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Designing High Performance MEP Systems for Supertall Buildings: A Review of Challenges and Opportunities

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Abstract

The design and construction of supertall buildings has grown dramatically in recent years. This area of practice has traditionally fallen within the purview of a very small group of architects and engineers, but this is rapidly changing, as unprecedented growth and densification has spread to markets not traditionally known for high rise construction. The design community has been increasingly committed to the adoption of green and sustainable design, and the integration of smarter, cleaner technologies across the building spectrum. This paper examines current supertall design trends, and suggests that recently completed and planned projects are trending towards more sustainable solutions, and that a unique set of best practices are emerging specific to Supertalls.

Keywords: Supertall, Sustainability, MEP systems, Distributed generation, Smart city

1. Introduction

Supertall buildings are truly unique, and frequently exhibit the characteristics of a small university or health-care campus in the complexity of their centralized utilities, systems distribution and controls strategies. Aside from the substantive impact on city skylines for generations to come, supertalls impact their surrounding environment through, access to sunlight, views, local microclimate and the overall character of the neighborhoods in which they are built.

Supertalls are often viewed as symbols of economic progress and prosperity, and a pathway to economic growth and maturity. As the population of our planet continues to grow, it is anticipated that urban centers will increase in density, with continued economic growth, and a corres-ponding further demand for these slender and massive structures. Buildings of the scale and importance of the typical supertall represent a sizeable investment, encourag-ing the pursuit of sustainable design certifications, such as; LEED, BREEAM, WELL Building, while often exploring the potential for Living Building and Passive House Certi-fication. The formal process of certification introduces a degree of structure and rigor with environmental design and contractor engagement, but fails to provide guidance for designers who seek to navigate the unique design challenges encountered with supertall buildings.

Building energy benchmarking, corporate social respon-sibility, and transparency statutes have become the norm in many countries around the world, and have placed a spotlight on the previously uncharted environmental imp-acts of large commercial buildings. The release of energy benchmarking data provides unprecedented access to a building's operating efficiency data, information to pros-pective tenants on utility expense, insights for buyers concerning potential deferred maintenance and system renewal requirements, and a comparative performance metric to building owners engaged in the highly compe-titive world of commercial real estate. Typical energy benchmarking ordinances enacted thus far across the Uni-ted States have focused on larger, high density buildings in downtown markets. Chicago's energy benchmarking ordinance when first introduced in 2014 targeted larger buildings with areas greater than 23,000 m^2 (250,000 sf) before widening the inclusion criteria to 4,600 m^2 (50,000 sf) and varying program types after several years (Chicago, 2014).

As a result, prominent, high visibility supertalls have been at the forefront of the benchmarking process, with their energy performance data in full view for the world to see.

This high visibility demands that those involved in the planning, design and development of supertalls be fully aware of the challenges that exist in this building typo-logy, and of the opportunities available to dramatically enhance performance through a deeper understanding of the role that Mechanical, Electrical, Plumbing & Fire Pro-tection (MEP/FP) engineering systems play in the fulfill-ment of the owner's project objectives, the support of an architectural vision, and the realization of a project within budget.

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2. The Challenge

The landmark United Nations agreement on Climate Change (UNFCCC, 2016) set the course for the majority of world's carbon dioxide producer to address emissions in a structured and aggressive manner, with the goal of limiting global temperature rise below 2 degrees Celsius by the end of this century. In many parts of the world, these requirements will be satisfied in part through building codes. Codes play an important role in stabilizing carbon emissions from new buildings, while related regulatory, voluntary or market driven initiatives will fuel increased efficiencies in the existing building sector. In this vein, a large community of architects, planners, municipalities and corporations around the world have voluntarily adopted "The 2030 Challenge" (2030Challenge, n.d.), a pledge to design all new and major renovation projects to be carbon neutral by the year 2030. Supertall buildings will be expected to comply with this protocol.

2.1. Stacking

The design of complex, supertall buildings requires an MEP/FP engineer to work collaboratively with the architect and vertical transportation consultant to organize the building into independent, vertically stacked zones, frequently reflecting the functional occupancies found in a mixed-use building. These vertical zones facilitate the organization of MEP/FP equipment into manageable capacities and working pressures that can be constructed and operated efficiently. The first step in the realization of a highly sustainable supertall building is the planning of MEP equipment rooms and vertical riser pathways, in close coordination with the project architect and structural engineer. Dedicated Technical floors establish vertical zones extending up the height of the tower. These floors can be single height, serving a single zone immediately above or below; double height, serving zones above and below, or even triple height with a mezzanine to accommodate oversize equipment including air handlers, electrical transformers and water storage tanks. Technical floor planning typically includes accommodation of structural and architectural elements, including outriggers, belt trusses and transfer systems, elevators, sky lobbies and life safety areas of refuge.

Consider the design for the 116 story, Chengdu Tower supertall building illustrated below. This building includes 10 distinct MEP/FP vertical zones and 5 corresponding technical zones that serve them. In this project, there are 3 technical floors per technical zone.

2.2. Mechanical Systems

It is common for a single technical floor to support between 15-20 floors, either above or below its location. Technical floor spacing beyond these parameters will increase losses from friction and gravity forces, which diminish energy performance and give rise to ongoing operation and maintenance issues.

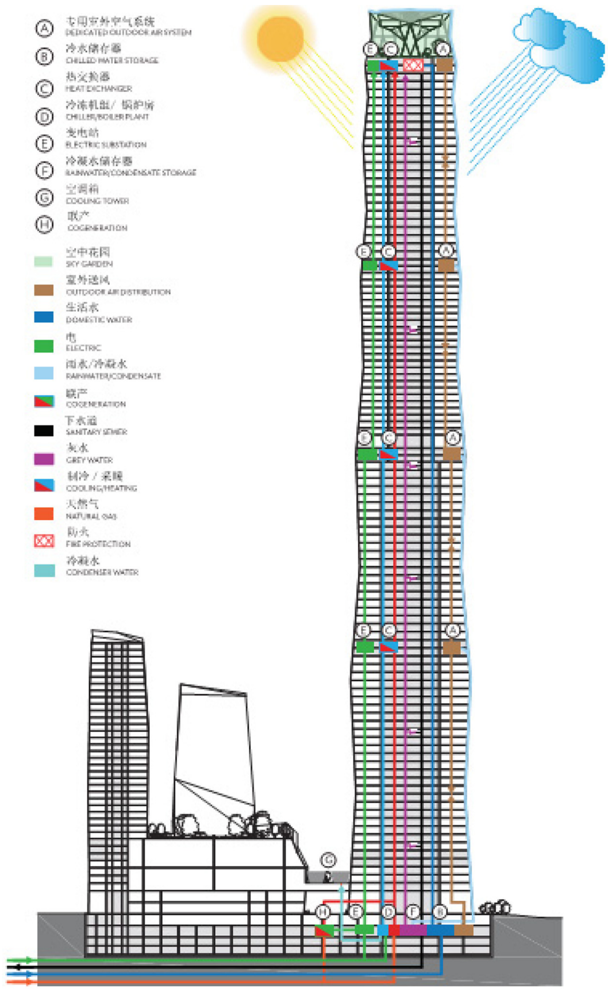

Figure 1. Greenland Tower, Chengdu.

Outdoor ventilation is introduced into technical floors via outdoor air louvers, and distributed within the core of the building at each floor, where it is supplied to occupied spaces. In residential and hospitality buildings, ventilation is supplied either via vertical shafts located in each living unit or corridors, and is coordinated with exhaust shaft requirements for bathrooms, kitchens, and laundries.

The opportunity for energy recovery from these exhaust air streams is maximized by locating air handling units alongside exhaust fans to facilitate the installation of an enthalpy wheel between the intake and exhaust airstreams. This can be achieved by stacking fans on top of one another or side by side. For supertall buildings, this fan placement can pose height clearance or floor space challenges within constrained technical floors. Sufficient space is required to ensure that outdoor air and exhaust louvers are placed on the exterior of the building with sufficient separation to avoid the cross-contamination of intake and exhaust air streams. A triple height technical floor configuration (or two adjacent 1.5X height floors) can normally achieve this.

2.3. Environmental Properties of Air

A major objective of mechanical ventilation systems in supertall buildings is the controlling air movement in and out of the building envelope, to properly control temperature, humidity, air speed, building air pressurization, and outdoor air quantities. Typically, centralized air handlers are located on technical floors, distributing outdoor air to floors below or above through ductwork installed within vertical shafts.

Supertall buildings are subjected to significant variation in the properties of air over the height of the building, including; temperature, wind speed and direction, air density and potentially air quality (Lstiburek, 2014).

Known as the lapse rate, the outdoor temperature (degrees Celsius Dry Bulb) can drop 6.5 degrees Celsius per km of elevation above grade. For a supertall building, this can result in a multiple design conditions across the different technical zones of the tower, as outdoor air is introduced. A particularly attentive design engineer might ask the question weather this variation in design conditions can reduce energy consumption for selected occupancy types within the building with the addition of air side economizer capability or operable windows.

Wind speeds at grade are typically impeded by surface friction or low-rise obstructions from surrounding buildings and vegetation. At heights above 300 meters, wind speeds are increasingly laminar and consequently much higher in velocity. This phenomenon can affect the placement of outdoor air intakes, exhaust louvers and cooling towers that all are designed around “prevailing” wind speeds (typically specifed 10 meters above ground at a local weather station). Adjusting “standard” design criteria for elevation is a key aspect of designing supertall buildings sometimes overlooked (Burton, 2015).

These physical properties pose major challenges unique to supertalls, but offer creative opportunities for enhanced sustainable design.

2.4. Stack Effect

A principal concern in the design of supertall buildings is the occurrence of stack effect. Stack effect manifests itself in the bulk movement of buoyancy driven air flow, creating issues with door closing at the base of the tower, uncontrolled moisture ingress, excessive noise, discomfort and difficulty in controlling temperature from airflow through elevator lobbies.

Stack effect occurs in two modes, driven by the natural buoyancy of air, and the relative difference in the properties of indoor and outdoor air (Simmonds, 2015). During the heating season, indoor air rises upward across what is referred to as the neutral plane, creating a negative pressure at the base of the tower, and drawing cold air in through lobbies and out of the top floors of the building. The effect is reversed during the cooling season, with cool

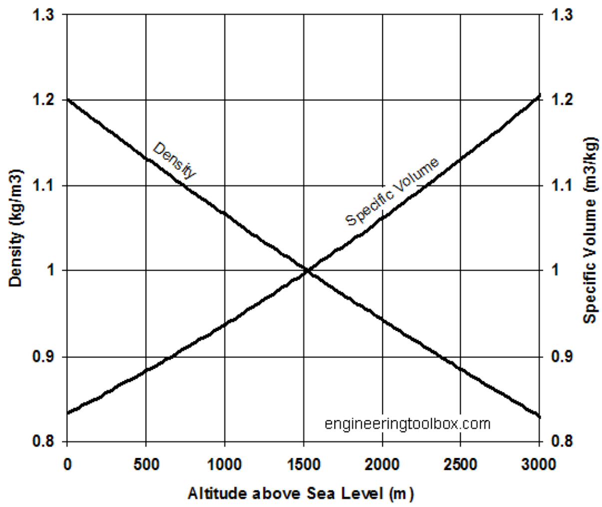

Figure 2. Properties of Air.

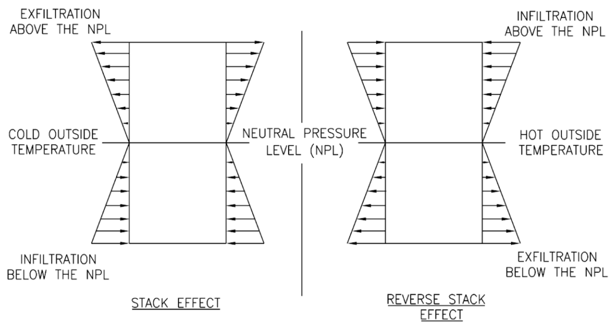

Figure 3. Stack Effect.

air dropping inside of the building, spilling out of the base of the tower, and resulting in uneven cooling loads along the height of the tower, if left uncontrolled. Because all air that crosses the thermal envelope of a building is subjected to heating and cooling requirements as controlled by the buildings thermostats, results in wasted energy.

Building stacking and the separation of Mechanical systems into smaller segments are key strategies employed to minimize the pressure difference along the height of tall shafts. The design of independent mechanical systems to pressurize elevator vestibules is critical to balancing the pressure differences in elevator shafts from elevator movements, improving the overall energy performance and functionality of a supertall.

Operable windows, balcony doors, vestibules and rooftop amenities pose major challenges with stack effect and the energy efficiency in a supertall, but can be accommodated successfully by adhering to basic principles of isolation and control. The (CTBUH, 2012) provides additional guidance on this topic.

While stack effect is commonly viewed as a naturally occurring force that needs to be controlled and minimized,

Figure 4. Dancing Dragons, Yongsan South Korea, Copyright AS+GG.

there have been effort in recent years to harness the energy potential for productive work.

Stack effect can be used to naturally exhaust accumulated heat gain in a large volume space, such as an atrium. An alternative strategy is the enhancement of natural ventilation in occupied spaces, providing passive cooling during periods of favorable outdoor air conditions. A recent design for a pair of supertall residential towers in the Yongsan District of Seoul, Korea (Gill, 2017) proposed an external "stack effect shaft", enhancing available natural airflow. The design enabled residents to cross ventilate their apartments through the use a naturally ventilated mullion system with a connected "stack effect shaft" which collected exhaust air from multiple units on a floor. The external shafts are subjected to solar gain which raises the buoyancy effect and corresponding air movement, a common practice in the design of low rise passive solar buildings.

For moderate climates found in western or northern Europe, these and other types of creative strategies can preclude the need for mechanically derived air conditioning year-round, a major first cost savings to the project.

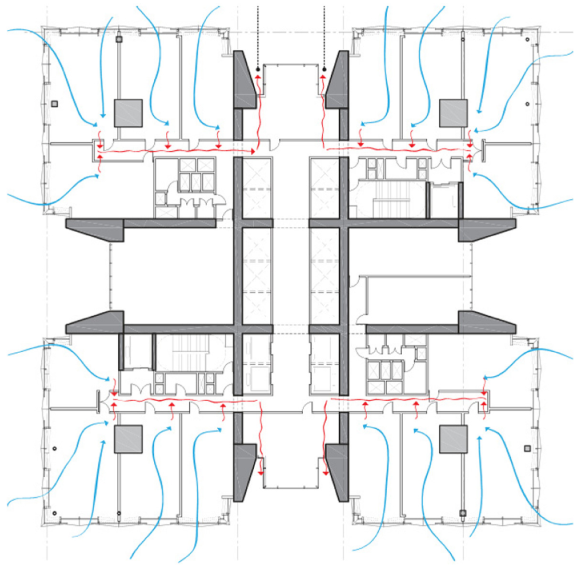

Figure 5. Dancing Dragons, Floor Plan with "Stack Effect Shafts".

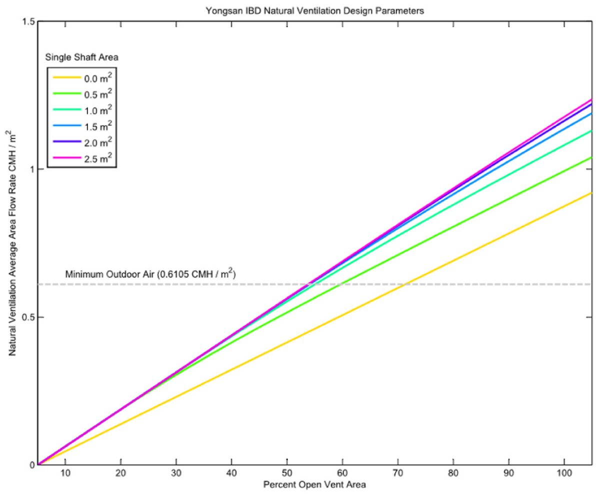

Figure 6. Dancing Dragons, "Stack Effect Shaft" sizing calculation results from Computational Fluid Dynamics Analysis.

2.5. Heating & Cooling Systems

Supertall building designers typically look to streamline the building form and envelope, and often seek to minimize or integrate the visual impact of exterior mechanical system elements or components. This objective mandates that heating and cooling source equipment (boilers, chillers, cooling towers) be located in either basement, mid-rise technical floor or rooftop enclosures. Distribution of chilled water/condenser water and/or heated water from these locations along the height of the tower is planned to minimize overall system pressure and typically requires the use of heat exchangers located at technical floors to transfer energy and separate hydronic zones. Piping from these heat exchanger locations extends to typical floor terminal devices, including Fan Coils, Variable Air Volume or various other terminal units serving occupied areas of the building. The heat exchangers serve to physically separate fluid flow, and limiting static pressures in distribution piping, fittings, and associated heating/cooling coils. Mixed-use buildings with a variety of occupancies and multiple tenants, frequently require heating and cooling services 365 days a year. The need for year-round operation requires the continuous operation of a chilled and hot water plant. This operational scenario can increase annual energy consumption, largely due to the part load performance limitations of large centralized equipment, standby / distribution losses across multiple pressures zones, and pressure drop present in long piping runs. The need to meter energy use by individual tenants presents yet another challenge with the design of supertall systems. Many supertall projects require the installation of independent central plants dedicated to individual occupancies (i.e. Separate boiler/chiller plants to supply a 30-story hotel stacked on top of 50 story office building below). Hydronic metering can be installed at heat exchanger stations and individual floors monitor individual tenants.

The size, scale, and mixed-use nature of super tall buildings requires a large, flexible source of heating/cooling and power. Operating diversity across the broad range of occupancies provides a significant opportunity for energy efficiency, and equipment sizing methodologies that realize both operating and first cost savings through reduced infrastructure requirements. (Utilities, electrical and mechanical equipment capacity and distribution pricing).

A popular "best practice" approach to the realization of these savings is the installation of an integrated energy plant serving the multiple tenants/occupancies in the building through one combined heating/cooling and power distribution plant. Within this plant, the sources of heating and cooling are planned to complement one another, maximizing operating efficiency and economies. One viable technology available for supertalls is a cogeneration system capable of generating simultaneous power, waste heat and chilled water through an absorption cooling plant. When properly sized, the system can supply the base heating/cooling demands, with excess generated power absorbed by the building or stored in onsite batteries or thermal storage systems, enabling the building to avoid peak electrical demand charges as was built for the 54 story high rise, One Bryant Park in New York City (Donnolo, 2014).

Large utility networks across the United States (PJM, 2017) are now offering utility frequency modulation programs, where private owners of battery storage systems supply "on demand" capacity back to the grid, enabling the utility companies to avoid the operation of expensive standby natural gas-fired "peaker plants". When factoring these economic business opportunities into the sustainability and resilience strategy for a supertall building, they become increasingly attractive.

A more common technology often used in campus / healthcare facilities but less common in supertalls is the heat recovery chillers. Heat recovery chillers utilize waste heat from the refrigeration cycle that is normally circulated to cooling towers for rejection to atmosphere. This waste heat is captured for re-use in the building's domestic hot water system or upgraded for use in any simultaneous heating requirements such as ventilation re-heat systems. Once again, this strategy is most effective when the building thermal loads are combined through a common central utility plant, and fully leveraging the benefits derived through the diversity of heating/cooling load demands.

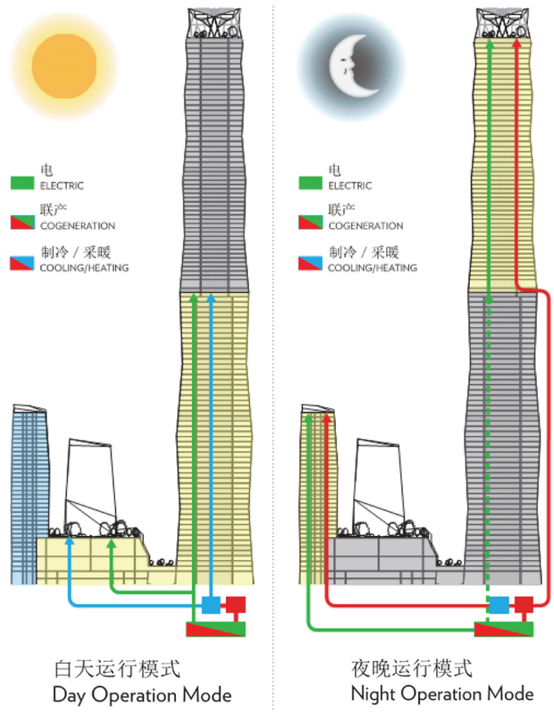

Figure 7. Greenland Tower Integrated Energy Plant with Distributed Generation Concept, Chengdu China.

A rapidly evolving technology that is dominant in Asia and is becoming increasingly popular with high-rise residential/hospitality buildings throughout the United States, is the refrigerant based heat pump system. These systems utilize distributed compressors connected to refrigerant piping to generate useful heating and cooling. These systems are frequently installed as standalone systems, with outdoor condensers placed on balconies, terraces or on mid-level technical floors along the height of the tower. This approach forfeits the true energy conservation potential of these systems. A preferred for supertall buildings is the installation of a centralized condenser water system that connected to a rooftop or site based cooling tower and boiler plant, to supply the required supplementary heating/cooling. In the best practice case, a more advanced refrigerant based system called a Variable Refrigerant Flow (VRF) system should be incorporated. VRF systems can be configured with heat recovery, enabling the system to circulate excess heat from an area of the building that requires cooling, to a location requiring heating. This type of system offers significant opportunities for energy conservation in all glass, deep floorplate and multi-use buildings. VRF systems are very versatile in how they are organized, and will potentially realize new and unique building stacking.

For low rise buildings, Heat Pump and VRF systems coupled with a geothermal ground loop array form the backbone of many Net Zero Energy strategies. Due to the complexity and structural / site planning requirements inherent in planning a supertall, installing an adequately sized geothermal well field is often space constrained and cost prohibitive.

There are several energy efficient HVAC systems that are potential contributors to high performing buildings, when considered holistically in the planning and design of a supertall.

Chilled ceilings that provide radiant cooling/heating offer one of the most efficient means of space conditioning in a commercial office environment, and when planned in concert with the building envelope and vertical stacking, may realize reduced mechanical services costs (removal of supplementary perimeter systems), and reduce the building floor to floor height.

The Pearl River Tower in Guangzhou, China (SOM, 2017) successfully incorporated a fully radiant chilled ceiling system coupled with displacement ventilation and a ventilated double wall façade. The unique combination of systems allowed for the removal of bulky recessed ceiling ductwork, reducing floor to floor height from 4.2 m to 3.9 m's, facilitating the addition of five additional floors for the same envelope cost while staying below the maximum building height stipulated by the city (Leung, 2014).

The Mies Van Der Rohe designed TD Center in downtown Toronto has recently undergone a $250 m renewal project, with a large portion of the original HVAC system removed and replaced with active chilled beams. This modernization effort provides "best in class" energy efficiency, improved air quality, and thermal comfort, contributing towards the receipt of a WELL Building Certification (Center, 2017).

3. Conclusion: The Resilient Supertall

Supertalls inherently require infrastructure with instrumentation and automation to support basic activities such as; Vertical transportation, building services, and communication systems. They have a unique scale and role in interacting with infrastructure systems that are built to support them. A "Smart City" is a term used to describe an urban environment that has sufficient intelligence, sensor driven data automation, and software analytics to facilitate informed planning decisions in areas such as public transportation networks, utility grid operations and logistics and industrial sectors. "Resilient cities" is a term developed to describe the ability of an urban environment to react positively, with the ability to adapt to unanticipated circumstances or events, such as an extreme weather event, an economic calamity, a public health and wellness occurrence, or related event physically impacting the built environment.

Supertall buildings can leverage their complexity and scale and contribute positively to their immediate built environments around both areas of consideration. These strategies when considered holistically with how a supertall building is planned, and how the systems are designed to meet these goals may result in the best buildings yet, something we might be able to look back on positively in the year 2030.

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