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Authors: Daniel Safarik, Editor-in-Chief, CTBUH
Will Miranda, Research Coordinator, CTBUH

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# Towards Post-Crisis Tall Buildings and Cities

Daniel Safarik

William Miranda

Authors

**Daniel Safarik,** Editor-in-Chief
**William Miranda,** Research Coordinator
Council on Tall Buildings and Urban Habitat
The Monroe Building
104 South Michigan Avenue, Suite 620
Chicago, Illinois
USA 60603
t: +1 312 283 5599
e: dsafarik@ctbuh.org
ctbuh.org

**Daniel Safarik** is Editor-in-Chief at CTBUH. His responsibilities include representing the Council at events and meetings, selecting and editing research papers, case studies and features for the CTBUH Journal. Safarik has co-authored or co-edited several of the Council's recent technical publications. He served as the Director of the China Office of CTBUH at Tongji University, Shanghai, from 2015 to 2017, spearheading the Council's efforts to expand influence and membership in China. Trained as an architect and a journalist, he was the director of marketing for Brooks + Scarpa Architects (formerly Pugh + Scarpa Architects) from 2008 to 2011. He holds a Master's degree in Architecture from the University of Oregon and a Bachelor's degree in Journalism from Northwestern University.

**William Miranda** is the Research Coordinator at CTBUH, and he contributes to the Council's research studies and data analyses. Originally from upstate New York, Miranda moved to Chicago to receive his Bachelor's in Architecture from the Illinois Institute of Technology. In 2016, he moved to Venice, Italy to provide editorial services and research assistance as a research fellow at the CTBUH Research Office at the IUAV. In 2019, Miranda returned to Chicago and, in addition to his research work, he manages drawings and data featured on the tall building database. Miranda is particularly interested in using data analysis to solve design problems from the human to urban scale.

## Abstract

*The COVID-19 pandemic has caused a massive and sudden rethink of how tall office buildings, and cities as a whole, should operate. With national and local government responses varying widely across the globe, and much about the virus still unknown, it is impossible to generate a single safe operational model for the immediate near term. However, the aggregate knowledge of the building industry can be activated by creating an indicative, general assessment of how today's tall buildings and their cities could be modified. This report collates the advice of the Council on Tall Buildings and Urban Habitat's Expert Peer Review Committee and its database of the global tall building industry, as well as the consultancies and professional organizations in the wider CTBUH orbit, forming a hypothetical model of the potential changes coming to the existing stock of tall office buildings and the cities where they are located, and speculates on the urban implications of extrapolating these changes.*

**Keywords:** COVID-19, HVAC, Pandemics, MEP, Tall Buildings, Vertical Transportation

## Introduction

At the dawn of a new decade, cities around the world are in a state of crisis greater than has been seen in living peacetime memory. In early 2020, the world experienced a pandemic of the coronavirus (COVID-19) on a larger scale than any seen since the influenza pandemic of 1918, radically altering, practically overnight, most of the precepts that make high density and urban life desirable, and pushing the global economy into a recession. In an effort to stem the spread of this deadly virus, much of the global population was placed under movement restrictions of some kind, shuttering mass gatherings and altering vehicular and pedestrian density in major cities around the world. The entire social proposition of cities seems to have been upended and left in a state of suspended animation, including the very premise of commercial real estate (CRE), given the broadly successful transition to home working for many. Until a widely available vaccine is developed, there is no way of predicting with any certainty when or whether urban life can return to "normal," or what the "new normal" will look like. Meanwhile, the crises already afflicting cities: including overpopulation, inequality, and climate change, have not abated. And yet, this is also a time of great opportunity, when bold moves can be made to reconfigure urban life in numerous aspects and unearth new potential.

This is the theme of the 2020 CTBUH Conference, "The Post-Crisis City: Rethinking Sustainable Vertical Urbanism," live-streaming from Singapore, London, and Chicago, across 21 hours on 17 November 2020. It also underscores the research in this special report, and informs the Tall Building in Numbers data study, "The Post-Crisis Tall Building," on page 22. In both this paper and the data study, the authors use a "generic" example tall building with many common attributes, as a means of modeling key alterations to building operations and systems due to public health guidelines.

## Current Macro-Trends

Since the beginning of the outbreak in early 2020, the media reported increasingly dire stories of infection rates, deaths, lockdowns and political squabbling over how to handle the crisis. For certain business segments dependent on large groups of people spending time together, especially retail, hospitality, entertainment, and transportation,

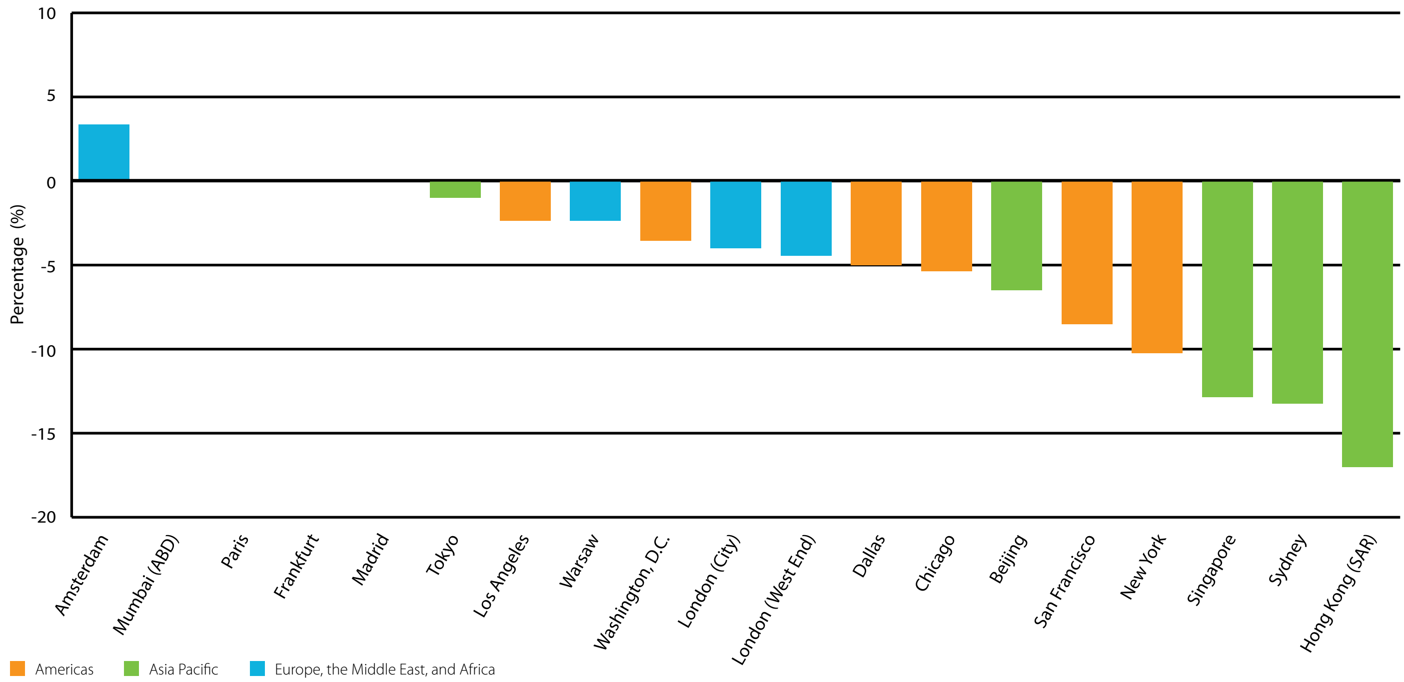


Figure 1. Full calendar-year forecasts for rent growth in the top global office markets for 2020. © CBRE Research, Q2 2020, redrawn by CTBUH

conditions were particularly tough, as public health guidance advised maintaining a "social distance" of at least 2 meters from others in enclosed spaces, or preferably, avoiding contact with others as much as possible. Worldwide gross domestic product (GDP) was expected to be down 5.2 percent for the year, and global commercial real estate volume (the total amount of money invested in commercial real estate) was expected to fall 38 percent from year-end 2019 to year-end 2020 (CBRE 2020). Rents would suffer less of an impact, falling by 3 to 6 percent by year's end in the aggregate, with potential for recovery in 2021, despite major dips in cities such as New York, Singapore and Hong Kong (ibid.)(see Figure 1).

Meanwhile, the traditional model of office life, with commutation in packed trains or on crowded roads to city cores by large groups of people, occupying office buildings five days a week, has been turned on its head in many places. Many office buildings and the service businesses they support have sat vacant for months, while employees increasingly relied on the Internet to work from the relative safety of their homes. This has led to a great deal of reconsideration of what the near- and long-term future of the high-rise office in the central business district (CBD) will be. None of the answers are certain at this stage, of course, but there is a consensus that changes already underway before the crisis are accelerating.

### United States

Office demand was down considerably in most US markets, according to real-estate consultancies CBRE, Colliers and JLL. The common measurement of the strength of commercial real estate markets is net absorption, the sum of area that became physically occupied, minus the sum of area that became physically vacant during a specific period (JLL 2020). According to Colliers (2020), in Q2 2020, US office markets reported net absorption below zero for the first time in 10 years. Of the top 25 US metro office markets, 19 were showing negative absorption rates in Q2 2020, and vacancy rates were as high as 20.5 percent in Houston, where declines in energy demand hit occupiers particularly hard (see Table 1). Not surprisingly, shorter-term lease renewals were also on the rise.

### Asia-Pacific

In Asia-Pacific markets, net office space absorption fell 34 percent from the first half of 2019 to the first half of 2020 to 16.3 million square feet (1.5 million square meters) (CBRE 2020a), the lowest in a decade, with a decline

> "The amount of money invested in commercial real estate globally was expected to fall 38 percent from year-end 2019 to year-end 2020."

to between 30 and 40 percent expected for the full year. Demand was expected to drop by 41 percent in China, with vacancy hitting as high as 30 percent in Shanghai and Shenzhen.

### Europe

Commercial real estate investment volume dipped 39 percent year-on-year in Q2 2020, and was predicted to fall between 30 and 40 percent for the full year 2020. Leasing volume fell 49 percent year-on-year for Q2 2020, to the lowest quarterly total in more than 20 years (CBRE 2020b). Vacancy rates hit as high as 10 percent in Bucharest, Milan and

| Rank | City | Total Inventory [SF (m²)] | YTD Net Absorption [SF (m²)] | Vacancy Rate | Availability Rate | Sublease Rate | Under Construction [SF (m²)] | Class A Asking Rates | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | CBD [per SF (per m²)] | Suburban [per SF (per m²)] |
| 1 | San Francisco | 94,803,023 (8,807,416) | -3,004,410 (-279,116) | 7.70% | 12.70% | 5.30% | 3,552,736 (330,057) | $89.80 ($966.60) | n/a |
| 2 | New York (Manhattan) | 526,139,482 (48,879,551) | -3,375,748 (-313,615) | 5.90% | 10.60% | 2.50% | 14,825,614 (1,377,333) | $85.12 ($916.22) | $85.12 ($916.22) |
| 3 | Boston | 220,468,735 (20,482,045) | -765,944 (-71,158) | 12.90% | 12.90% | 2.10% | 8,831,699 (820,485) | $71.05 ($764.78) | $31.63 ($340.46) |
| 4 | Washington D.C. | 436,234,305 (40,527,156) | 331,722 (30,818) | 15.50% | 19.10% | 0.90% | 8,774,577 (815,178) | $61.03 ($656.92) | $34.21 ($368.23) |
| 5 | San Jose/ Silicon Valley | 106,109,101 (9,857,776) | -1,102,822 (-102,455) | 6.50% | 10.90% | 3.00% | 11,881,078 (1,103,779) | $60.36 ($649.71) | $70.80 ($762.09) |
| 6 | Seattle/ Puget Sound | 145,367,678 (13,504,987) | 1,326,611 (123,245) | 8.00% | 11.40% | 2.50% | 7,711,550 (716,420) | $60.13 ($647.23) | $43.15 ($464.46) |
| 7 | Miami | 99,038,332 (9,200,886) | -873,335 (-81,135) | 9.70% | 14.30% | 1.00% | 3,802,320 (353,244) | $53.62 ($577.16) | $42.51 ($457.57) |
| 8 | Chicago | 311,268,367 (28,917,537) | -343,541 (-31,916) | 15.40% | 17.90% | 0.90% | 6,060,691 (563,052) | $48.12 ($517.96) | $30.75 ($330.99) |
| 9 | Los Angeles | 206,729,400 (19,205,630) | 170,000 (15,793) | 14.40% | 17.90% | 2.40% | 6,604,300 (613,554) | $47.76 ($514.08) | $41.40 ($445.63) |
| 10 | Houston | 224,527,806 (20,859,142) | -781,381 (-72,592) | 20.50% | 22.90% | 1.20% | 4,266,982 (396,412) | $43.84 ($471.89) | $32.24 ($347.03) |

Table 1. The top 10 office markets in the United States, ranked by average asking rents for Class-A space, Q2 2020. Source: Colliers International, redrawn by CTBUH

Moscow, with most major cities expected to see an increase in vacancy of 1 to 2 percentage points, though most would not hit any record highs by year's end.

## Global Demand Outlook

Though many aspects of the current situation are sobering, the virtual cessation of business travel and meetings, and the switch to home working, have provided some time to reflect on the kinds of workplaces we want to build in the near future. Though many CRE occupiers also used this time to consider reducing the space they own and lease, the majority plan to keep their portfolios more or less intact. Theoretically, this means greater reductions in occupant density than footprint. For instance, in the medium-to-long term, 50 percent of Asia-Pacific real estate occupiers said they would not change their total footprint, and 63 percent did not expect to change the number of sites they own or lease (JLL 2020b). Critically, however, the number of workers in a given space at any given time is likely to be reduced. In a survey by CBRE, 61 percent of respondents expected to adopt a more "hybrid" way of working, splitting time between home, flexible spaces, satellite offices and "third spaces" like cafés (CBRE 2020c).

## Building Industry Responses

The critical operative question this raises, of course, is "How should tall building operators adapt their spaces to ensure health and well-being for their occupiers in a pandemic-aware future?" This is the question the authors seek to answer, in general for the global high-rise market, in the remainder of this paper.

## Guidance on Office Occupancy and Density

It is well-established that office densities have been increasing over the past decade, with the rise in open-plan office space and hot-desking driving the average ratio of desks per employee down to less than one in many organizations. In reality, occupant densities can vary significantly, based on the type of business, local norms, and amount of shared space (e.g., conference centers, training rooms, etc). For instance, the Workplace Standards Benchmarking, published by the US General Services Administration and Gensler, surveys workplace standards, space programs, and floor plans from offices across eight industries in the public and private sector. This report notes that call centers average 103.2 usable square feet (9.6 square meters) per person; the legal field uses an average of 335 square feet (31.1 square meters) per person (ibid.). The Architecture/Engineering and Social Services sectors average 168.4 square feet (15.6 square meters) per person and 207.3 square feet (19.2 square meters) per person, respectively (see Figure 2).

In a survey of corporate real estate professionals by CoreNet Global, approximately 68 percent of workplaces in the US were reported to include between 125 and 225 usable square feet (11.6 to 20.9 square meters) per person, with only 19 percent having more and 14 percent having less. The most common range, 23 percent of all respondents, report space of 200 to 225 square feet (18.5 to 20.9 square meters) per person (GSA 2012). The same report cites a prevailing standard workspace average of 200 square feet (18.5 square meters), with a median of 193 square feet (17.9 square meters), as compared to the 190 square-foot (17.7 square-meter) Federal benchmark (GSA 2011) (see Table 2).

In the near future, globally, companies expect to avoid exceeding 50 percent occupancy of their spaces until a vaccine is successfully implemented, as lower density reduces risk of infection. Achieving this may be very difficult for co-working spaces with 5 to 10 square meters per person; the legal sector, with 30 to 35 square meters per person, will find this shift less challenging (JLL 2020a). Presently, restrictions vary enormously from city to city, country to country, and change frequently, making even theoretical space planning very challenging.

### Guidance on Changes to MEP Systems

The most detailed prevailing guidance on mechanical, electrical and plumbing (MEP) systems, and heating, ventilation and air-conditioning (HVAC) comes from professional organizations such as the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), the Chartered Institution of Building Services Engineers (CIBSE), and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA), as well as from engineering professionals on the CTBUH Expert Peer Review Committee.

*Increased Ventilation and Outside Air*

Engineers advise that building operators increase the amount of outdoor air ventilation so as to reduce the amount of recirculated air in the space. In hotter and more humid climates, the struggle will be to keep the space below acceptable temperatures and relative humidity for comfort; in colder climates, the challenge is maintaining a high enough temperature and relative humidity. With winter approaching, ASHRAE has been advocating high efficiency filters, which can approach similar results to 100% outside air over time. The "infectivity" (infectious capability) of viruses is reduced by keeping relative humidity between 40 and 60 percent (ASHRAE 2020).

Careful monitoring of the building's relative humidity is critical and must be considered against the local climate. In colder climates, a 40 percent RH is uncommon when heating systems are in use, as active humidification systems are atypical. In warmer climates, dehumidification systems can be used, as above 60 percent RH can contribute to mold and condensation issues (Jayayerian, 2020).

The combination of humidity and temperature control is effective in increasing the airborne decay rate of the COVID-19 virus. For instance, at 70°F (21°C), a UV index of 0, and 24 percent relative humidity (RH), it takes 63 hours for 90 percent of the virus to decay, while it takes only 100 minutes for the same decay level at 60 percent RH with the other conditions unchanged. Likewise, with UV Index of 0, and constant 40 percent RH, 90 percent of the airborne droplets would decay in 4.25 hours at 68°F (20°C); it would take only 2.5 hours at 76°F (24.4°C) (DHS 2020). In other

| Usable Area per Employee | | Percentage of Companies |
|---|---|---|
| ft² | m² | |
| <75 | 7 | 3% |
| 75–100 | 7–9 | 4% |
| 100–125 | 9–12 | 7% |
| 125–150 | 12–14 | 11% |
| 150–175 | 14–16 | 17% |
| 175–200 | 16–19 | 17% |
| 200–225 | 19–21 | 23% |
| >250 | 23 | 19% |

Table 2. The average net usable area per office employee, based on a survey of 180 companies, with the following distribution: North America, 79%; Europe, Middle East and Africa, 9%; Asia, 7%; Australia and New Zealand, 3%. Source: GSA 2011

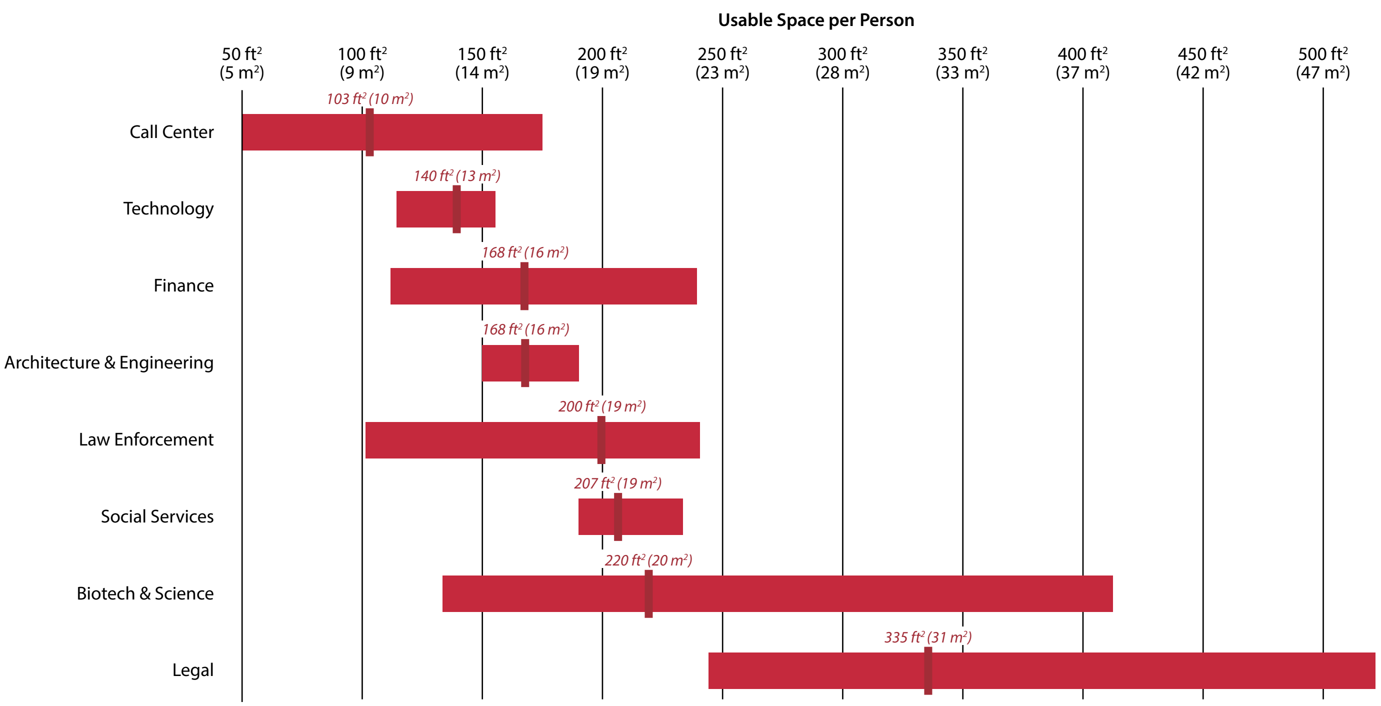


Figure 2. This chart illustrates the average and range of space allocation per person by industry sector, based on a survey by the US General Services Administration and Gensler. Source: GSA 2011, redrawn by CTBUH

words, making offices more humid and hotter than typical set-points could go a long way towards viral spread mitigation.

Importantly, increasing the level of outside air can increase the burden on building systems and the overall energy consumption. For example, increasing the proportion of outside air from 20 to 90 percent doubles the requirement for chilled water and for the amount of coolant coming from the chiller plant (ibid.). Many engineers recommend using HVAC systems with "economizer" capabilities, at least while outdoor conditions are mild, which has more limited impact on the cooling requirement (Jalayerian & Jensen 2020). This is more difficult for a central core building; if there is a floor-by-floor fan room next to an exterior wall, or if the air is from a centralized variable air volume (VAV) system, close to 100 percent outside air can be provided (Leung 2020).

*Improving Filtration*

ASHRAE recommends that mechanical filters be at least minimum efficiency report value (MERV) of 13 or above (ASHRAE 2020). Many existing HVAC systems were installed to operate with MERV 6 or 8 filters. Upgrading filters may require more energy to push air through the filter. While the ASHRAE Journal indicates the pressure difference between MERV 5 and MERV 13 is not significant, care should still be taken to avoid negatively impacting the system's ability to maintain the ideal temperature and humidity settings as described above (Zhang et al. 2020).

The corresponding recommendation from REHVA states: "From the filter replacement perspective, normal maintenance procedures can be used. Clogged filters are not a source of contamination in this context, but they reduce supply airflow, which has a negative effect on reducing indoor contamination levels. Thus, filters must be replaced according to the normal procedures when pressure or time limits are exceeded, or according to scheduled maintenance" (REHVA 2020).

*Flushing*

It is also critical that buildings use their HVAC systems to "flush" the space (with increased ventilation air if feasible) before and after occupancy to help remove contaminants that may linger in the air. ASHRAE (2020) recommends flushing periods of 2 hours before and after occupancy (4 hours total); REHVA (2020) advises "Switch ventilation to nominal speed at least 2 hours before the building usage time, and switch to lower speed 2 hours after the building usage time." During milder outdoor conditions, HVAC systems equipped with economizer operation can provide a higher rate of flushing.

## Guidance on Changes to Vertical Transportation Systems

Elevators are the smallest spaces that office building occupiers will encounter in a typical day, and because of their criticality to movement through tall buildings, social distancing requirements are particularly complex to maintain. Assuming optimal elevator functionality at full building occupancy, and that each car can be filled to approximately 65 percent of its rated load (Elevating Studio 2020), the following basic formula can be used to determine if a building can still function as before with altered population and distancing guidelines:

- Pandemic building population (PBP) = (full building population x elevator car capacity during quarantine) / (0.65 x original load of elevator car)

If the building population exceeds the pandemic building population (PBP), the elevators will not be able to cope with the traffic (Elevating Studio 2020). The average PBP for a fully leased building with a maximum of four people per elevator car is:

- PBP = (4,925 people x 4 people per elevator) / (0.65 x 14 people) = 2,165 (greater than pandemic population, but below normal building population)

For other scenarios, see Table 3. With three or four people able to occupy each elevator car, a building population greater than 25 percent of the full building population can be accommodated. If only two people use an elevator car at a time, only slightly under 25 percent of the normal building population can be accommodated. To mitigate this problem, instituting flexible work schedules can also help reduce the load on the elevator system.

| Office Space | Lease | Normal Building Population | 25% Building Capacity | Maximum Pandemic Population | | |
|---|---|---|---|---|---|---|
| | | | | 2 People per Elevator Car | 3 People per Elevator Car | 4 People per Elevator Car |
| 9 m² per person | Partial Lease | 6,440 | 1,610 | 1,415 | 2,123 | 2,831 |
| 9 m² per person | Full Lease | 7,662 | 1,916 | 1,684 | 2,526 | 3,368 |
| 14 m² per person | Partial Lease | 4,140 | 1,035 | 910 | 1,365 | 1,820 |
| 14 m² per person | Full Lease | 4,925 | 1,231 | 1,082 | 1,624 | 2,165 |
| 18 m² per person | Partial Lease | 3,220 | 805 | 708 | 1,062 | 1,415 |
| 18 m² per person | Full Lease | 3,831 | 958 | 842 | 1,263 | 1,684 |
| 28 m² per person | Partial Lease | 2,070 | 518 | 455 | 682 | 910 |
| 28 m² per person | Full Lease | 2,462 | 616 | 541 | 812 | 1,082 |

Table 3. Recommended maximum pandemic building population (PBP) relative to elevator capacities and restrictions on occupancy. Source: de Jong 2020.
Note: Partial Lease = Area exclusive of corridors and common areas. Full Lease = Area includes entire floor plate to edge of elevators/core.

| Facts | |
|---|---|
| Building Function | Office |
| Structural Material | Reinforced Concrete Core; Steel Columns; Composite Floors |

| Figures | |
|---|---|
| Height: Architectural | 200 m (656 ft) |
| Height: Occupied | To top MEP floor: 177.3 m (582 ft);<br>To top office floor: 173.3 m (569 ft) |
| Floors Above Ground | 43 |
| Floors Below Ground | 1 |
| Gross Floor Area *(Whole Building)* | 103,200 m² (1,110,835 ft²)<br>• MEP: 4,800 m² (51,667 ft²)<br>• Lobby: 2,400 m² (25,833 ft²)<br>• Office: 96,000 m² (1,033,335 ft²) (2,400 m² x 40 floors) |
| Net Internal Area | Core: 480 m² (5,167 ft²) per floor<br>• MEP: 3,448 m² (37, 114 ft²)<br>• Lobby:<br>  • With Retail: 1,016 m² (10,936 ft²)<br>  • Without Retail: 1,724 m² (18,557 ft²)<br>• Office: 68,960 m² (742,279 ft²) (1,724 m² x 40 floors)* |

| Elevators | |
|---|---|
| Core Location | Center |
| Elevator Banks *(3 no.)* | Bank 1: Floors 1–15; Bank 2: Floors 16–28;<br>Bank 3: Floors 29–43 |
| Number of Elevators | 18 (14-passenger rated) |

| HVAC | |
|---|---|
| MEP Location | Floor 15 and Floor 43 |
| Temperature Set Point | 70°F (21°C) |
| Target Average Internal Relative Humidity | 40% |

| Occupancy | |
|---|---|
| Modeled Density | 14 m² (150 ft²) usable space per person |
| Global Average Density *(minus building maintenance and security)* | Office Lease*<br>• 4,925 people (68,960 m² / 14 m² usable space per person) |
| U.S. Average Density *(e.g., average U.S. space)* | Density<br>• 18 m² usable space per person (194 ft²)<br>Office Lease*<br>• 3,831 people (68,960 m² / 18 m² usable space per person) |
| High Density *(e.g., call center)* | Density<br>• 9 m² usable space per person (100 ft²)<br>Office Lease*<br>• 7,662 people (68,960 m² / 9 m² usable space per person) |
| Low Density *(e.g., law offices)* | Density<br>• 28 m² usable space per person (300 ft²)<br>Office Lease*<br>• 2,462 people (68,960 m² / 28 m² usable space per person) |

*Assumes no subdivision of tenant space (i.e., does not factor floors with multiple offices, which may include additional circulation and elevator lobbies).

Table 4. Project data of a "generic" tall office building in a central business district in North America, established to aggregate the collective effects of COVID restrictions on building occupancy. See *Tall Buildings in Numbers*, page 22 for more interpretation. © CTBUH

In an analysis conducted by Alan Taylor of HKA Elevator Consulting (2020), an average 60-story building with a 150,000 square-meter GFA and a population reduced to 25 percent of normal, the average wait time and average time to destination (TTD) for elevator service can actually decrease, compared to pre-pandemic service, if peak arrival times are staggered over 2 hours, instead of 1 hour.

To reach mid-rise floors in an average 60-story office building, there can be an average TTD of 76.4 seconds, with an average 12.7 people per car and a 1-hour peak time; TTD can go down to 52.2 seconds, when only an average 4.5 people ride each car, but peak time is staggered over 2 hours.

Also, passenger ingress and egress must be considered in lobbies, in order to ensure proper social distancing. Vertical transportation systems that utilize destination dispatch, which groups passengers by destination, can help vary the flow into elevators and ensure social distancing can be maintained in lobby queues.

> "At 70°F (21°C), a UV index of 0, and 24 percent relative humidity (RH), it takes 63 hours for 90 percent of the virus to decay, while it takes only 100 minutes for the same decay level at 60 percent RH with the other conditions unchanged."

## Generating the Post-Crisis Tall Office Building Base Model

This research set out to create a "generic," highly representative tall office building such as would be found in the CBD of many major cities throughout the world. The project information, including occupancy, vertical transportation and HVAC systems (see Figure 3 and Table 4) is derived from the CTBUH.org database, and the previously mentioned professional organization advice and research. Multiple municipal occupancy requirements were studied. The authors determined the chances of infection for full building occupancy and buildings following the Chicago Phase IV COVID guidance for commercial buildings, which is limited to 25 percent of full capacity for all indoor spaces (City of Chicago 2020).

The assumptions behind the building are as follows:

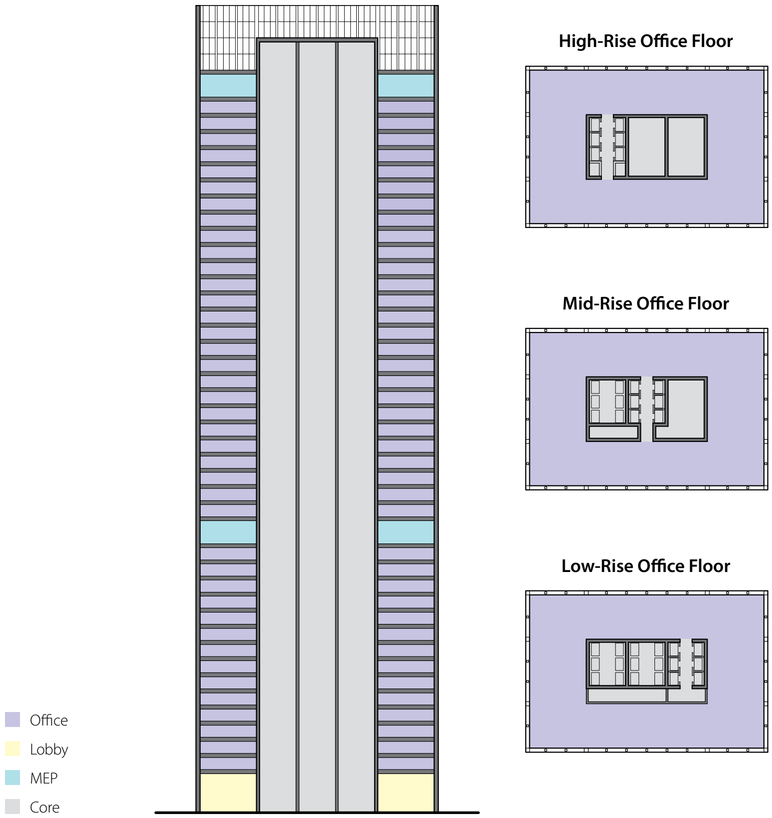


Figure 3. Section drawing and plans of the sample generic building used for the research. There are 18 passenger-rated elevators in three banks, serving floors 1–15, 16–28, 29–43, respectively. MEP floors are located at floors 15 and 43. © CTBUH

> "In an average 60-story building with a 150,000 square-meter GFA and 25 percent of normal occupancy, the average wait time and average time to destination (TTD) for elevator service can actually decrease, compared to pre-pandemic service, if peak arrival times are staggered over 2 hours, instead of 1 hour."

*Age range.* The average lifespan of all buildings listed as "demolished" in the CTBUH database is 41.2 years. As buildings built before 1980 would likely need replacement or major renovation, only buildings built between 1980 and 2020 were analyzed as case studies/references.

*Floor count.* For all tall buildings on the CTBUH database between 150 and 250 meters, the average floor count is 42.4 floors and 1.6 basement levels. From these numbers, the example building was determined to be 43 floors, with an additional basement level.

*Program/functions by floor*. The 43 floors include 40 office floors, two MEP floors, and a lobby (see Figure 3). As noted by Burton (2017), "It is common for a single technical floor to support between 15–20 floors, either above or below its location." Tall office buildings typically use centralized air-handling systems with dedicated mechanical floors serving 15 to 20 occupied floors (Jalayerian 2020).

*Area.* For all tall buildings on the CTBUH database between 150 and 250 meters of height, the average gross floor area (GFA) was about 100,000 square meters (95,324 square meters exactly). This helped determine a GFA for each floor plate in the example building, which was determined to be between 2,325 and 2,500 square meters. Through examination of modern office building floor plans with geographic diversity, it was determined that the core-to-GFA ratio for floor plates would be approximately 1:5. This means that the space that the core would occupy, for each floor plate, would be between 465 and 500 square meters. Example studied buildings included CIBC Square I (Toronto), 22 Bishopsgate (London), Block 16 (Austin), 110 North Wacker (Chicago), 1 Bligh Street (Sydney), Shanghai Wheelock Square (Shanghai), Bund SOHO (Shanghai), and U-Bora Tower (Dubai).

*Population*. With the floor areas of the building determined, the amount of space occupied by each employee could indicate the approximate population of the building. This could in turn inform the load on the building's HVAC and vertical transport systems, based on the guidance cited previously. With this information, it was determined that the average worker in the example building would occupy approximately 14 square meters (150 square feet) of the net internal area of a given floor space. This puts the full building population at approximately 4,900, with some variation, based on whether the office floors include private offices, and whether the floors are subdivided and require additional circulation. Population of the building was calculated for high- and low-density situations (see the "Occupancy" section of Table 4).

## Modifying the Post-Crisis Tall Building Model

With the example building being theoretically placed in Chicago, and taking all of the above assumptions into consideration, the authors then used a COVID-19 Airborne Transmission Tool calculator created at the University of Colorado at Boulder (Jimenez 2020) to develop baseline parameters for the example building. This calculator assumes a social distance of 2 meters (6.6 feet) between people in a workplace setting, and does not account for the transmission rate of droplets through the air across distances shorter than 2 meters.

Among the most important factors are the probability of infection, quanta emission rates, ventilation rates, and breathing rates of the occupants.

### Emission Rate

Examining the emission rates of quanta, which are defined as "an infectious dose of the aerosol pathogen, whose inhalation leads to infection" (Riley, Murphy & Riley 1978), the activity of oral breathing while resting has a 2.0 quanta/hour, while light exercise and normal speaking can be up to 26.3 quanta/hour. For different office functions, this rate can vary. For example, a call center not only includes a higher density of occupants, but also an increased quanta emission rate, as all employees will be speaking for large portions of the day. Even while speaking in a state of resting, this will reach 9.4 quanta/hour.

### Ventilation Rate

The ventilation rate, measured in air changes per hour (ACH), varies by jurisdiction. Chicago ventilation code requires a minimum 4.0 ACH of fresh and recirculated air for offices with ceiling heights of 9 feet (2.7 meters), of which one-third (1.33 ACH) must be fresh air (Jalayerian 2020). This simulation accounts for the 1.33 fresh-air changes per hour only. This is a higher rate than minimum requirements outlined by ANSI/ASHRAE 62.1-2013, which determines minimum fresh air-change rates based off the people outdoor air rate (Rp), area outdoor air rate (Ra), and occupant density. For the example building, with a 3-meter (9.8-feet) ceiling height, the ACH according to ANSI/ASHRAE 62.1-2013 would be approximately 0.66 by default occupancy density for office spaces, and 0.85 at a density of 14 square meters of space per worker (Jimenez 2020). The ACH must be balanced with ventilation effectiveness within the space, and above all, its benefit must be measured with respect to other system improvement, such as filtration, isolation, air economizer application (space air purge capability), energy consumption, and so on. For reference, in an average residential home, ACH can vary from 0.5 to 1.5 with windows closed, and can increase to anywhere from 3 to 15 with windows opened. It is assumed for the purposes of this model that windows cannot be opened.

### Other Simulation Inputs

To simulate the office floor condition, the authors used the general risk estimations from University of Colorado's COVID-19 Airborne Transmission Tool. The scenario involved a 1,500 square-meter office space with 3-meter (9.8 feet) floor-to-ceiling heights, set at 21°C and 40 percent relative humidity, an 8-hour workday, with 261 workdays per year. The ventilation rate adjustments were 0.66, 0.85, and 1.33 ACH, based on the parameters described above.

As of October 2020, for the City of Chicago, the probability that at least one person was already infected with COVID was 28.5 percent within a floor population of 123 people, but this goes down to approximately 8.1 percent with the floors at 25 percent capacity (31 people) (Compass Community Collaborative 2020).

For persons aged 21 to 61, the mean breathing rate ranges from 15.7 to 16.0 cubic meters per day. An average of 15.85 cubic meters per day (or 0.66 cubic meters per hour) was selected, along with a quanta exhalation rate of 6.0.

### Testing and Analysis

Two tests were run, the first to reflect the pre-COVID "normal" operating condition; and the second to reflect COVID restrictions and infection rates for Chicago at the time (see Table 5). In the first test, assuming a 123-person occupancy per floor, with no masks being worn, and MERV 8 filters, there

| Test | Floor Occupancy | Filter Efficiency | Fresh-Air Ventilation Rate (ACH) | Chance of 1 person on floor already infected | Chance of infection per day | Chance of infection per year at same rates | No. of new persons infected per year |
|---|---|---|---|---|---|---|---|
| 1 (unmasked) | 123 (100%) | MERV 8 | 0.66 | 28.5% | 0.08% | 18.86% | 23 |
| 1 (unmasked) | 123 (100%) | MERV 8 | 0.85 | 28.5% | 0.08% | 17.82% | 22 |
| 1 (unmasked) | 123 (100%) | MERV 8 | 1.33 | 28.5% | 0.07% | 15.64% | 19 |
| 2 (masked) | 31 (25%) | MERV 13 | 0.66 | 8.1% | <0.01% | 0.95% | <1 |
| 2 (masked) | 31 (25%) | MERV 13 | 0.85 | 8.1% | <0.01% | 0.92% | <1 |
| 2 (masked) | 31 (25%) | MERV 13 | 1.33 | 8.1% | <0.01% | 0.84% | <1 |

Assumptions:

- Total floor plate area: 1,500 $m^2$
- Ceiling height: 3.0 m (9.8 ft)
- Temperature: 21°C
- Relative humidity: 40%
- Normal floor occupancy: 123 people
- Breathing rate: 15.85 $m^3$/day (or 0.66 $m^3$/h)
- Quanta emission rate: 6.0
- Spread rate ($R_0$): 0.966
- Cook County infection rate: 0.27% of population infected
- Seven-day COVID infection average, Cook County: 877 cases per day

**Table 5. Analysis of potential viral spread on one floor in the example office building, using University of Colorado Boulder COVID-19 Airborne Transmission Tool. Sources: Jimenez 2020; City of Chicago; US Census Bureau**

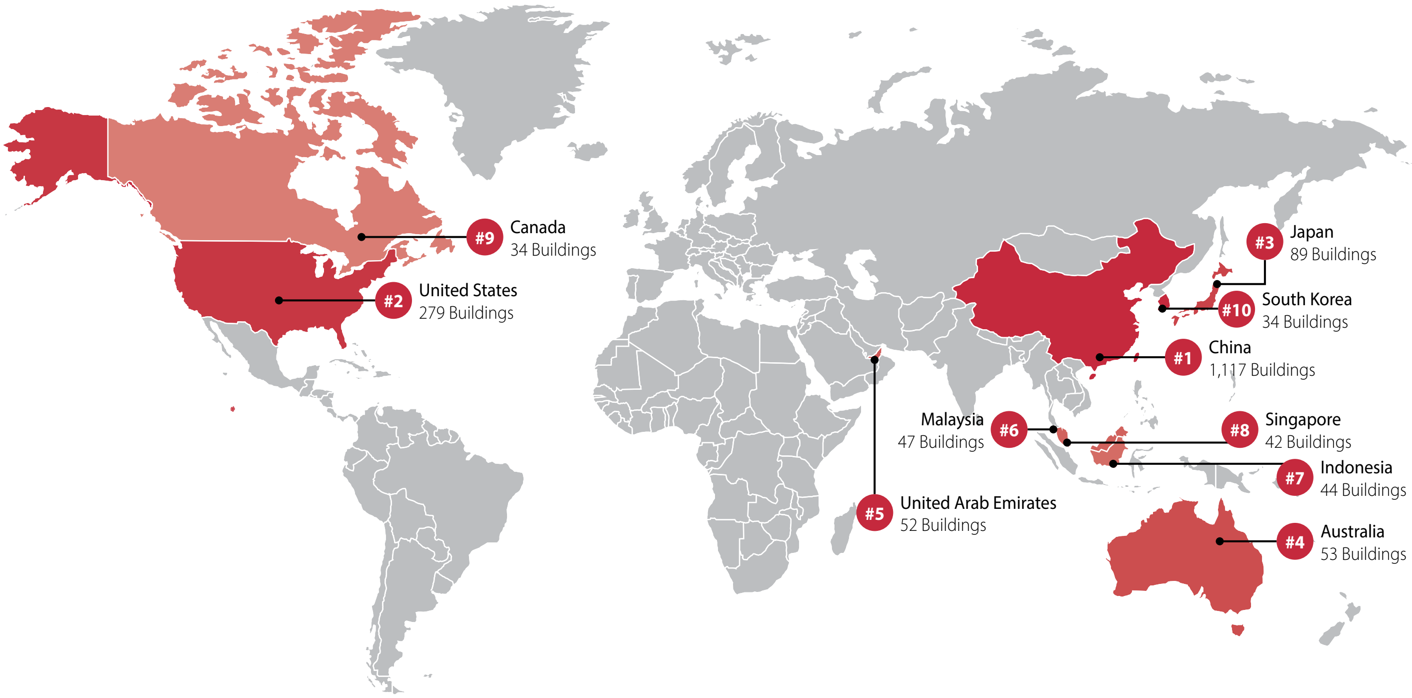


Figure 4. Geographic distribution of all-office buildings 150 meters and higher, worldwide, completed or under construction, since 1980, which could be affected similarly to the generic research case in this paper. Numbers in bubbles indicate country rank in terms of number of buildings for the top 10 countries. © CTBUH

would be a 0.07 percent chance of infection per day at 1.33 ACH. Extrapolated to a full year with micro-bacterial buildup and COVID infection rates remaining level, and without building flushing periods, there would be a 15.64 percent chance of infection (19 people out of 123 per floor) at 1.33 ACH and a 18.86 percent chance (23 people out of 123 per floor) at 0.66 ACH.

The second test assumed the building to be at 25 percent occupancy (31 people on the floor), that all people would continuously wear masks, and that MERV 13 filters are being used. Under these conditions, the chance of infection per day at both 0.66 ACH and 1.33 ACH is below 0.01 percent. Extrapolated to a full year, there would be a 0.84 percent chance of infection at 1.33 ACH and a 0.95 percent chance at 0.56 ACH.

The effects of these adjustments on several key components of the example building can be seen in the accompanying *Tall Buildings in Numbers* data study, page 22.

## Urban Implications

According to the CTBUH tall building database, 2,084 all-office buildings of 150 meters or greater height have been constructed since 1980 or are currently being constructed. The distribution of buildings that could potentially be affected similarly to those attributed to our example building is shown in Figure 4.

The effects of the pandemic will extend beyond individual buildings to entire cities, of course. Public-transit systems have seen ridership and revenues plummet to mere fractions of those seen in normal times, but are obligated to run longer trains and more buses than demand requires, in order to maintain onboard social distancing. The news media are already full of stories of urban dwellers moving to the perceived relative safety of the suburbs, particularly in expensive markets like New York City and San Francisco (Haag 2020), although relatively little hard research has been done on the trend.

A return to the mass suburbanization and sprawl of the latter half of the 20th century is neither desirable nor sustainable, but some preliminary research from Australia suggests more people will work from home than previously, and that this may mean less frequent, but longer, commutes to central offices. It may also simultaneously drive increased sprawl and reinforce the primacy of the largest and most dynamic cities, disadvantaging smaller cities (Lennox 2020).

Then again, there is anecdotal evidence that high-density urban growth in second- or third-tier, more affordable cities, will continue, as considerations about affordability and more breathing room (literally and figuratively) are counterbalanced with the market demand for walkable urban living that has prevailed for the past two decades (Jones 2020). In the US at least, the rising skylines of cities such as Charlotte, Nashville and Austin would seem to support this notion, though these trends, like many others, were already underway before the pandemic. Municipal governments around the world continue to pursue the "15-minute city" concept, the idea being that most daily needs are within a 15-minute walk, bicycle or scooter ride. Once the pandemic hit, many cities took the opportunity of reduced auto traffic and the need for socially-distanced dining to expand restaurants into public streets, reclaiming them for pedestrians and human-scaled activity, to wide acclaim. It remains to be seen if these changes will become permanent.

Likewise, the prevalence of massive parking requirements in many cities may be reduced even sooner than was already the case, if fewer people are routinely commuting to large office buildings. The typical office building today has between 1 and 4 parking spaces per 1,000 square feet (93 square meters) (White 2020). But with the development of ride-sharing services, electric and autonomous vehicles, mobility-as-a-service (MaaS), and technology-driven demand management, the paradigm of treating a parking garage as a system for stacking vehicles may experience effects similar to the paradigm of tall office buildings as an efficient way of stacking people. It is not difficult to imagine a reduction of the need for parking and for road space, and a return to green space (and more breathing room) in cities and suburbs alike, which would change the idea of what "suburban sprawl" and "the urban core" look like altogether.

In short, at this time, it is much more difficult to predict what the "Post-Crisis City" will look like with a reliable, data-driven argument, than it is to provide advice about how existing buildings can be modified to support better health outcomes in the near term. But if it can be accepted that the pandemic is an accelerator of some of the more progressive trends in the urban habitat—with some necessary modifications—there is reason to be optimistic that urban quality of life will improve, and importantly, that cities will be better prepared for the next challenge. ■


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