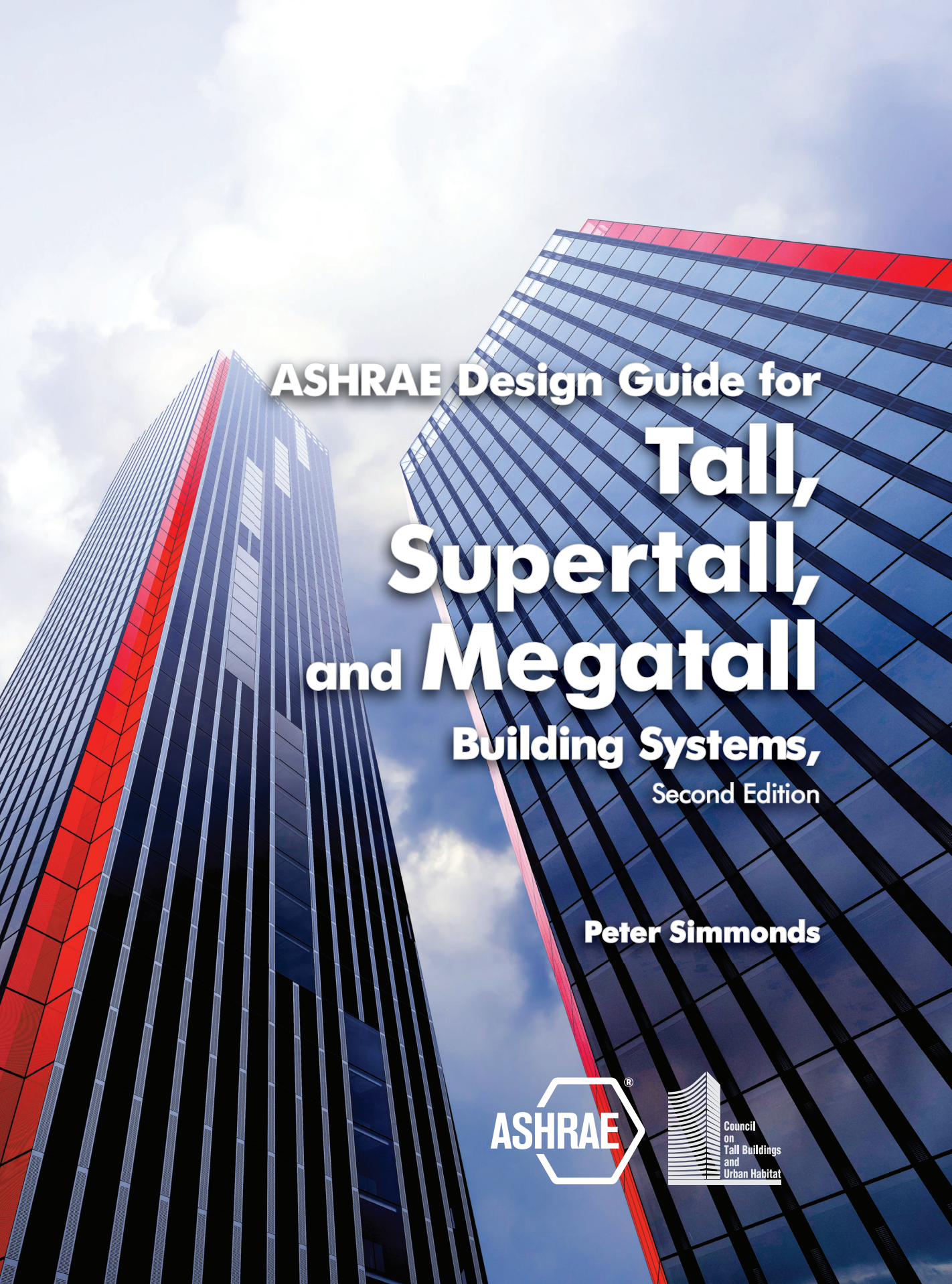


ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems,

Second Edition

Peter Simmonds

ASHRAE®

Council on Tall Buildings and Urban Habitat

ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems, Second Edition

This publication was written under the auspices of ASHRAE Technical Committee (TC) 9.12, Tall Buildings. TC 9.12 is concerned with the function, operation, energy, and human safety for buildings in excess of 300 feet in height. Also included is the determination of requirements related to hydraulics, airflow, infiltration, thermal insulation, water vapor retarders, environmental control, fire and smoke control, and maintenance.

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He has authored or coauthored more than 60 technical papers, articles, and books and is a member of several ASHRAE Technical Committees.



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The Council on Tall Buildings and Urban Habitat (CTBUH) is the world's leading resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities. Founded in 1969 and headquartered at Chicago's historic Monroe Building, the CTBUH is a not-for-profit organization with an Asia Headquarters office at Tongji University, Shanghai; a Research Office at Iuav University, Venice, Italy; and an Academic Office at the Illinois Institute of Technology, Chicago. CTBUH facilitates the exchange of the latest knowledge available on tall buildings around the world through publications, research, events, working groups, web resources, and its extensive network of international representatives. The Council's research department is spearheading the investigation of the next generation of tall buildings by aiding original research on sustainability and key development issues. The Council's free database on tall buildings, The Skyscraper Center, is updated daily with detailed information, images, data, and news. The CTBUH also developed the international standards for measuring tall building height and is recognized as the arbiter for bestowing such designations as "The World's Tallest Building."

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Peter Simmonds

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ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems, Second Edition, is accompanied by online content. These files provide helpful spreadsheets. If the files or information at the link are not accessible, please contact the publisher.



FOREWORD

As the tall building industry moves into a new decade, it is appropriate to stand back and take stock of what we've accomplished, but also to be honest about where we have fallen short. The foreword to the first edition of this book, published in 2015, highlighted the critical issues of tall building design, especially concerning environmental footprint, in terms of both embodied and operational energy. We are duty-bound to continue to reiterate this as our highest priority. The fundamentals have not changed, though there have been some encouraging advances in the intervening five years.

First, let us review what remains the same. As always, architects and engineers determine how program, structure, and services will support each other efficiently. And, in each case, it falls to building services engineers to determine how a spatial arrangement of stacked floors will be ventilated, heated, cooled, and how it will interact with the envelope that surrounds it.

Tall buildings continue to require enormous amounts of energy to move their occupants from floor to floor, exhaust the heat they and their many electronics generate, and provide chilled air or heat to keep conditions comfortable. They require enormous skill and effort to seal envelopes and keep them airtight against the elements and to prevent unpleasant pressure changes as elevators hurtle up and down their lengths.

We are still faced with an overstock of tall buildings constructed following a protocol that dates from the 1950s—seal the building, cover it head-to-toe in glass, and air condition it 24 hours a day. For all of the advanced engineering work that goes into making these astounding structures stand up and function, from an MEP standpoint a large number of them are dinosaurs. For how iconic they are, many of these monoliths are not built for longevity.

It is commonplace to talk about a tall building's design life (or at least those of its critical constituent parts) as being 25, 50, or 100 years. It is particularly discouraging that one of the new "height records" from the past five years is that a tall building of greater than 656 ft (200 m), the Union Carbide/JP Morgan Chase headquarters building in New York, is now being dismantled for the first time. This 1960 office building fit the "dinosaur" paradigm to a tee, but it had been extensively retrofitted twice already, in 1982 and 2011, yet still the owners concluded it needed to be demolished and replaced to meet contemporary needs. We have to do better from the outset if we do not want to see buildings we construct today meet the same fate in 50 years.

Recladding in the conventional sense is enormously expensive and wasteful of materials. We should be designing not for 100 years, but for the ages, and that means designing envelopes and mechanical systems that can be replaced and improved over time as technology improves, or as human tolerance for adverse temperature conditions improves—and probably both.

That's why a design guide like this is so important, as is the practice of updating it with the latest developments in subsequent editions. There is so much research, so much unrealized potential in both passive and active systems—operable façades, dynamic façades, energy-generating

façades, vertically vegetative façades, "breathing" façades, etc.—that embrace, rather than resist, natural environmental conditions. Of course, a solution for a one-story building is not going to work for a 100-story building if it is simply copied upwards 100 times. But the fact that tall buildings do require special engineering in order to achieve the same levels of environmental performance as their shorter peers is not a justification for not attempting it; rather it is a call to action to elevate the practice of tall building engineering to meet this challenge.

One of the more interesting opportunities for super- and megatall buildings is the stratification of climate that exists in any one location with height. Effectively, with the extreme heights now being achieved in tall buildings, we are designing one building that cuts across several climate zones. Significant temperature differences exist between the top of the building and the street level. Tall buildings should be exploiting this for their advantage—cool air is heavier and naturally drops, warm air rises—yet most continue to extrude the same vacuum-sealed façade upwards for hundreds of meters, with all of the energy expenditure that implies. Façades and building systems need to vary with height and reflect the climatic stratification that naturally occurs along their length.

This is already being done, and has been done for more than 20 years—it just hasn't been done nearly often enough. Double-skin façades like that pioneered in the 1997 Commerzbank Tower, Frankfurt, perform as environmental "switches" and provide for natural ventilation, while mediating the indoor temperature to a level that does not require 24/7 conditioning. Newer projects like the Shanghai Tower, with its large atria and communal sky gardens, take this idea to the next level, a social as well as a highly functional series of spaces.

Consider also the potential of those seemingly inexhaustible high-altitude resources—wind and solar. A handful of buildings have attempted to harness the wind and derive energy generation by directing it through sculpted gaps, towards turbines in their masses, and numerous skyscrapers now incorporate solar arrays. However, the implications of capturing wind energy at height have not been fully resolved, and is there the potential for high-rise façades to incorporate solar/thermal technologies, rather than just PV arrays.

Green walls offer a range of benefits, from increased energy efficiency to aesthetic appeal and the reduction of the urban heat island effect. The same exterior vegetation we find charming on low-slung collegiate buildings can also be exploited to great effect at height, providing significant cooling to the façade while blocking glare, enhancing the psychological well being of the occupants, and reducing impact on mechanical systems. Again, this is not a simplistic project of extrusion upwards, but it is being done, in places like One Central Park, Sydney, Oasia Downtown Hotel, Singapore, and the Bosco Verticale, in Milan, Italy.

We've also seen sophisticated mechanical, operable façades that adjust to solar conditions, such as at the Al Bahar towers in Abu Dhabi. Other cutting-edge façades, like the Doha Tower in Qatar, or the Shenzhen Energy Headquarters in China, incorporate historic building techniques to reduce thermal gain and thus improve efficiency. We should be seeing many more of these.

One of the most stunning innovations of recent years is also one of the simplest—a tall building in Tokyo, the NBF Osaki building, uses envirotranspiration to shed heat via rain-filled ceramic pipes that double as *brises-soleil*. In other words, it "sweats," and the microclimate surrounding it benefits from lowered temperatures. Multiply this across a whole city and the urban heat island phenomenon begins to seem less intimidating.

The superlative achievements of tall buildings in terms of height and stability have yet to be fully realized in the MEP department, but they can and must be if tall buildings are to be a positive force in urban environmental sustainability. Five years on from the first edition of this guide, it remains the case that there is much research and hard work ahead of us. Many one-off, bespoke solutions exist around the world, but there are few standardized sets of practices. In the work of our two organizations, ASHRAE and CTBUH, and in the pages before you, lie the bases for building that expertise.

Dr. Antony Wood
CTBUH Chief Executive Officer
Studio Associate Professor, Illinois Institute of Technology, Chicago
Visiting Professor of Tall Buildings, Tongji University, Shanghai

PREFACE

ASHRAE Technical Committee (TC) 9.12, Tall Buildings, has defined a tall building as one whose height is greater than 300 feet (91 m). At the time of the publication of the *HVAC Design Guide for Tall Commercial Buildings* in 2004, there were only about 300 buildings taller than 656 ft (200 m). This number had risen to 600 in 2010, and it was predicted that there would be 765 buildings taller than 656 ft (200 m) in 2012. Since 2004, there has also been an introduction of two new classes of tall buildings (CTBUH 2015):

- Supertall, which are buildings taller than 984 ft (300 m)
- Megatall, which are buildings taller than 2000 ft (600 m)

With the increasing migration of people into cities, tall buildings continue to be in demand. More specifically, at the time this document was going to press there were 1730 buildings already constructed around the world higher than 328 ft (100 m), the ASHRAE definition of a tall building in the previous design guide. 163 buildings have been constructed with designed heights of at least 984 ft (300 m) (CTBUH 2019), and there are 10 buildings either constructed or in design with heights more than 1980 ft (600 m). At press time there are seven buildings proposed with a height of more than 1980 ft (600 m) and 148 proposed with a height of more than 984 ft (300 m)

Tall commercial buildings present a series of design problems that differ from those found in other projects in the built environment. The previous *HVAC Design Guide for Tall Commercial Buildings* provided guidance in both understanding the HVAC design problems of tall commercial office buildings (with heights of 328 ft [100 m] or more) and in detailing their solutions.

This revision will be of interest to owners, architects, structural engineers, mechanical engineers, electrical engineers, firefighters, and other specialized engineers and consultants. The design guide not only focuses on the efforts of designers of the heating, ventilating, and air-conditioning (HVAC) systems, but also addresses the importance of the design team and their collective efforts and concerns that are the critical elements in determining the ultimate solutions to the projected needs of a tall building. This guide addresses design issues for tall commercial buildings, which are very often mixed use, consisting sometimes of low-level retail, office floors, residential floors, and hotel floors. Additionally, the matters discussed and the recommendations and comments that are developed, with various modifications, can be applied to other project types within the built environment. As buildings get taller, there are different climatic effects which vary over the height of a building. The façade becomes important, not only because of the building size, but also because of how it responds to ambient con-

ditions and contributes to the building's heating and cooling loads. The façade also contributes to daylight harvesting.

Additionally, building intelligence presents a significant impact on tall building operation; how do the different building systems talk to each other and optimize their usage? What intelligence is provided for tenants? This is addressed in this guide.

Reflecting the addition of these subjects and the coverage of the newer classes of tall buildings, this new work is now the second edition of *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems*.



Figure P.1 A tall building more than 984 ft (300 m) in height.

ACKNOWLEDGMENTS

This updated design guide would not have been possible without a whole army of experts who have generously contributed in one way or another.

First, there is ASHRAE Technical Committee 9.12, chaired by Luke Leung, who master-minded the revision and production of this design guide.

Second, we have a list of experts that really reads like who's who in tall, megatall and supertall buildings around the world:

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The primary author of the second edition of *ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems* was Peter Simmonds of Building and Systems Analytics, LLC. The first edition was supported by ASHRAE Research Project RP-1673.

CHAPTER 1
Introduction

INTRODUCTION

ASHRAE Design Guide for Tall, Supertall, and Megatall Building Systems was first published five years ago. It provided design information for tall (more than 300 ft [91 m] high) buildings and was written specifically for commercial buildings. The three current classifications of tall buildings are:

- Tall, more than 328 ft (100 m)
- Supertall, more than 984 ft (300 m)
- Megatall, more than 2000 ft (600 m)

A great deal has happened in the years since the first edition was published. Two megatall buildings are under construction, joining 86 constructed supertall buildings, 27 supertall buildings that have been architecturally topped out, and 44 supertall buildings that have been structurally topped out since 2015 (CTBUH 2019). There are also 97 tall, supertall, or megatall buildings under construction, and one proposed (see Figures 1.1 and 1.2). In this revised guide, we will only refer to *tall buildings*, but these include tall, supertall, and megatall buildings. Where there are any specific differences between tall, supertall, and megatall buildings, they will be fully described.

This book is accompanied by online content. These files provide helpful spreadsheets. If the files or informa-tion at the link are not accessible, please contact the publisher.

The use of tall buildings has also changed in the last five years (see Figure 1.3). While the original design guide was specific to commercial buildings (office buildings), a modern-day tall building has many different functions. Many are "mixed use," where at ground level there may be retail and food and beverage space, the first section of the building may be commercial and/or offices, the second section may be residential, and the lucrative high-level section a hotel. Tall buildings are now not only taller but have many different functions and different code requirements. With specifics such as life safety, we sometimes venture into unknown territory.

The goals for this revision, based on discussions with some of the world's leading experts on HVAC designs for tall buildings, include the following aspects:

1. **The effect of ambient air temperature over the height of buildings, especially supertall and megatall buildings.** The ambient climatic conditions vary with altitude, and these changes in ambient conditions can seriously affect load calculations and performance of supertall and megatall buildings.

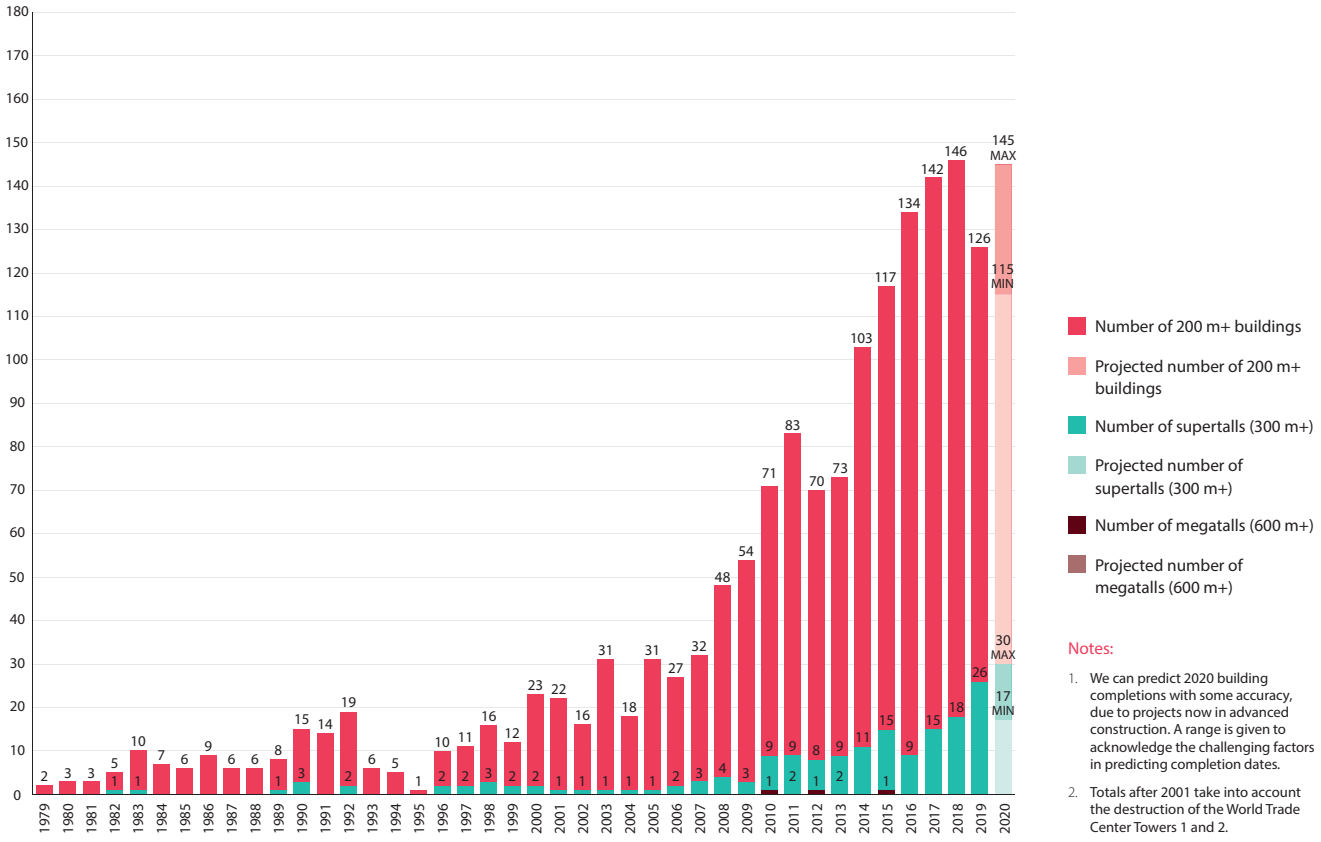


Figure 1.1 Increase in tall building construction from 1960 to 2019.

2. **Façades for tall buildings, leakage rates, and pressure resistance.** As the façade dimensions increase in proportion to the building's height, so too do the requirements for limiting leakage rates and increasing pressure resistance of façades.
3. **Natural ventilation for tall buildings.** There have been frequent requests for spaces to be naturally ventilated during recent years. Ambient conditions at higher levels are often complicated, and therefore natural ventilation design becomes critical.
4. **Energy calculations and consumption for tall buildings.** Nearly all new buildings are required to comply with some level of U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED®) green building certification program. Many building codes require compliance with an energy code, in many cases based on ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, and therefore the energy performance calculations become critical. The newly harmonized International Green Construction Code (IgCC) and ASHRAE Standard 189.1 will also be referenced in the future (ICC 2018).
5. **Revised stack effect calculations for tall buildings.** As buildings become taller, the calculation and impact of stack effects become more critical.
6. **Green/sustainable tall buildings.** With both ASHRAE and the AIA issuing challenges for buildings to be net zero, the sustainability of tall buildings becomes more critical.
7. **Present-day trends in tall building HVAC systems, such as active beams and variable-refrigerant-flow (VRV) systems.**

This second edition provides information on the following aspects of tall building designs:

- Chapter 2, Architectural Design, does not address the aesthetics of buildings but does discuss possible core layouts and emergency egress routes and refuge floors from an architectural perspective. Floor efficiencies are also outlined.

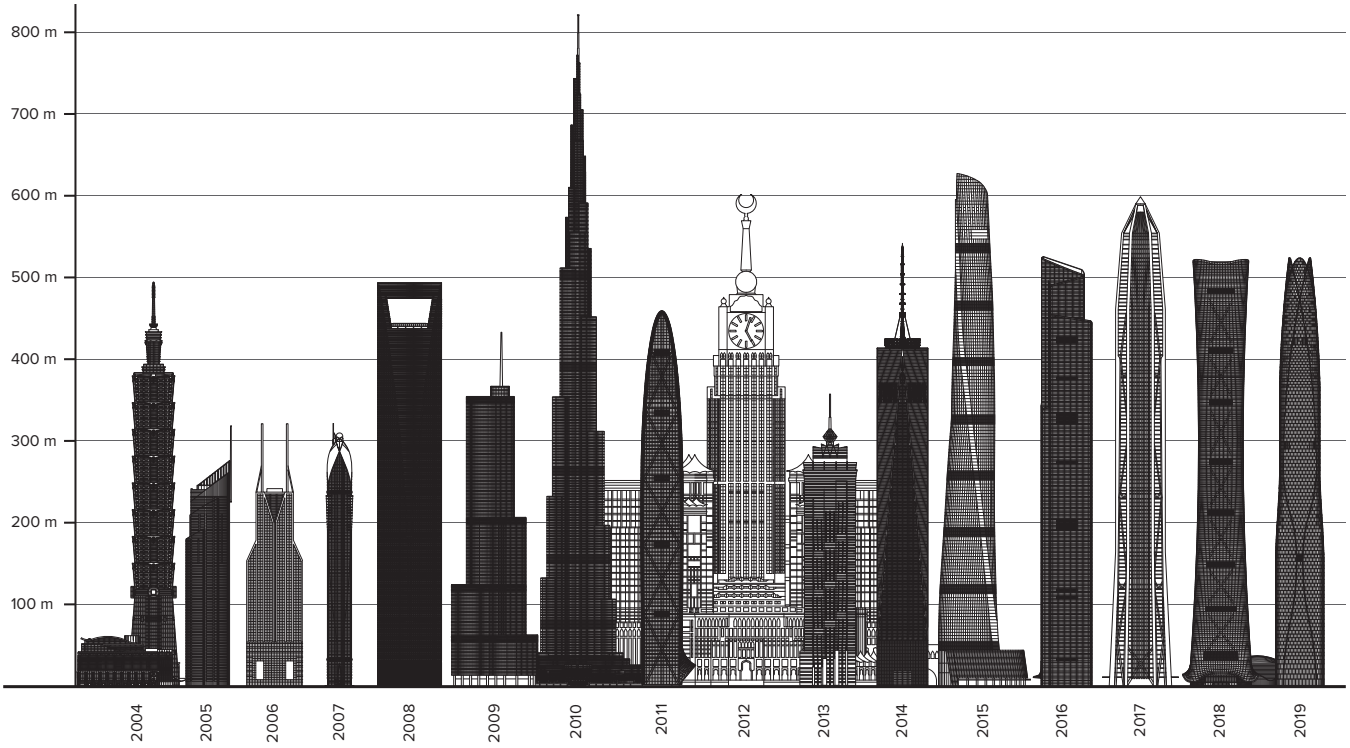


Figure 1.2 The world's tallest buildings completed by 2019.

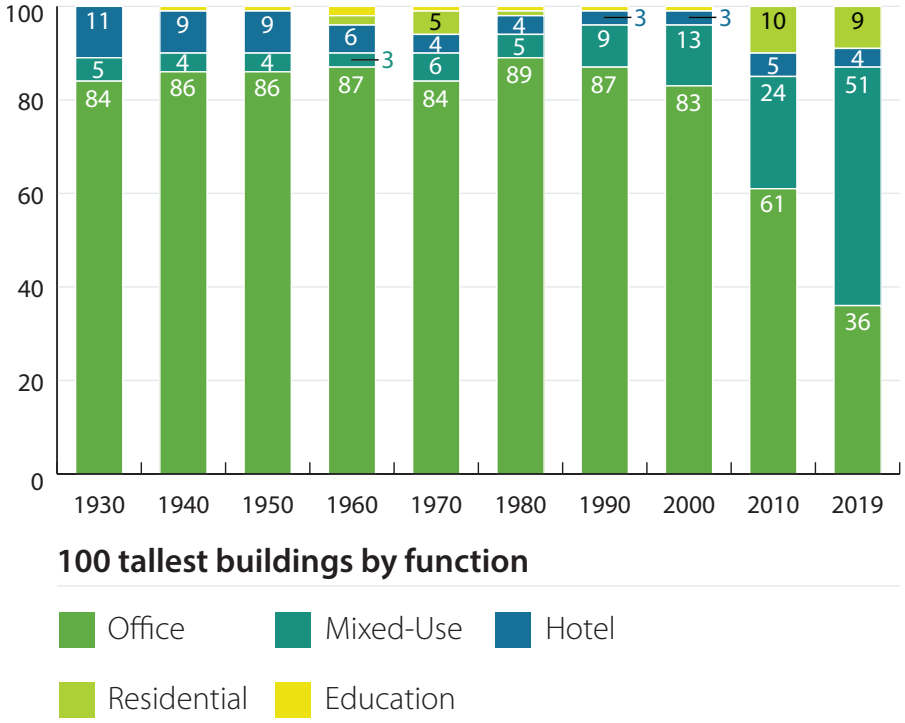


Figure 1.3 The world's 100 tallest buildings by function.

- Chapter 3, Climate Data, reviews different aspects of climatic data vertically over the height of a building.
- Chapter 4, Façade Systems, does not cover any structural engineering but does provide information on interpreting present-day energy codes that present some stringent challenges for tall buildings, and includes leakage rates and pressure resistance.
- Chapter 5, Stack Effect, is now a separate chapter including many new advances in stack effect calculations.
- Chapter 6, Heating and Cooling Loads, is a new chapter including vertical climate data.
- Chapter 7, Indoor Air Quality and Thermal Comfort, provides guidance on required ventilation aspects of tall buildings, especially when investigating the possibility of naturally ventilating residential and even office spaces. The thermal comfort of occupants is also important, not only because of the large number of occupants in these buildings but also in evaluating glazing and the mean radiant temperature (MRT) near it, specific HVAC systems, and the application of natural ventilation when assessing occupant comfort by the adaptive comfort method.
- Chapter 8, HVAC Systems, presents and traditional systems and some newer trends such as radiant systems and active and passive beams.
- Chapter 9, Central Mechanical Equipment, discusses essential mechanical, electrical, and IT equipment rooms.
- Chapter 10, Central Heating and Cooling, presents new specifics on traditional central plants.
- Chapter 11, Water Distribution Systems, has been revised to include specifics for modern-day tall buildings of heights over 2000 ft (600 m).
- Chapter 12, Energy Modeling and Authentication, is a revised chapter and provides information on how to model tall buildings and their systems and, most importantly, how to authenticate the proposed energy usage.
- Chapter 13, Vertical Transportation, outlines the dramatic improvement in this area over the last 15 years, not only because of the different building types in tall buildings but also because of improvements in elevator technology and the logistics of people movement
- Chapter 14, Plumbing Systems, includes information on traditional plumbing systems and also specifics such as gray and black water systems.
- Chapter 15, Life Safety Systems, contains new code requirements and solutions for life safety systems in tall buildings.
- Chapter 16, High-Rise Residential, is a new chapter with specifics for residential spaces in tall buildings.
- Chapter 17, Electrical System Interfaces, deals with difference between the landlord's electrical supply and tenants' electrical supply as well as the diverse requirements for standby power in a modern-day tall building and electrical distribution.
- Chapter 18, Intelligent Building and Controls, is a revised chapter that presents some of the many requirements of modern-day tall buildings and includes smart systems.

The design of any tall building is the result of the collaborative effort of owners, architects, structural engineers, mechanical and electrical engineers, and other specialized engineers and consultants.

Every building is a product of its location, the time during which the building is designed and erected, and the specific client for whom the building is being constructed. Although a building is constructed of multiple commercially available products, how these products are assembled will differ in its completed state. Accordingly, every building will usually differ in many ways from other buildings regardless of apparent similarities.

This design guide addresses design issues for tall commercial office buildings, but the matters discussed and the recommendations and comments that are developed, with various modifications, frequently can be applied to other project types within the built environment. This is particularly true in the matters discussed in the General Overview section of this chapter. However, it is necessary to cover these matters to lay the groundwork for matters discussed



Figure 1.4 The Burj Khalifa, the current tallest structure in the world.

subsequently in this design guide, many of which are more exclusively applicable to the tall commercial office building.

GENERAL OVERVIEW

The design of mechanical and electrical systems for large commercial office buildings is a continually evolving art form that progressively responds to the local market economic and political concerns, the space utilization needs and requirements of the specific user who will occupy the building, and the building's geographic location.

The techniques and design alternatives for a tall commercial office building, because of its inherent size, physical location in major urban areas, and typically sophisticated group of owners, occupants, architects and engineering designers, are subject to a particularly intense response to the complex requirements of any building. The HVAC design engineer, as a significant member of the design team, must complete the design with due consideration of first cost, operating expense for the completed building, the present and future needs of the building occupants, the resiliency of the building, as well as environmental issues and the conservation of energy, regardless of source, in the completed project. The architectural profession responds to the same pressures, but, in addition, is subject to the requirement to create buildings that are attractive to the public at large, the real estate industry, and, most importantly, the owner of the building.

The purpose of mechanical and electrical systems in commercial office buildings has not changed, in any fundamental sense, over the history of the construction of buildings used for

such occupancy. Clearly, the primary purpose of these systems was and is to provide space in the building that will permit the occupants to conduct their business in a productive, comfortable, and safe atmosphere.

In addition to the important advent of air conditioning, a series of changes have significantly modified the basis of the design of the air-conditioning systems for the tall commercial office building.

These changes include the following:

- The evolution of energy-conserving building designs that consume significantly less energy than energy code requirements.
- Expanding and changing zoning and building codes, which have impacted the architectural designs of buildings, the internal energy systems that can be used in buildings, and the enlarged life safety systems mandated to protect both the occupants and the contents of the building.
- The changing real estate market, particularly in the area of developer buildings (as contrasted with owner-occupied buildings). Potential tenants have become more knowledgeable and demanding with regard to the various proposed solutions capable of meeting their perceived needs.
- The altered utilization of buildings, largely driven by the personal computer and alternative telecommunication systems.
- The availability of new or modified air-conditioning designs and the commercially manufactured equipment to allow an altered response to the needs of buildings.



Figure 1.5 A rendering of a 2000 ft (600 m) high tower.

- Resiliency in tall buildings as occupants may stay in the building for a prolonged period.
- Finally, and of major impact, the recognition of the design profession that buildings must respond to environmental and green building concerns including, but not limited to, energy conservation as an end unto itself, indoor air quality (IAQ), sustainable design considerations, and new technology that will better address the global environment of both the present and the future (Figure 1.6).

This is a significant list of altered perceptions and design requirements to which the design community must respond. Nowhere is it of greater import than to the HVAC design professionals who are responsible for the documents that define the basis of the installations that are provided for any large commercial office building. How that response is determined and framed is a matter that must be given the full focus and the intellect of the HVAC designer of tall buildings, regardless of the location of the building.

Building Codes and Standards for Tall Buildings

The relevance of these codes and standards to this design guide is that they all invoke specific design requirements as a result of their definition of a tall building. This includes all codes and relevant standards, not just the model codes. The design of any building must respond to the requirements of the code that is applicable for the building and to the interpretation of that code by the local authority having jurisdiction over the project. All codes affect the design of any building in that they mandate specific design responses to environmental conditions such as solar heat gain, building envelope thermal opaqueness, air transport efficiency criteria, and pipe and duct insulation performance. They also detail the project seismic requirements for all building equipment with specific emphasis on life safety equipment, including the need for restraint of the sprinkler piping, emergency generators, and fire pumps. The codes address the

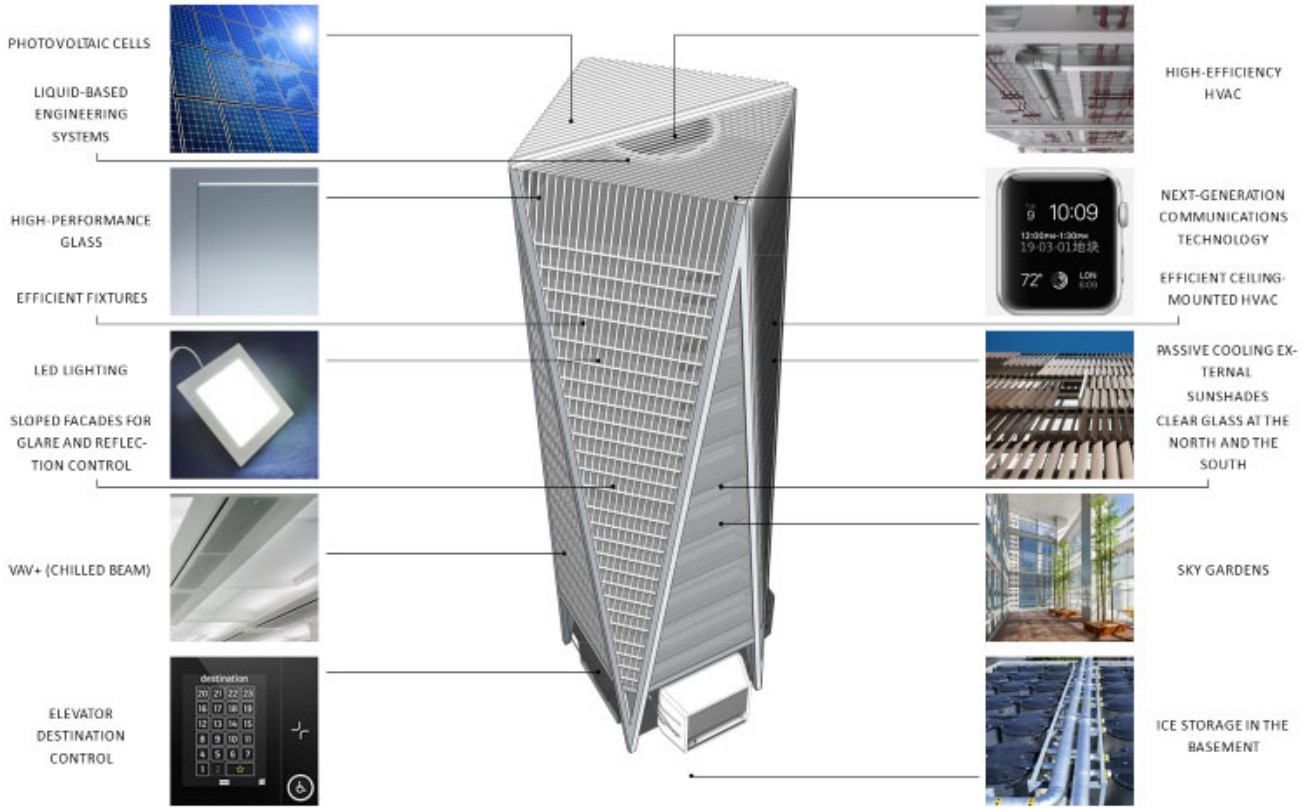


Figure 1.6 Various sustainable systems that can be applied to tall, supertall, and megatall buildings.

tall commercial building in detail regarding smoke management needs and the venting of elevator shafts. Many of these matters are discussed in more detail by topic in later chapters of this design guide.

ENERGY STRATEGIES

The fundamental strategy is to minimize energy usage, resource consumption, and plant space. Several factors affect this strategy, including the following:

- Minimization of solar energy gain to occupied areas through the façade/envelope
- Use of daylight to minimize lighting, and reduction of lighting when levels rise above the required level
- Maximizing re-use of 60% or more of the building energy use
- Minimize fan and pump energy use, possibly by floor-by-floor service
- Utilization, if possible, of wind-driven ventilation and cooling, as well as passive technologies.
- Low-energy terminal devices on occupied floors
- Allowing indoor temperature and humidity to fluctuate within comfort limits

We first propose a framework for understanding the energy consumption differences between tall and low-rise buildings. This framework is then mapped onto city-wide energy consumption data from New York City to discuss differences between tall and low-rise buildings. Finally, correlations between the data and framework are highlighted as well as additional noteworthy trends.