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3for2: Realizing Spatial, Material, and Energy Savings through Integrated Design

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As the world adapts to dual trends of climate change and urbanization, tall office buildings in hot and humid climate zones near the equator are among the prime candidates for a significant change in design approach. Though many individualized improvements to operating systems, envelopes and material selections have been introduced in recent years, it is generally agreed a holistic approach is needed to truly capitalize on the smaller-scale innovations. With a focus on reducing the necessary size of the services plenum, in this paper, an alternative paradigm for the optimization of space, material, and energy use in buildings is presented: a holistic integration of all building systems – structural, mechanical, and electrical – across a building's entire lifecycle, from early-stage design to construction and operation.

Introduction

The built environment is currently facing two important global challenges: climate change and urbanization, with the latter challenge not to be understated despite climate change's dominance at the forefront of geopolitics. In 2007, for the first time in human history, the earth's urban population exceeded its rural population (UNEP 2007). Should this trend continue, by 2050, it's expected that 66% of the world's population will be living in cities. This growth is predominantly happening and is forecast to continue to happen in Africa and Asia, with many cities situated in hot and humid climate zones near the equator. Increasing pressure on these future cities in terms of limited space and resources will lead to dense, mixed-use developments as has already occurred in key regions of Southeast Asia, such as Singapore. For instance, tall non-domestic buildings were among the types of buildings experiencing the largest increase in Singapore's commercial gross floor area over the last several decades (BCA 2014), making office buildings a prime target for improving the space, material, and energy utility of the city-state.

The building sector in Singapore is both aware of and responsive to these drivers, as are many other countries. For several decades, a variety of approaches and technologies have been developed for reducing the operational energy consumption or material intensity of new buildings, with many of these developments focused on the integration of separately-optimized individual components, such as

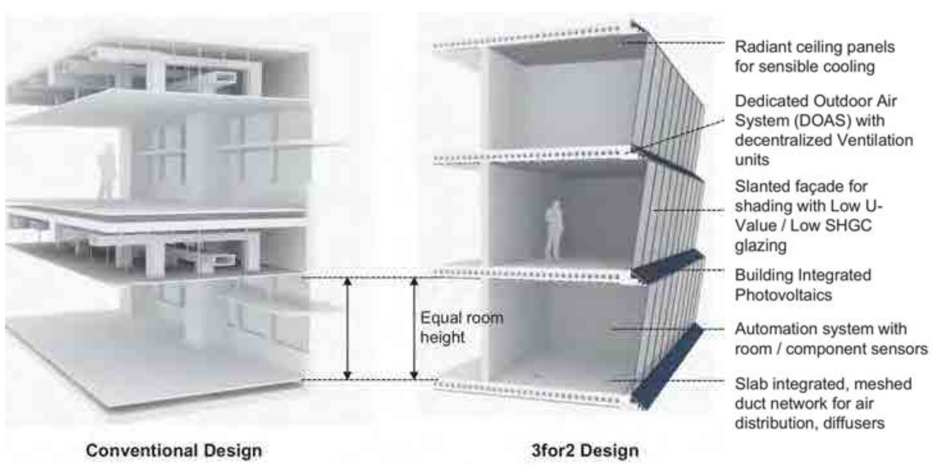


Figure 1. Conceptual schematic of an idealized 3for2 building section compared to a conventional building section.

glazing, air conditioning, lighting, and building structures. They have generally neglected, however, a holistic dimension. In this paper, the authors challenge one aspect of the modern high-rise building form that has not changed fundamentally for more than a half century, outside a few examples in central Europe. Despite its impact on building material use, space intensity, and energy consumption, ceiling plenums and dedicated floor spaces that shield a building's mechanical and electrical systems from the view of building occupants continue to prevail.

Observations have shown that ceiling plenums in conventional commercial high-rise buildings occupy up to one-third of the enclosed building volumes. Typical floor-to-ceiling heights are approximately 2.8 meters, and typical ceiling plenum heights range up to 1.5 meters on average (Parker & Wood 2013). However, the historical prevalence of plenum spaces in buildings should not give one the impression that they are fundamental components of high-rise building construction.

In fact, to understand how ceiling plenums and central air handling systems may adversely affect building material and space use intensity, one needs only to imagine the alternative: a high-rise building that altogether negates any functional need for plenums or dedicated floor spaces for air handling equipment, while still providing energy services (e.g., lighting, air conditioning, etc.) in an efficient, architecturally-appealing manner. This principle is at the core of the "3for2" design concept for high-rise buildings (see Figure 1).

Key Design Principles and Technology

The 3for2 concept calls for a systematic approach to sustainable building design that goes beyond mere energy efficiency of technical systems and operational energy savings. It has been developed for hot and humid climates, but it is also applicable in other climates.

There are three sequential design principles that underlay the 3for2 concept:

1. The decoupling of sensible and latent cooling into independent air-conditioning systems
2. The decentralization of ventilation and latent cooling equipment
3. The integration of decentralized air conditioning equipment and distribution pipe/ductwork into a building's floor and façade structures.

The concept is enabled through three key building technologies, described further below:

1. Water-based chilled ceiling systems
2. Compact fan coil units optimized for latent cooling
3. Void-form construction of floor slabs.

Decoupling sensible and latent cooling/moving to water-based sensible cooling systems

In conventional central air conditioning systems, sensible cooling (the control of indoor air temperature) and latent cooling (the dehumidification of indoor air) is performed using a single, centrally-located air handling unit (AHU). However, air is not the only medium that can be used to accomplish sensible cooling, nor is there any physical reason why a single system must provide both sensible and latent cooling. For over a century, occupants of buildings in cold climates have been accustomed to the use of water-fed radiators that perform sensible heating. Very similar technologies exist for cooling and for combined heating-and-cooling applications. Radiant ceiling panels and passive chilled beams are examples of water-based cooling systems that utilize large, thin, water-fed surfaces to cool indoor spaces in the form of radiant heat transfer and natural convection.

One of the immediate advantages of using water-based systems for sensible cooling is space and material savings. Water can transport the same thermal energy as air, using less than 0.03% of the volume. Hence, water-based cooling can be considerably compact and vertically thin (Meggers et al. 2012). Water-based cooling systems can also be highly energy-efficient, owing to the fact that they can provide cooling at temperatures considerably higher (~17–20°C) than conventional AHUs (~4–8°C). The implementation of chilled water plants that are optimized for high-temperature cooling can lead to water-based cooling systems consuming 40% less electricity for sensible cooling than their conventional air-based counterparts (Wellig, Kegel & Meier 2006).

Decentralization of AHU for latent cooling and ventilation

With sensible cooling covered by water-based systems, the 3for2 concept still calls for an air-based approach to indoor air dehumidification and ventilation. However, in lieu of utilizing single, centrally located AHUs to condition a single floor, the 3for2 concept proposes the decentralization of the floor's latent cooling and ventilation system into several miniature AHUs, served by low-temperature chilled water. Decentralizing the air handling system in this manner provides several advantages, and has been explored in prior research (Baldini, Goffin & Leibundgut 2011).

First, the miniaturization of the air handling system into several small AHUs allows for the integration of AHUs into previously unutilized spaces, such as the building's floor and façade structures. The advantage of this is to alleviate, as much as possible, any need for dedicated AHU rooms or complete AHU

> "The historical prevalence of plenum spaces in buildings should not give one the impression that they are fundamental components of high-rise building construction."

floors in a building, as will be discussed in the following section.

Second, by positioning decentralized AHUs as close as possible to the zones they supply, the cross-sectional area and the length of the ducts throughout the ventilation system can be reduced beyond the savings earned by decoupling sensible and latent cooling into separate systems. In addition, pressure drops within the duct network are minimized, and central ventilation shafts within the building become unnecessary. This leads to reduced fan power requirements for the decentralized AHUs, thereby reducing the electricity consumption of the ventilation system altogether.

Third, the use of many miniature AHUs for latent cooling ventilation provides the opportunity to tailor each unit for specific uses. Some may be configured as dedicated outdoor air systems (DOAS) – providing 100% fresh outdoor air – or as 100% recirculated air fan coil units (FCUs). The high granularity available to the configuration of the overall decentralized system can lead to an equally high granularity of control for indoor air humidity and quality (Baldini, Goffin & Leibundgut 2011).

Integration of mechanical and electrical systems within the building floor and façade structures

As a consequence of splitting sensible and latent cooling in combination with decentralization, the overall building air conditioning becomes considerably compact and, crucially, vertically thin. This situation facilitates the integration of components and distribution systems into structural elements, such as the building's floors and façades. The use of void-form construction for floor slabs has already been successfully used to integrate pipework, ductwork, and electrical conduits for entire building systems in central Europe – where heating and cooling loads are natively smaller and more amenable to the size of decoupled and decentralized systems.

The integration of mechanical systems into façades plays an important role in the 3for2 concept. The slanted nature of the façade is also deliberate. Though this depends on the geographic location of the building and time of year, by slanting the façade in the order of 10–15 degrees, peak solar heat gains can be passively reduced, and ample passive shading can be provided without reducing indoor daylight quality. This can result in the ability to provide an efficient, highly-glazed façade that uses low-cost glazing products with fairly high Solar Heat Gain Coefficients (SHGCs). Moreover, the slanting produces cavities that host the miniature decentralized AHUs and other technical devices for mechanical systems. Last, the slanting creates horizontal offsetting surfaces oriented to the sun, which therefore can be used for decentralized electricity generation using building integrated photovoltaic (BIPV) systems. A seamless digital chain from design to digital fabrication for such systems has been established (Schlueter 2011).

Pilot Implementation of the 3for2 Concept

Throughout 2014 and 2015, a single-floor 550-square-meter pilot implementation of the 3for2 concept was designed and constructed in Singapore. The pilot project area sits within the larger 20,000-square-meter high school building of the United World College South East Asia (UWCSEA), an independent school in Singapore. UWCSEA's management staff has occupied the space as a regular office since the beginning of December 2015. Figure 2 provides an overview of the site footprint – a near-rectangular space with north and south-facing façades.

The pilot project is designed as a living laboratory. While on one hand, the space is occupied and treated as a regular office, on the other, it is being intensely surveyed by researchers over a multi-year period. The overall goal of the research program is to observe and enhance several aspects of the

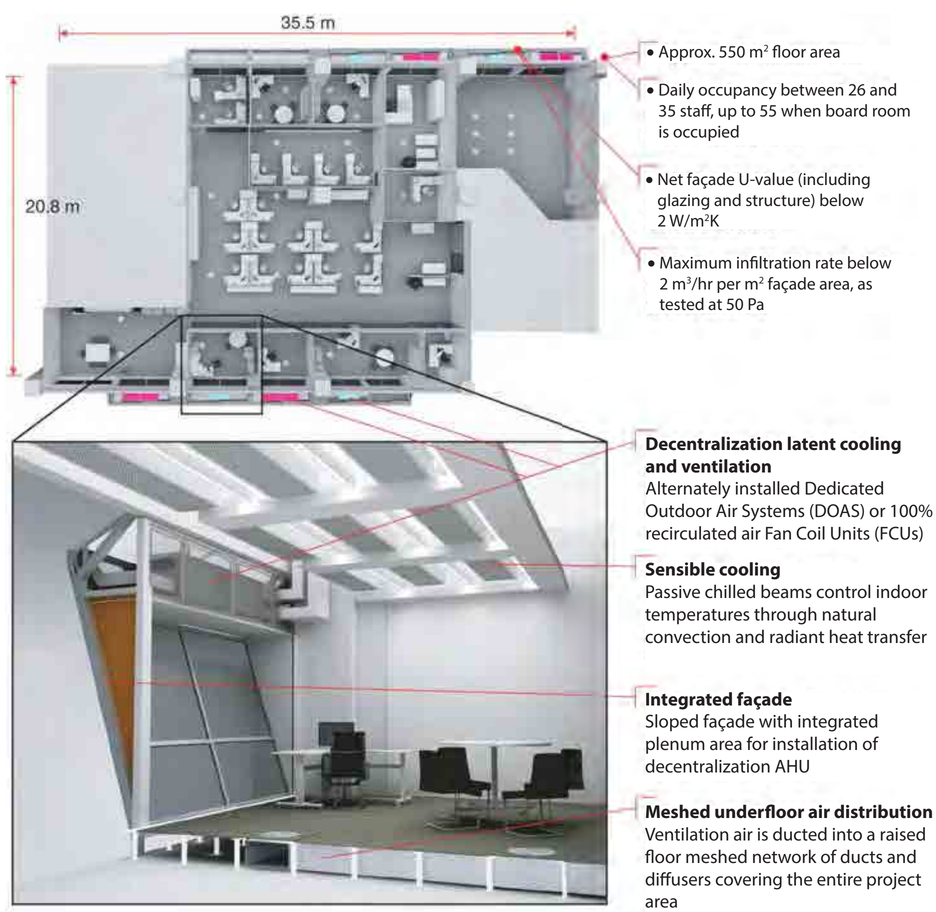


Figure 2. Overview of systems installed in 3for2 pilot implementation at UWCSEA in Singapore, 2015.

building system, such as occupant thermal comfort acceptability, energy performance, and control system behavior.

Project objectives

While the 3for2 concept proposes a holistic approach to space, material, and energy use in multi-story buildings, the pilot project in Singapore is primarily aimed at studying the energy savings potential of the key air-conditioning technology underlying the concept. The ability to fully study the concept's potential for space and material savings was limited from the project's outset by the fact that the pilot area would only cover a portion of a single floor within a larger building. It was not possible to replace the core building structure – lightweight steel-reinforced concrete slabs – for only the project area.

Hence, specifically, as a research project spanning 2016–2018, the 3for2 pilot project has the following objectives:

- Study the holistic energy performance of the 3for2 concept, from electricity consumption to thermal gains, through façades and infiltration.
- Study the control behavior of the decoupled, decentralized 3for2 air conditioning concept, and propose new techniques for optimizing the behavior of these systems for occupant comfort and energy efficiency.
- Study the advantages of combining chilled ceiling technologies with low-lift chillers tailored for high-temperature cooling applications.
- Serve as a showcase of decentralized, façade-integrated ventilation systems that can function suitably in a high-load climate.

As part of the living lab, a 64-square-meter room in the project space has been fit out with both the 3for2 air conditioning system and conventional ductwork from the building's central air handling system, allowing for the future performance characterization of the 3for2 system against like-for-like room operating conditions.

Overview of system design

A summary of the key design features of the 3for2 pilot project is provided in Figure 2, with considerable emphasis on the project's air conditioning system. The components include passive chilled beams for sensible cooling, alternately installed DOAS and 100% recirculated-air FCUs for latent cooling and ventilation, and a meshed, interconnected duct network serving an underfloor air distribution network (UFAD). For the research aspects of the project, over 1,000 sensors and control points have been installed throughout the system. This includes two indoor air temperature, humidity, and CO_2 sensors every 10–15 square meters (one at occupant height and one at ceiling height), and energy meters that measure water temperatures and flow rates to each chilled beam cluster (more than 25) and decentralized AHU (eight in total). It also includes air pressure sensors and air flow meters within ducts, electronically actuated air duct and diffuser dampers, motorized control valves, etc. Data from all sensors and control points are captured and stored at one-minute intervals and can be assessed in real time by the research team.

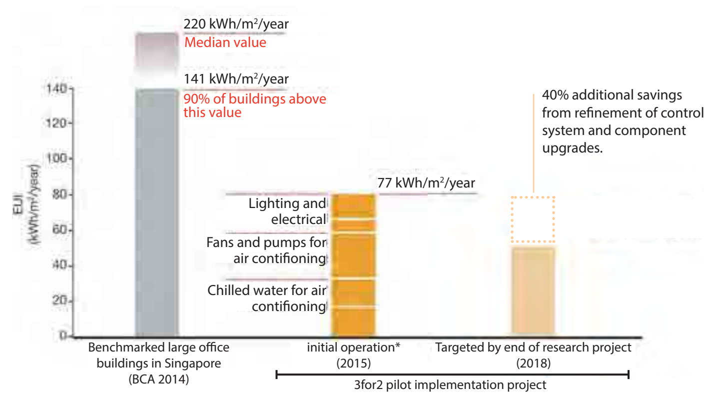
Overall, each individual room in the 3for2 pilot implementation space has the ability to independently regulate air temperature (using the PCBs), humidity (using the FCUs), and CO_2 set points (using the DOAS). This feature alludes to one of the main advantages of the 3for2 system overall, and which is to be further studied in the research phase of the project: high-fidelity control allows for improved occupant comfort while reducing periods of wasteful operation.

Initial outcomes

Full occupation and operation of the pilot space occurred in December 2015, with Figure 3 illustrating a photo of the exterior façade marking the building's completed construction. Though the majority of the pilot project's research objectives will not be achieved for several years, it has already become possible to assess initial energy consumption data of the 3for2 system.

Figure 4 provides an example of this early analysis, showing an aggregate of the building's energy use intensity (EUI) over a month of operation at the end of 2015. By taking data retrieved from the project's building automation system (BAS) over 18

Figure 3. Photo of constructed 3for2 pilot façade at UWCSEA in Singapore, 2015.



* Aggregation of 18 days of operational data from December 2015 – assumes 252 days of system operation per year. System operates between 7am and 6pm each weekday, with indoor air conditions set to 22.5ºC and 60% relative humidity.

Figure 4. Comparison of energy use intensity (EUI) among benchmarked Singapore office buildings, the first month of operation of the pilot 3for2 space, and the pilot project's future goals.

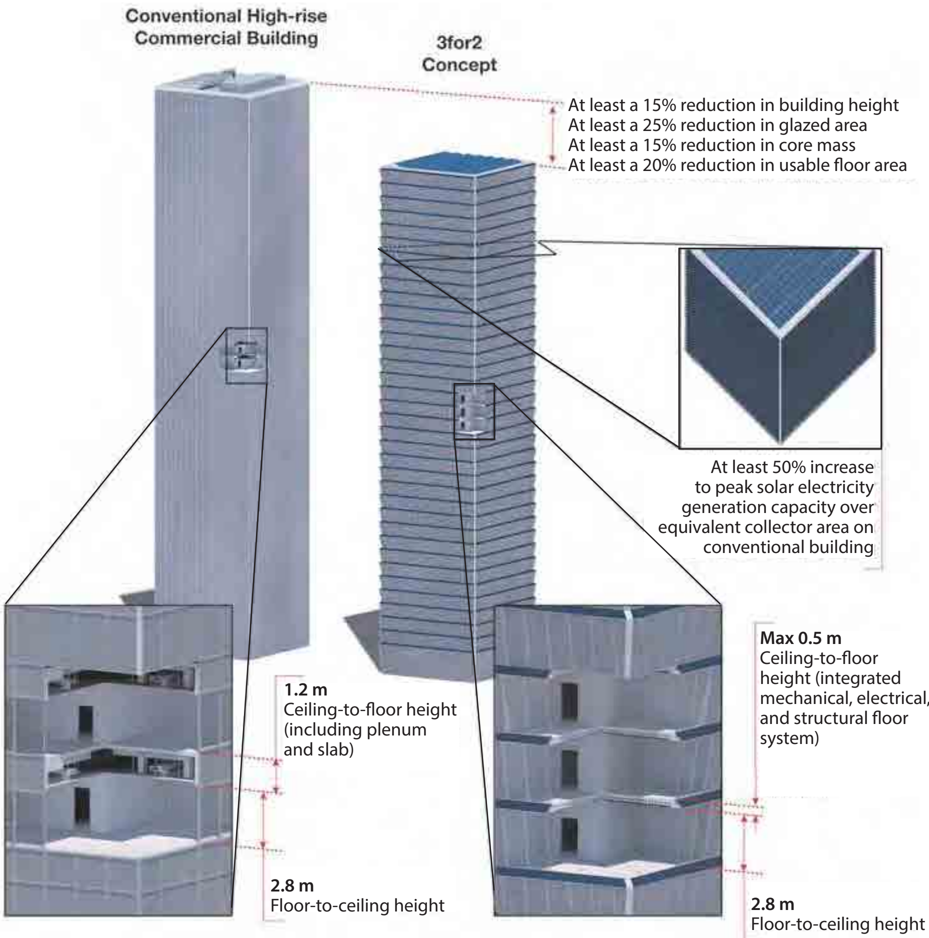


Figure 5. Conceptual overview of a high-rise 3for2 building and its key space and material savings over conventional buildings.

weekdays of operation in December 2015, we estimate the annualized energy consumption of the pilot project space is currently at 77 kWh/m^2/year, well within the upper 90th percentile of surveyed low-energy office buildings in Singapore (BCA 2014).

Towards the Future: Drivers and Barriers Facing 3for2 Buildings

The 3for2 concept is a proposal for an integrated approach to high-rise commercial building design that saves space, material, and energy. Despite the Singapore pilot project's current focus on energy efficiency, the experience of designing and constructing the space has made it possible to establish geometric and form principles that could be applied to a whole-building case study.

One such example is shown in Figure 5, which compares a 37-story 3for2 building concept with a conventional high-rise building that follows international norms for building structure, ceiling and plenum heights, and mechanical systems (Parker & Wood 2013). The savings with respect to space and materials are not trivial, as will be explored further in the following section. However, from a practical standpoint, perhaps one of the greatest advantages of the 3for2 concept is that it might mend a well-known and critical barrier to energy efficiency in the global commercial building sector: the nature of split incentives between landlords and tenants, and between owners, developers, and building occupants. The 3for2 concept provides an incentive for all key players in the building development process to buy-in: developers can capitalize on material savings; owners/landlords on space savings; and occupant/tenants on energy savings and improved comfort.

Estimating the financial impact of a 3for2-concept building

To gain a better sense of the economic scale of the 3for2 concept, the conceptual dimensions and savings from Figure 5 are here applied to a practical study. One Raffles Quay in Singapore, a 50-story office high-rise in the central business district of Singapore, contains more than 80,000 square meters of office space (see Figure 6). Notable for this building is that its ceiling heights were notably smaller and lower by convention: it's proposed that, had it employed the 3for2 concept, One Raffles Quay may have saved up to 9% in glazed surface area and 15% in core structural volume, while increasing tenable floor area by approximately 5% through decentralization of the air-conditioning system. These estimates are based on rules of thumb for preliminary design (Allen & Iano 2007) and from the existing floor plans. While it is assumed that the implementation of the 3for2 concept could have resulted in a potential whole-building energy use intensity below 50 kWh/m^2/year, we assume the baseline building consumes 220 kWh/m^2/year, equivalent to the median annual energy consumption of office buildings in Singapore (BCA 2014; EMA 2014).

The scale of potential benefits for these savings is estimated in Table 1. While this study is preliminary and omits several other aspects of the 3for2 concept that affect both the concept's cost and benefits, notably labor intensity and technology first costs, the beneficial impact of the 3for2 concept on tenable floor area is potentially exceptional. If recent market rates for rented floor space persist, the ability to earn revenue from an extra 5% of the building's floor area would generate up to S$40 million in earnings over a 30-year lifespan.

Known risks and challenges

The 3for2 pilot project has become a successful demonstration of the concept's proposed air-conditioning system and architectural form. The project has shown that a decoupled and decentralized air-conditioning system can function efficiently in the tropical climate and provide comfortable indoor conditions. However, several key challenges face the scaling up of the 3for2

Cost Component	Nominal cost/ revenue (S$)	Size		Cost / Revenue (S$ million)		Potential savings by 3for2 (S$ million)
		Conventional Design	3for2	Conventional Design	3for2	
Glazing*	$196.3/m^2 glazing	23,370 m^2	21,267 m^2	$4.6	$4.2	$0.5
Structural core mass*	$91.4/m^3 concrete	18,973 m^3	15,811 m^3	$1.7	$1.4	$0.3
Rentable floor area	$85.63/m^2 per month	25,000 m^2	26,250 m^2	~$25.7/year	~$27.0/year	$1.3/year
Energy consumption	$0.26/kWh	220 kWh/ m^2/year	50** kWh/m^2/ year	~$1.4/year	~$0.34/year	$1.06/year

* Material costs only; does not include labor and installation
** 2018 target for 3for2 implementation project

Table 1. Estimate of cost savings/revenue streams possible had One Raffles Quay been implemented as a 3for2 building.

concept from single-floor pilot project to skyscraper.

Firstly, the availability of skilled design, engineering, and construction teams to fully realize the integration needed to construct a 3for2 building is not yet commonplace. The project structure necessary to promote full integration between diverse trades at all stages of the building development process is also not yet common. Secondly, economic drivers for entire 3for2 buildings may not fully align developers with a a low-carbon trajectory. If it's possible for a developer to sell physically high floors at a greater premium than floors at lower height, he or she may be averse to a concept that would inherently shrink the total height of a conventional building. For such developers, the 3for2 concept may be primarily an appealing approach that removes suspended ceilings, thereby offering tenants higher floor-to-ceiling heights.

While these and many other open matters require further research, it's hoped that the message is clear: by approaching building design with a fully integrated view to the architectural, structural, mechanical, and electrical domains, a paradigm shift may occur in how to realize low-carbon high-rise buildings.

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Unless otherwise noted, all photography credits in this paper are to the authors.

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Figure 6. One Raffles Quay, Singapore. © Meinhardt

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