Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world***
Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Effect of Structure and Morphology on Natural Ventilation Potentials, Comfort, and Energy Use in Tall Buildings

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Abstract

In recent years, more and more tall buildings have a mixed-use or residential program. This shift from formerly mainly office use requires new evaluations and guidelines for occupant comfort. This paper examines the relationship between the structural core of the building, its floor plan, the overall shape and its potential for natural ventilation, and how these relate to human comfort, energy efficiency and structural performance. The results are qualitative recommendations for the initial design stage of a tall building in a given climate zone.

1 Introduction

Tall buildings address sustainability in terms of increasing density in cities, thereby reducing travel distances and land use. In recent years, more and more tall and super tall buildings are offering mixed-use layouts (see Fig. 1). This requires that comfort issues in tall buildings increasingly need to be considered from a residential perspective rather than only from an office perspective.

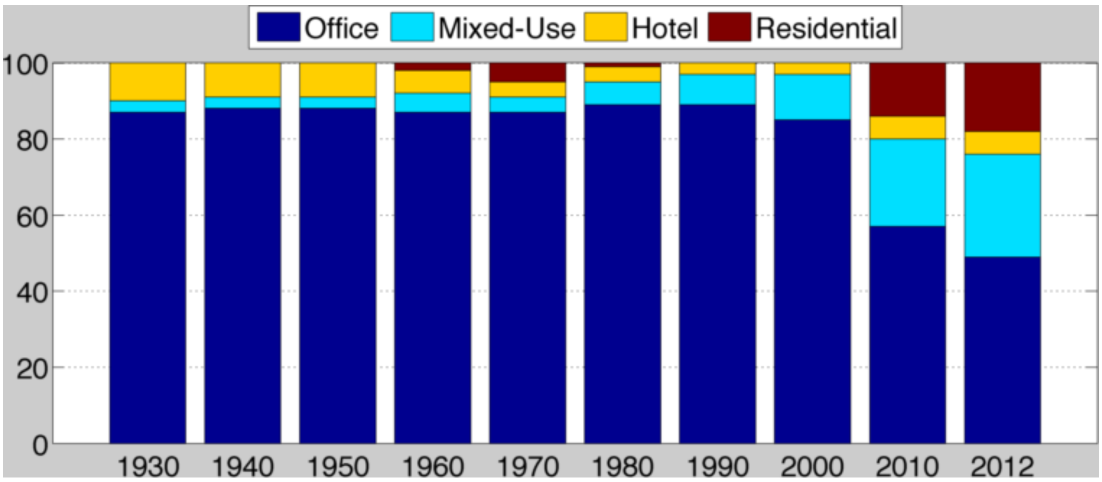

Figure 1. Different uses of tall buildings throughout history (adapted from Brass, Wood and Carper, 2013)

In particular, this research is concerned with potentials for natural ventilation. We argue that tall buildings must be designed with the possibility for natural ventilation, even if it is only used for part of the year or for a few hours out of the day, especially in order to increase comfort for residential inhabitants and to reduce incidences of sick building syndrome. Natural ventilation increases comfort by providing a means to exchange air and a means for cooling, while also reducing energy demands. In tall buildings, natural ventilation typically takes the form of either operable windows, the use of stack effect, ventilated double façade, or a combination of these.

Further, we focus on the use of operable windows specifically, as this form of natural ventilation is considered to offer the greatest feeling of control to the occupant, especially in a residential setting. Comfort levels through operable windows are achieved through reducing indoor temperature and encouraging air movement. (Nicol and Humphreys, 2004), (Brager, Paliaga, de Dear, 2004)

When designing tall buildings, structure and form need to be considered to reduce wind loadings. Ventilation and thermal strategies are often secondarily, as the operational costs of the building come second to the investment costs of the initial construction. But in considering environmental impacts, both the embodied energy and operational energy requirements need to be considered.

Individual guidelines exist for designing tall building structures for comfort, such as core placement and building morphology for thermal performance. Guidelines also exist for aerodynamic forms. However, these objectives are not yet considered in a holistic way along with natural ventilation for tall buildings. Specifically, little research exists on the combined potential of all of these objectives for natural ventilation in the form of operable windows.

In this research, we provide an overview of design guidelines, which shape the building based on all of these considerations equally, for a given climate zone and wind direction. The results are initial design guidelines and recommendations that can serve as starting points when designing a new building for a particular location.

2 Background

In this section, research for each topic: Structure and Energy Efficiency, Aerodynamic Forms, and Natural Ventilation, in the context of tall buildings, is briefly reviewed.

2.1 Structure and Energy Efficiency

Krem analyzes the trade-offs in the design of structural systems for both structural and energy performance. (Krem 2013) He bases his work on Yeang's classification, which suggests optimal floor plans and core placements to reduce energy consumption in four climate zones (Yeang, 1999). These are shown in Figure 2. For example, in a cold climate the central core is found to be most efficient, but for a tropical one, two cores placed on the most sun-exposed sides perform better, as the cores reduce solar heat gain.

Based on structural and environmental simulations, Krem further analyzes Yeang's structural configurations (placement of core and building shape) for specific climates, both for their structure and environmental performance combined. He concludes that some of the best energy performance configurations would require significantly greater structural mass, and therefore proposes future research is needed so that these objectives can be balanced.

Therefore, for him, a first step is to consider the environmental performance of a form, and then find what structural solution could make it work.

For natural ventilation, as well, considering the environmental performance of the form is the first step. Avoiding solar heat gain complements any natural ventilation strategy, as, according to Wood and Salib, increase in solar gain would overwhelm any comfort gains of natural ventilation. (Wood and Salib, 2012)

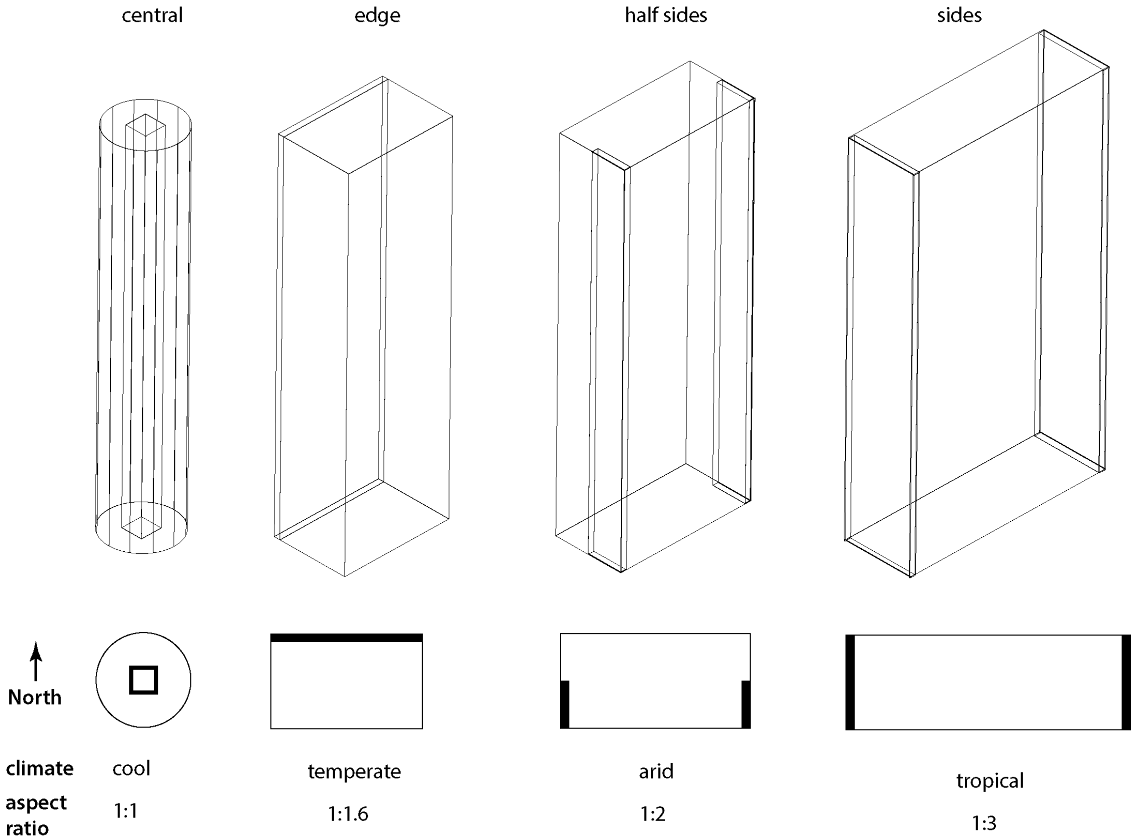

Fig. 2. Yeang's proposal for optimal core and floorplan configuration to reduce energy consumption by climate zones (adapted from Yeang, 1999).

Therefore, in this work, we also examine Yeang's proposals as a basis for further studies on the structural performance, energy performance, and comfort through ventilation combined.

2.2 Aerodynamic Forms

Since tall buildings are exposed to high wind loads, the structural design must consider horizontal loadings as the governing force. Further, the shape of the building can contribute to the reduction of wind loadings, for e.g., by presenting only a small area of the building in the direction of the prevailing wind and/or pointing or curving this face. Aerodynamic forming of tall buildings is becoming increasing popular both due to the advances of computational fluid dynamics and the realization that the reduction of wind loading can reduce the initial cost of the construction by means of reducing the amount of structural material needed.

Recent designs including curvilinear floor plans or curved and tapering profiles have contributed to considering shape optimization for wind loading. See (Kareem, 2013) and (Felkner, 2013) for an example of the use shape optimization for the design of tall structures.

Alternatively, micro modifications can affect aerodynamic performance. For example, rounding the corners of a tall building can reduce the base moment of a square section by as much as 25% compared to a square section, as in the Tapei 101 building. (Irwin, 2006)

(Alaghmandan and Elnimeiri, 2013) recommend numerous approaches for improving the aerodynamic performance of tall buildings. For the purpose of this paper, we consider first the basic approach of orienting the building with the smallest face facing the prevailing wind, as this approach will least alter the proportions and layout proposed by Yeang for thermal performance.

2.3 Natural Ventilation

Wood and Salib, 2012 present a compilation of case studies of natural ventilation strategies in built tall office buildings, analyzing each in depth, and grouped into three categories: single-sided ventilation, cross-ventilation, and stack ventilation. For the purposes of this paper, we differentiate between ventilation coming from single and double skinned facades, and consider only the case of a single skinned façade. According to Wood and Salib, access to operable windows provide a greater feeling of control over their environment and can, "lead to an increased tolerance for a wide range of thermal comfort standards and allow an adaptation to temperature fluctuations …while the windows are open." Moreover, operable windows have the potential for higher possible air exchange rates, affording occupants the benefit of both real and "psychological cooling". Psychological cooling is the phenomenon in which higher indoor air speeds make occupants feel cooler.

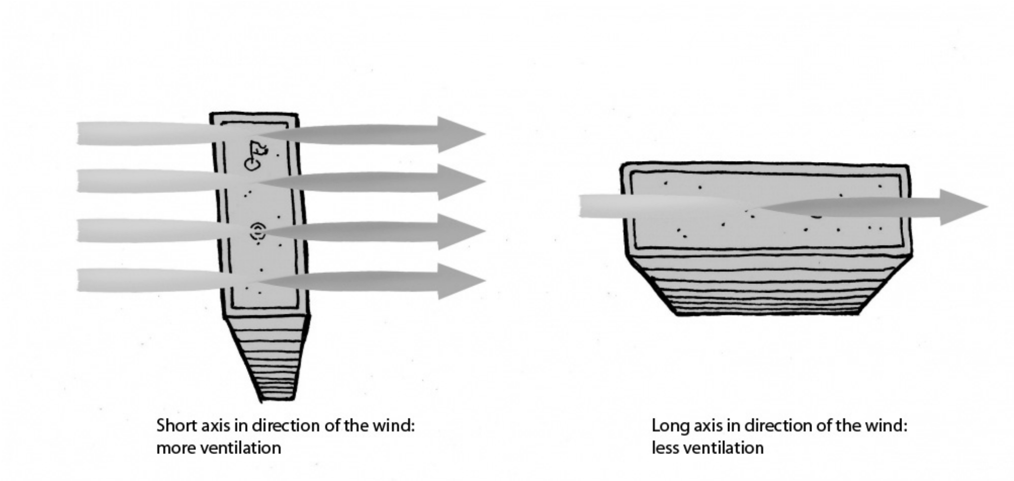

Fig. 3 Comparison of short versus long axis orientation in direction of wind in terms of ventilation (adapted from Autodesk Sustainability Workshop)

For this paper, the strategies for natural ventilation can be roughly grouped into four categories: stack effect, double skinned facades, operable windows, and the use of wing walls (Mak et al, 2007).

We are considering as the main priority the operable window effect for further analysis, because it is considered to be the one parameter likely to offer the greatest perceived comfort and control by the resident in a residential context. In terms of building form and orientation to facilitate the use of operable windows, the shorter axis of the building should be aligned with the prevailing wind direction (see Fig. 3)

Considerations for naturally ventilating tall buildings with operable windows

A distinction must be made what is comfortable for a residential versus office space in a tall building. While a residential space could better tolerate fluctuations in temperature and air exchange, office spaces are prone to having papers disturbed or becoming too damp from humidity. In a mixed-use building, a hybrid cooling and ventilation system would ensure that office comfort levels remain constant (e.g., through double skinned controlled systems, or smaller window openings), whereas residential portions of the building could allow greater control through larger windows.

2.4 Approach

In the next section, we qualitatively analyze the combination of the three strategies, structural configuration to reduce heat gain, aerodynamic forms and natural ventilation, as a first step to creating a guide to help architects create a synthesized building shape that best creates a potential for natural ventilation, while still reducing heat gain (operational energy) and structural mass (grey/embodied energy).

The analysis begins with four forms that have already been proven to be optimal for energy consumption in the four respective climate zones. From a structural point of view, some of these forms would be problematic in particular wind directions, according to Krem. (Krem, 2013) Others would also be inferior for ventilation via operable windows in particular wind directions. Therefore, supplementary structure and possible modifications to the designs are a given. The four options are therefore evaluated in terms of their structural performance and ventilation potential in all wind directions

3. Results

In Figure 4, the four forms presented by Krem for each climate zone are evaluated in terms of their potential for natural ventilation via operable windows in conjunction with their aerodynamic performance. (Stack effect and double façade ventilation are already considered to be applicable to all four cases, depending on the layout, and are therefore not included in the analysis.)

However, when following the recommendations for natural ventilation via operable windows, one must take more care to align the shortest axis of the building (the widest face) in the direction of the prevailing winds, see Section 2.3.

Contrarily, for aerodynamics, the long axis of the building should be in the direction of the wind, meaning the building should present its shortest face (or corner) to the wind, see Section 2.2. (While a truly aerodynamic form would be curved, the following figure, Figure 4, is representative of proportions only.)

Figure 4, shows the wind direction, climate, and building form. Each combination is evaluated with the aforementioned guidelines in terms of wind loading reduction (aerodynamics) and comfort (operable windows).

As can be seen, in a cold climate, the center core with a symmetric building shape is most optimal for all wind cases.

The group in blue, which endure winds from the east and west, offers decent aerodynamic performance, as their shortest sides are in the direction of the prevailing wind, and only fair natural ventilation potential via operable windows, as their sides facing the wind do not offer as much area. In order to improve the operable window potential, wing walls could be introduced to the north and south.

For the group in orange, all experiencing northerly and southerly winds, structural performance is problematic, while the feasibility for natural ventilation through windows is quite strong. Recommendations in this group would be to investigate aerodynamic performance strategies that do not alter the aspect ratio dramatically nor introduce excessive material usage. One possibility would be introducing micro-modifications, such as rounded corners. A macro-modification could be curving the entire face enduring the strongest wind loading, and tapering the form along the height.

		energy efficient core placement and floorplan for each climate region			
prevalent wind direction	wind related design parameters	cool	temperate	arid	tropical
N-S ↓	aerodynamics	✓	✗	✗	✗
	operable windows	✓	✗	✓	✓
S-N ↑	aerodynamics	✓	✗	✗	✗
	operable windows	✓	✓	✓	✓
E-W ←	aerodynamics	✓	✓	✓	✓
	operable windows	✓	fair	fair	✗
W-E →	aerodynamics	✓	✓	✓	✓
	operable windows	✓	fair	fair	✗

Figure 4. Qualitative assessment of optimal structural configurations for four climates with respect to their aerodynamic performance as well as suitability for operable windows in different wind directions.

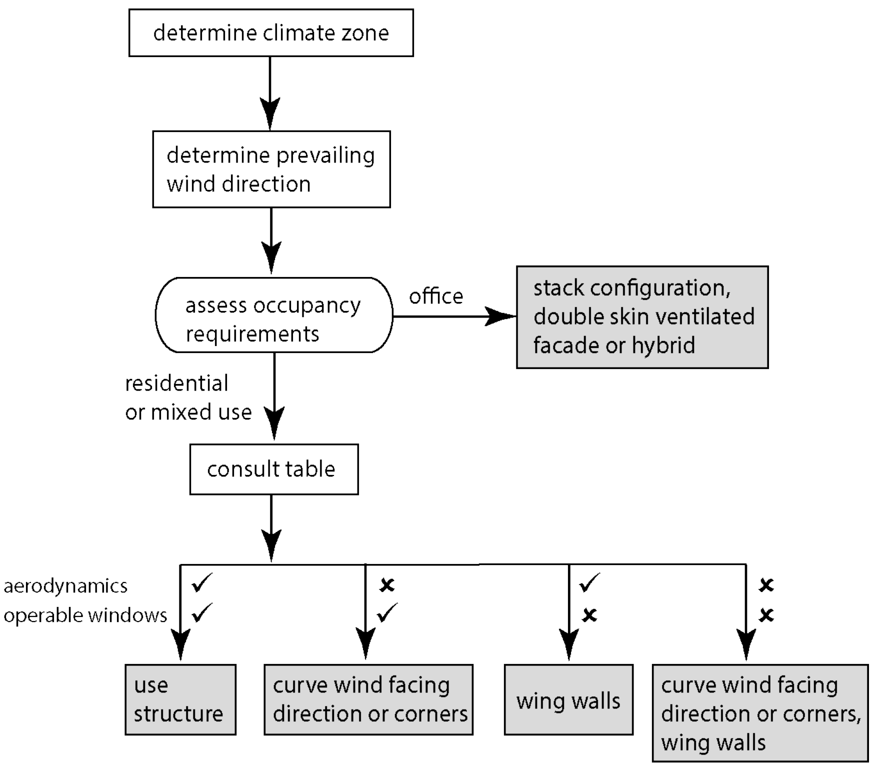

Figure 5. Flow chart to generate initial configuration of core and floor plans

The group in yellow shows decent aerodynamic profiles, but poor natural ventilation potentials via operable windows, as the cores are placed on the faces in the direction of the wind. A solution for this group would be the use of wing walls on the north and south facades.

The apparent worst performer of all is marked in red, with both poor aerodynamic and comfort (operable windows) performance. However, in terms of the aerodynamics, this could be remedied in the vertical through tapering, and horizontally through rounding the northern face. Micro-modifications such as curved corners could also help. In terms of comfort, the ability to open windows could be enhanced through wing walls on the east and west facades.

Figure 5 gives a flowchart how to generate initial design ideas based on the results in Figure 4. As can be seen, purely office spaces will have different criteria and potentials for other forms of natural ventilation. Mixed-use and residential building designers, however, can benefit from referring to the operable window feasibility table.

As noted by Krem, all plans that are asymmetric in any direction of the wind would possibly experience torsion without heavy material compensation. The compensating structural stiffness through extra material needed would possibly negate the savings in operational energy by increasing embodied energy in the structure, though he notes a full life-cycle assessment would need to be performed in order to quantify the difference. However, curving the plans in the direction of the wind would reduce this impact. Therefore, the ideal way to use the results from Figure 4 would be to imagine that all forms presented could be enhanced by curving.

For example, take the case of a mixed-use tall building planned for a site in England that has a prevailing wind generally coming from the south or southwest to the north, according to the wind rose. As England is temperate, the user would look at the temperate column in order to see the ideal morphology for energy performance. Looking at the cell in the temperate column and S-N row, one sees that Yeang's suggested form for energy performance is also an ideal form for natural ventilation, but not an ideal form for aerodynamic performance. Therefore, the user would see that more time and attention would need to be dedicated to making this form more aerodynamic or structurally efficient, without drastically changing its overall layout. A curved face and/or optimized structural system falling within the general boundaries would be possible directions to explore in addressing this trade-off.

4 Discussion

The analysis presented in this paper serves as a guideline and should not be considered prescriptive nor prohibitive of any arrangement. Architectural and or site constraints or justifications, such as important views or neighboring buildings, could all have major influences on the arrangement of the core and shaping of the floor plans. This is certainly the case, for example, with the Leadenhall building, whose location in London required specific views, and relied on other means of natural ventilation, such as a double skin façade (Young, Annereau, Butler, Smith, 2013), all while being ideally oriented for thermal comfort based on solar paths. Moreover, certain climates, such as tropical and arid, would most likely also need to employ a hybrid cooling system, allowing only residential portions or circulation areas to be ventilated via operable windows. Reference to ASHRAE psychrometric charts can further inform comfort levels for different climates, such as ones accessed through Climate Consultant, seen in Figure 6.

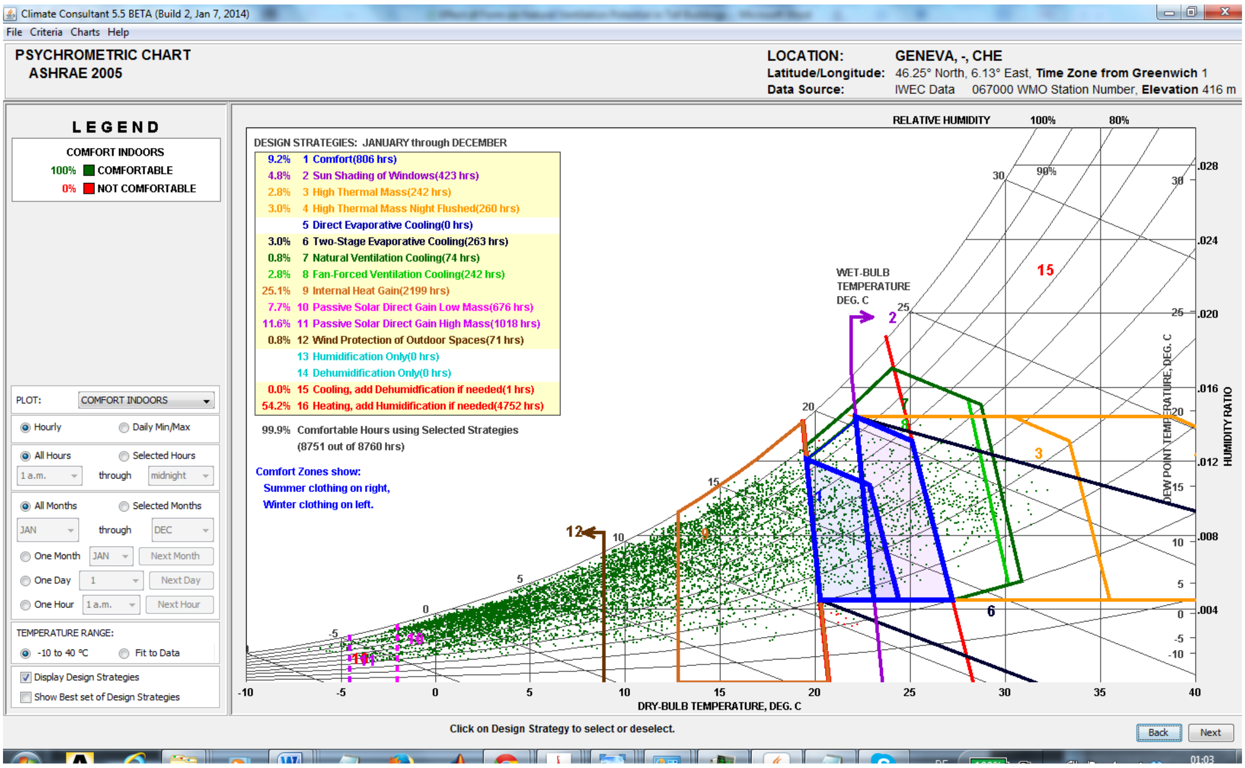

Figure 6. Example psychrometric chart showing Geneva, Switzerland

Nevertheless, the guidelines in this paper offer a starting point, should the architect wish to give residents the feeling of control over their environment that operable windows uniquely offer, without compromising the environmental or structural performance.

As can be seen, many of the possible combinations present trade-offs. Therefore, future research directions could include how to optimize for both natural ventilation and aerodynamic performance, i.e., weighing the trade-offs of increasing the size of the side of the building facing the predominant wind for natural ventilation purposes, even though shaping and sizing the same face for aerodynamic loading would require making it smaller for ventilation. Finding a middle ground between the two constraints in a quantitative approach using further air flow and energy simulations could lead to more specific recommendations for how to make natural ventilation via operable windows in structurally efficient tall buildings feasible.

References

Alaghmandan, M. and Elnimeiri, M. Reducing Impact of Wind on Tall Buildings through Design and Aerodynamic Modifications (Architectural and Structural Concepts to Mitigate Wind Effect on Tall Buildings). in Proc. AEI Architectural Engineering Conf., pp. 847-856., 2013

Al-Kodmany, K. and Ali, M.M., The future of the city: Tall buildings and Urban Design, WIT Press, 2012

Barnes, J. and Hendricks, J. "The Bow, Calgary", CTBUH Journal 2013, Issue III

Brager, G.S., G. Paliaga, and R. de Dear "Operable Windows, Personal Control and Occupant Comfort", ASHRAE Transactions, Vol. 100, Part 2., 2004, pp.17-35

Brass, K., Wood, A., and Carver, M. “Tall Buildings in Numbers: 2012 A Tall Building Review”, CTBUH Journal 2013, Issue I

J. Felkner, E. Chatzi, T. Kotnik, “Interactive Particle Swarm Optimization for the Architectural Design of Truss Structures”, 2013 IEEE Symposium Series on Computational Intelligence, IEEE SSCI 2013, April 16-19, Singapore

HOK, [ONLINE] "Workplace Strategies that Enhance Performance, Health and Wellness", http://www.hok.com/thought-leadership/workplace-strategies-that-enhance-human-performance-health-and-wellness/, accessed, February 2014

Kareem, A., Spence, S., Bernardini, E., Bobby, S., and Wei, D. "Using Computational Fluid Dynamics to Optimize Tall Building Design", CTBUH Journal 2013, Issue III

Krem, M., Hoque, S., Arwade, S, and Brena S., “Structural Configurations and Building Energy Performance”, J of Architectural Engineering, Vol 19, No 1, pp.29-40, 2013

Mak, C.M., Niu, J.L., Lee, C.T., and Chan, K.F. "A numerical simulation of wing walls using computational fluid dynamics", Energy and Buildings, Volume 39, Issue 9, Sep 2007, pp 995-1002

Nicol, J. Fergus, and Michael A. Humphreys. "A stochastic approach to thermal comfort-Occupant behavior and energy use in buildings." ASHRAE Transactions, Vol. 110, Part 2, 2004, pp. 554-568.

Oldfield, P, "Embodied carbon and high-rise". in Proc. of the CTBUH 9th World Congress Council on Tall Buildings and Urban Habitat. pp. 614-622, 2012

Sivakumar, P, Palanthandalam-Madapusi, H., and Dang, T. "Control of Natural Ventilation for aerodynamic high-rise buidlings", Building Simulation, Vol.3., Issue 4, pp.311-325, 2010

Wood, Antony and Salib, Ruba. 2012. Natural Ventilation High Rise Buildings SALIB & WOOD. Abingdon, Oxon: Routledge.

Yeang, K. “The green skyscraper”, Prestel, New York, 1999

Young, A., Annereau, N., Butler, A. and Smith, B. "The Leadenhall Building, London", CTBUH Journal 2013, Issue II.