues. **Double Skin Façades** (DSF) were shown in this research to have a high potential for energy conservation in the climatic conditions of a hot humid Mediterranean climate and can potentially improve controlled ventilation even at higher altitudes with higher wind velocities. An additional advantage of the DSFs which was not investigated here, yet others have extensively addressed it, are the **acoustic advantages** inherent in DSFs, a very valuable attribute in densifying and noisy cities.

The **microclimatic and air quality impact** of skyscrapers on their urban environment must be further studied to establish **planning and design criteria**. These must address the often violent and dangerous downdrafts and Venturi effect wind patterns, as well as the extensive shadows cast by such building volumes. These may well reverse the changing climate in altitude, shaping wind patterns on the **pedestrian level** which may reach velocities twice as high as those on the skyscraper roof, and air temperatures significantly lower on the shaded pedestrian level than on the sun exposed roof high up, as series of onsite spot measurements undertaken within this research have shown time and again. Thus, **wind protection and solar access on the pedestrian level may become major planning, design and detailing parameters in environmentally responsive usable**

skyscrapers. The interaction of such buildings with their urban environment, in particular its **traffic** volumes and the way these impact air quality, needs to be carefully and extensively studied. Ensuring good air quality with **acceptable levels** of PM10, PM2.5, NOx, SOx and other **pollutants** will improve conditions on the pedestrian level around skyscrapers, and will improve the potential for passively ventilating and cooling them without compromising IAQ. Such issues are currently being studied by this team, keeping in mind that these aspects have an important influence on **public health**, both related to indoor air quality, and how skyscrapers are situated within the neighborhood in terms of people's **access to open spaces and physical activity**, **access to green areas** and the latter's influence on **physical and mental health**, as well as **community organization** leading to **resilience** in times of extreme events and the need for mutual help when centralized services and infrastructures may collapse.

This paper has not addressed the impact of skyscrapers on **land values**, the **high operational and maintenance costs**, the **gentrification** processes shaped by these, or other **socio-behavioral issues** impacted, e.g., socialization, in particular among **toddlers and younger children**, as well as the **elderly** population.

Lastly, the **safety and security** issues related to skyscrapers need to be urgently addressed to avoid injury and even loss of lives in cases of **fire, earthquake, war or terrorist attacks**, all of which have been experienced around the globe.

The question should be asked by planners, architects, engineers, decision makers, public health officers, sociologists and economists, on the **necessity for and sustainability of this building type**, and the appropriate ways to make it more sustainable if indeed it is really necessary, unavoidable.

This team continues its research and study hoping to come up with more insights and invites like-minded colleagues to interface and collaborate towards **developing a more comprehensive and urgently needed framework of the interrelations between skyscrapers and the city.**

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