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Using Height-Relative Variables To Design Tall Buildings

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John Jory holds a Masters in Architecture from the University of Queensland. He has worked in United Kigndom, Dubai, Oman, and Australia, and is currently a PhD Candidate at Queensland University of Technology. His research topic is "vertical variations in the urban environment, and their potential utilization in tall building design," defined by the construct "Height-Relative Variables" (HRV). It is expected that significant benefits may result from the development of a design methodology that utilizes HRV data to leverage the effects of height.

Abstract

This paper investigates height-variable phenomena in the urban context, and their relevance to the design and performance of tall buildings. It proposes a design approach relevant to variable conditions as encountered along height, demonstrates its potential viability for further development and eventual application.

Presented are two novel concepts: the first concerns Height-Relative Variables (HRVs), factors that vary along height that may influence the design and utility of a tall building, and are proposed as a new class of design data, for which a taxonomical structure and data format is devised. "Eco-strata" (a construct from ecology and stratification) proposes and defines the model for a stratified design response utilizing HRV. The hypothesis is that HRV, when applied in design using "eco-strata" methodology, may demonstrate that an urban high-rise so configured could improve the tall building typology.

Keywords: Urbanization, Environment, Design Process, Sustainability

Introduction

Tall buildings in dense, compact urban developments have the potential to contribute to sustainability, and when within larger dense areas, to more efficient use of land, infrastructure, and transport. Is there a better, more efficient, model for tall urban buildings? A guiding hypothesis underpinning this research suggests that there may be. The proposition is that in the urban context, variations along height may have unrealized potential for beneficial utilization in tall building design. This study investigates that theory, and proposes a methodology to realize by design the improved paradigm offered by that proposition. Tall buildings generally are not being designed to comprehensively address vertical variability, and they would potentially be more energy-productive, environmentally efficient, and user-appropriate if they were to draw from the efficiency inherent in matching their design to varying conditions as encountered vertically.

Vertical Variation and the Urban Climate

Atmospheric vertical variations are naturally occurring phenomena, and the benefits of harnessing them are well – established. Temperature and pressure differentials have been utilized for millennia by using the "flue effect" (essentially nature correcting an imbalance), and with specific regional applications such as windmills and turbines.

International standards define "ideal" pressure, temperature, density, and other variables as altitude above sea level (ISO 2533:1975), but the urban vertical profile is essentially characterized by its man-made origins, and is affected by low-altitude phenomena such as anthropogenic heat, particulate aerosols, pollutants, humidity, and weather.

Oke, when investigating the Urban Heat Island (UHI) effects and associated vertical variations in 1976, identified two distinct layers: the lower layer between urban elements up to roof level he named "the Urban Canopy", and the upper he called "the Urban Boundary Layer" (Oke 1976). Figure 1 shows Oke's schematic representation of

"The urban vertical profile is essentially characterized by its man-made origins, and is affected by low-altitude phenomena such as anthropogenic heat, particulate aerosols, pollutants, humidity, and weather."

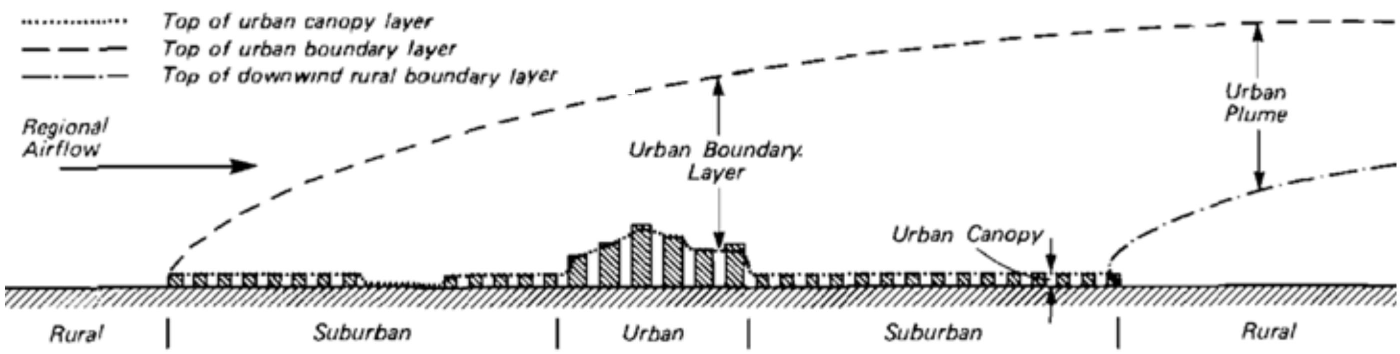

Figure 1. Schematic representation of the urban atmosphere, illustrating proposed two-layer Canopy and Boundary Layers classification. Source: Oke,1976

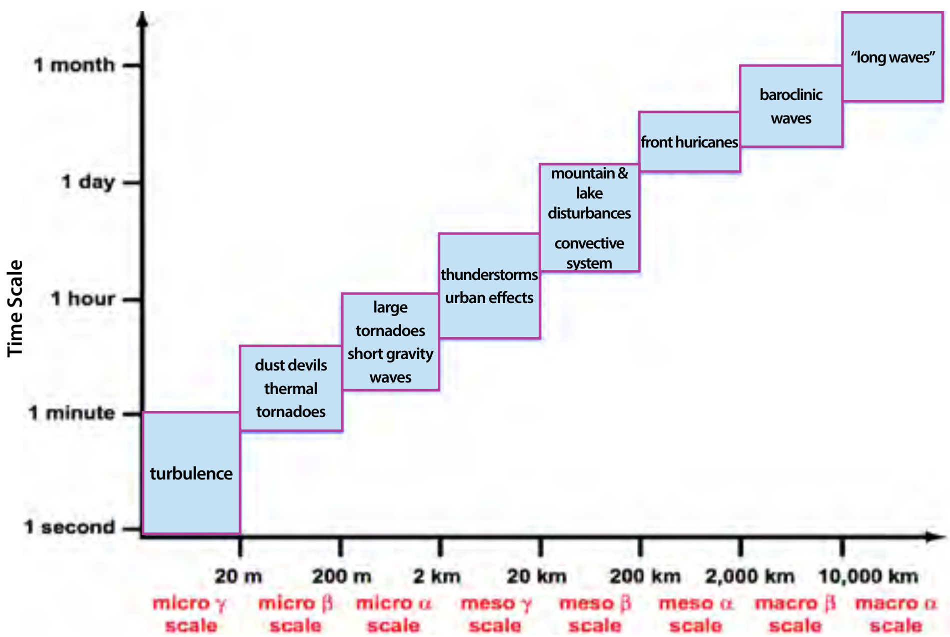

Figure 2. Meteorological space and time scale. Source: Markowski and Richardson 2010.

these layers. Today, urban buildings are generally considered as within the locality-specific "micro-scale" Urban Canopy Layer (UCL), characterized by local airflow and energy exchanges below average roof level, and the zone above is the "meso-scale" Urban Boundary Layer (UBL), influenced by a larger area that may include urban and rural elements.

This distinction in scale between UCL and UBL fundamentally changed urban climatology by introducing the realization that the UBL may not be in equilibrium with the urban elements below (Arnfield 2003). In other words, taller urban buildings could have upper levels within the UBL. Significantly, this distinction between the UCL and UBL offers the possibility of leveraging those differences by design.

Meteorological time and distance scales are linked (see Figure 2). A "micro-scale" climatic event will range from a few meters to two kilometers in horizonal length, and from a few seconds to an hour; whereas "meso-scale" activity may extend over a length of 2 to 200 kilometers, and last up to a day.

The UCL/UBL divide also contributes to a complex cycle of energy exchanges, with a dynamic vertical profile characterized by the influences of anthropometric, diurnal, and seasonal variations. Figure 3, a schematic from Oke (1987), shows urban energy exchanges.

Design Research and Vertical Variation

A substantial body of research on the urban environment exists, but few studies address vertical variation relative to tall building design and performance. Among notable exceptions is a 2005 simulation by Ellis and Torcellini for New York's One World Trade Center, which modeled altitudinal variation for every floor in terms of air temperature, wind speed, shading, and reflection. They found that, along the building's height, atmospheric changes acting together with imposed urban environmental factors "… create a microclimate that can vary from floor to floor of a tall building" (Ellis and Torcellini 2005).

In Leung and Weismantle (2008) coined the phrase "Sky-Sourced Sustainability." Citing the scope of Ellis and Torcellini, they added air pressure, moisture and air density in modeling a hypothetical one-kilometer tower set in Dubai. Finding that altitudinal variations have the potential to offer significant energy-saving opportunities, they also suggested architectural design may be varied over height to reflect different environmental exposures. Another kilometer-high tower simulation was undertaken in 2012, this time set in a temperate Korean climate, modeling annual meteorological variation across five 200-meter vertical zones. Large differences in HVAC loads along the height were found, compared with conventional single-zone calculations (Song & Kim 2012). Tong, Chen, and Malkawi (2017) in researching natural ventilation, simulated diurnal and seasonal vertical profiles for wind speed, temperature,

> “As a consequence of crossover effect and multiple classifications, HRVs tend to be interactive, and may also be subject to additional dynamic variation from seasonal and diurnal cycles.”

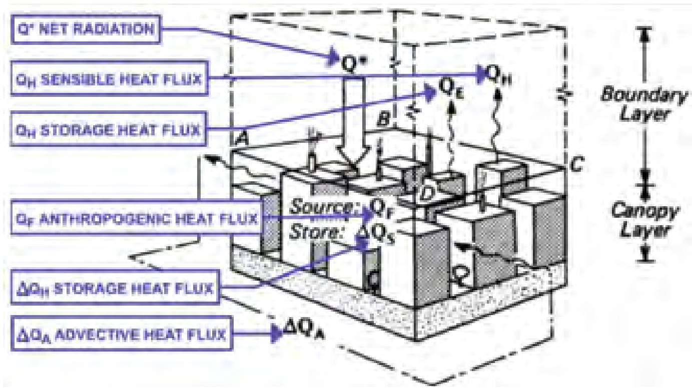

Figure 3. Schematic depiction of Urban Energy fluxes, with Canopy and Boundary Layers. Source: Oke 1987.

and specific humidity variations over heights of 0 to 300 meters for six US cities in different climate zones. Figure 4, derived from their research, illustrates the typically dynamic nature of vertical variation.

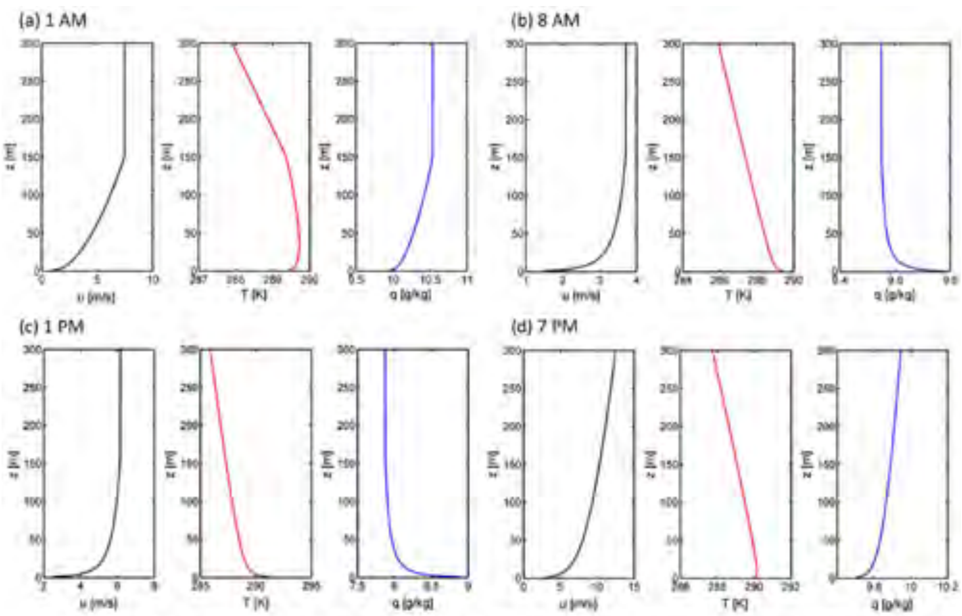

Figure 4. Vertical profiles of wind speed (u), absolute temperature (T), and specific humidity (q) at different times of day during the summer solstice in Los Angeles. Source: Tong et al., 2017.

The importance of vertical variation is also recognized by ASHRAE, which notes that, although the climate at 100 meters is not the same as at 600 meters above ground, “rarely does the design of the upper level of the building capitalize on that difference” (Simmonds 2015).

The literature investigation has shown that, published work so far largely deals with vertical climatic variation, which in itself is of primary importance, but many height-influenced non-climatic effects may also be present. Therefore, this study also includes those aspects of vertical variation that may hitherto have gone unrecognized, to demonstrate the relevance and potential benefit of a comprehensive approach to HRV application.

The Investigative Framework

This study has been underpinned by investigation of interrelated topics that represent the theoretical framework adopted at the outset. Primarily an exercise in design thinking, the aim of this research is to develop a systematic approach to the design of urban tall buildings that holistically reflects variations that occur indoors and outdoors along a tall building’s height, using as its methodological model “eco-strata”, a hybrid of “ecology” and “stratification,” outlined later in this paper.

Figure 5 represents the four primary topic areas: at the top, Tall Urban Buildings; at the bottom, Variations over Height, with Climate (left) in a sense representing how things are, and Design (right) representing how they might be. This illustrates the divide between the natural sciences and the “sciences of the artificial” (Simon 1996). Here again, the sub-categories at the overlaps tend to reflect the natural sciences on the left and the “artificial sciences” on the right; at the central intersections sits “eco-strata” as the height-optimized expression of these interrelated topics.

Height-Relative Variables (HRV)

The construct “height-relative variables” (HRV) has been coined for height-influenced and dependent variable conditions. These naturally include climatic and atmospheric variations, such as air temperature, humidity, pressure and density, wind speed and flow, daylight, shade, and so on. Importantly, in addition to those, there are many non-climatic variables along building height that may also influence the design and utility of a tall building, for example: access, connectivity, safety and security, noise, view, cost and valuation. All are subject to height-related variation, and all, if advantageously utilized, can facilitate a comprehensive design approach. Figure 6 shows the schematic concept for HRV.

Classifying HRV

Nobel laureate Herbert A. Simon is widely regarded as originator of the notion of "design as a way of thinking." In ***The Sciences of the Artificial,*** Simon suggests a "taxonomy of representation" will aid the understanding of "any set of phenomena" (Simon 1996). This study is no exception, and an essential preliminary was to devise a taxonomical structure for the classification of relevant HRV, thereby providing a definitive framework for the research variables.

The classic taxonomy is Carl Linnaeus' 18th-century model for natural history, an eight-level hierarchical taxonomy still used in biology today (Linneaus 1758). Typically taxonomies provide a scheme of classification for precise definition, as is the case with Linnaeus where the last two categories, genus and species combine as an unequivocal defining binominal. But what would be the appropriate taxonomical structure for HRV? It can be argued that the requirements differ, in that, to define HRV within a hierarchy is not relevant; instead it is required to categorize effects and influences which are often subjective, may change, may or not be quantifiable. The scope of HRV may be considered theoretically indeterminate; therefore, in addition to definition, a structure related to design methodology may be beneficial. The simplest interpretation of the information required to design a building defines: where it is, what it is, and what it's for. On that basis, three primary HRV categories are proposed, respectively characterizing: location (climatic and physical environment); performance (configuration and built environmental interactions); and the utility of a building. These categories are hierarchical, only insofar as they reflect broadly the conceptual sequence of design. They not only classify but also provide the structure for a design-centric HRV vocabulary and are defined as follows:

1. *Climatic HRV:* relating to the climate generally, the modified urban climate, and climatic effects characterizing the location and its natural and built environment.
2. *Performative HRV*: relating to buildings in urban settings and capable of influencing the form, construction, and performance of a building.
3. *User HRV:* directly relating to a building's utility and capable of influencing its occupancy and use.

As HRVs define effects that influence design, performance, and utility, they have distinctive characteristics. HRVs, and can manifest in diverse ways. A temperature-relevant HRV, for example, may arise from: altitudinal lapse rate, wind chill, solar exposure, shade, stack effect, reflected heat, and so on. The same HRV effect can also occur as different categories; for example, air pressure variation is normally a Climatic HRV, yet where that pressure differential is utilized to induce airflow, it may act as a Performative HRV. As a consequence of crossover effect and multiple classifications, HRVs tend to be interactive, and may also be subject to additional dynamic variation from seasonal and diurnal cycles.

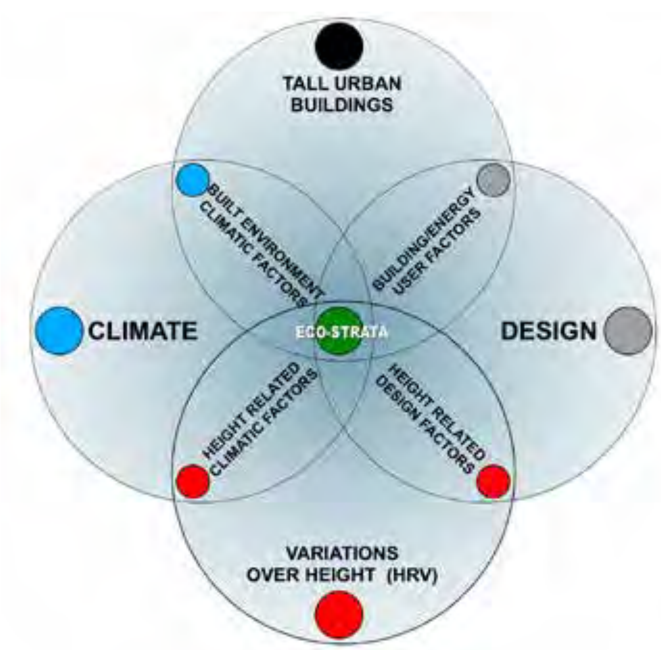

Figure 5. Venn diagram showing theoretical framework for HRV-linked design.

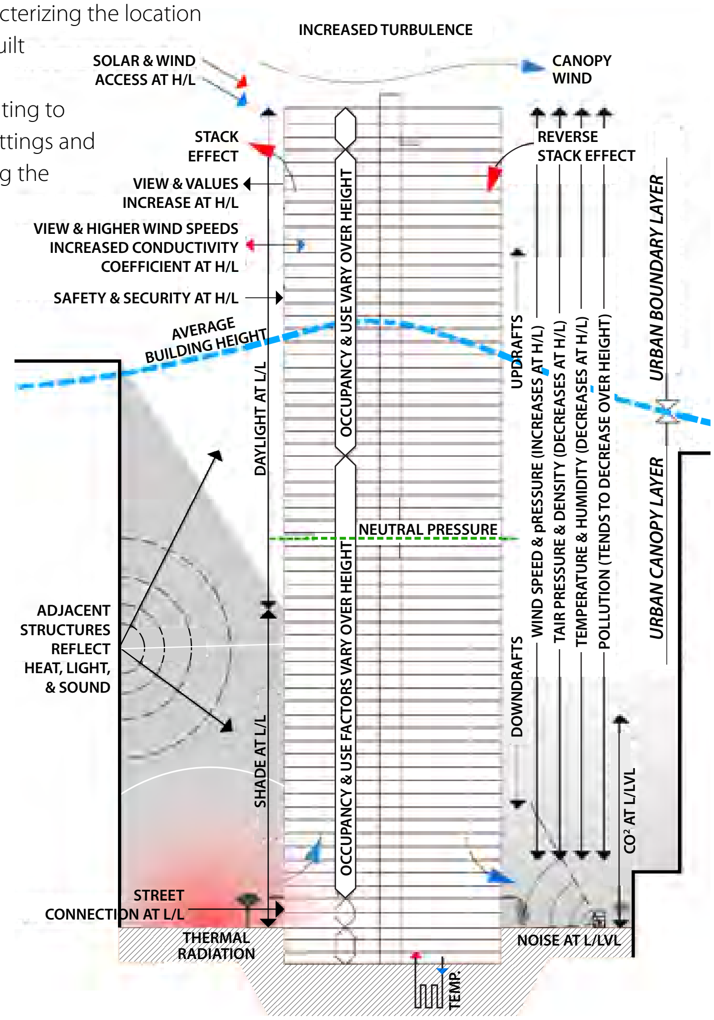

Figure 6. Preliminary schematic diagram for the HRV concept.

Description/Definition	Category	Quant.	Rate/Unit of Measurement	HRV/Utility Rating	Notes: Action/Interaction	Reference
Temperature (atmospheric variation over height)	CLIMATIC (Primary)	Yes	-0.65°C/100 m of altitude	L	This is the dry adiabatic lapse rate which has a linear relationship to altitude	• ISO 2533:1975 (US Standard Atmosphere & International Standard Atmosphere) • ANSI/ASHRAE Standard 55-2010 • ASHRAE Tall Buildings Guide 2015
Category: CLIMATIC/PERFORMATIVE/USER **HRV/Utility Rating: H** (High); **M** (Medium); **L** (Low); **N** (Nil/Marginal)				**Quant. (Quantifiable):** Yes/No		

Table 1. Proposed format for an HRV datasheet entry.

The design of a tall building should ideally reflect all variables likely to be encountered along its height. But as the entire range of vertical variations has not previously been considered collectively, it is expected that where HRVs are comprehensively utilized in a design methodology, the increased scope of the design data may contribute to a more optimally purposed and efficient building.

Formatting HRV data

Defined and verifiable HRV data is fundamental, and the compilation of an HRV database is a key component of this study. The methodology involves the identification and definition of HRVs from analysis of available secondary data gathered on height-related effects and phenomena. With the data extracted, a process of review is undertaken to evaluate evidence and corroborate individual HRVs' relevance to tall building design and performance. From this an index is compiled, formatted to include for each HRV: description (and definition); category (and sub-category where applicable); quantifiability ("Yes" or "No," and if "Yes," the unit/method of measurement); HRV utility rating (rated potential for utilization); notes (on actions and interactions); and references (data reference documents). Table 1 shows the format proposed for a HRV datasheet entry.

Tall Building Configuration and Eco-Strata

If the rationale of considering HRVs a valid phenomenon is accepted as applicable to the performance of tall buildings, then the notion of a vertically stratified design response is implicit to their utilization. The method proposed for the realization of that aim is "eco-strata" (a combination of "ecology" and "stratification"), a concept that considers the elements and composition of a tall building as a three-dimensional volume subject to a multiplicity of influences and effects, internally and externally, that will vary along its height. The eco-strata approach promotes design differentiation along height on the basis of responses to climatic, performative, and user HRVs. The hypothesis is that an urban high-rise configured according to eco-strata principles will reflect the efficiency inherent in matching design to the specific conditions of its stratum, and will also benefit from the lack of redundancy implied by such a design response.

Typically tall buildings are configured in vertical segments, as levels (or groups of levels) on a functional basis, often, even in the case of mixed-use buildings, with segmented functions nearly indistinguishable behind a smooth exterior, except perhaps in the case of mechanical floors. In rarer cases, segments are expressed, such as at Commerzbank, Frankfurt, where 12-story vertical office segments, each with four-story "sky gardens," are stacked and distinct. This approach to configuration has been termed "repeating modules" (Liu, Ford & Etheridge 2012), and can also be seen at 432 Park Avenue, New York, where between each of the 12 floor residential segments, there are "open" floor levels mitigating wind forces in this exceptionally tall and slender tower. What these examples of configuration have in common is that, generally, the vertical disposition of uses or levels, whether or not segmentation is expressed, does not reflect the differences in climate along the height. The segments are stacked and repeated, rather than being individually rendered specific to conditions at their respective vertical locations. Figure 7 shows examples of configuration, some of which begin to hint at what an "eco-stratified" tall building would look like.

The term "strata" is used to differentiate eco-strata from floor levels; eco-strata are more complex, and as they do not necessarily equate to floor levels. An eco-stratum, which may span one or more levels in whole or in part, is a zone in terms of its characteristics relative to those above, below and around it. Eco-strata relate to specific conditions and responses, not to consistent horizontal lines parallel to the ground, and therefore may overlap vertically, or differ horizontally by aspect. As an eco-strata configuration is derived and defined directly from consideration of vertical variables and appropriate locational design responses, it may differ vertically as optimal strategies specific for that stratum are integrated by design.

Implementing HRV-Based Design

HRV-based tall building design requires a methodologically defined process for the comparative analysis of variable actions and influences along height. This research investigates the proposition that such a process in the form of HRV/eco-strata-based design may be viable. It bears mentioning that this is an exploratory academic investigation of theory and application, which aims only to conceptually devise, assess, and advocate for the process.

Given a proposed tall building and project-relevant data, how would the evaluation of identified HRV and height-relative external and internal actions and interactions be undertaken? Eco-strata analysis requires a conceptual "modeling volume;" this is proposed as a "virtual building" BIM model (within which the project's design, construction, and contextual data is represented). Relevant HRV data is applied to the model to initiate the assessment and selection of HRV-based strategies.

Clearly, the analysis of interactive design and performance is inherently complex, notwithstanding the fact that design is an unbounded process; therefore, depending upon the scope of HRV data, an effective model is likely to test cognitive limits. For that reason, HRV/eco-strata methodology in its ideal (eventual) form would benefit from dedicated computer programs that consider that design is not a direct, linear process, and which are able to mimic the processes of human design decisions, wherein analyzed data is rated by decision routines that apply implicit and explicit knowledge. Ostensibly, this represents a formidable requirement, and it's necessary to add here that no computer programing has been undertaken in this study. But height-relevant strategies, for example natural ventilation or height-optimized occupancy, while "interactive" to varying degrees, typically tend to be separable in design terms. Therefore, it is suggested an HRV-based eco-strata approach has the potential for partial application. Therein, as it evolves incrementally, so will the scope of HRV-based design aids, thereby facilitating verification and development. As virtual building modeling is considered essential, it is also expected that the expanding scope of information describable by BIM models will stimulate HRV analysis, perhaps appearing as CAD add-on programs for the representation of explicit and implicit design knowledge in modeling. Aksamija and Iordanova (2010), in their paper on multimodal representation of architectural design knowledge, may provide an insight.

An HRV/Eco-Strata Design Framework

As Eco-strata analysis may be expected to prompt optional configurations, it is intended to commence from the concept design stage, well before a project's component parts, their composition, relationships, and form are fixed, and also to be multi-disciplinary from the outset. Once initiated strategies are evaluated and adopted, they would be refined and developed through to detail design.

Figure 8 shows the HRV/eco-strata design process as proposed, sequentially numbered and starting with the project's brief and preliminary concept (1). This would be constructed simultaneously with the input of relevant HRV and non-HRV data (2); followed by HRV audit and analysis (3). From evaluation modeling, HRV utilization hypotheses are generated (4), enabling an updated HRV-strategized concept design (5). Design development (7) follows, both with concurrent design review (6), finally validating the HRV-optimized final design (8).

Vertical Variation and Building Height

The minimum height at which an HRV-based design approach is worthwhile is a matter of conjecture, and one that this research may

Figure 7. Examples of configuration, from left to right: Guangzhou International Finance Center, (unexpressed configuration); Commerzbank Tower, Frankfurt, and 432 Park Avenue, New York (repeating module configuration).

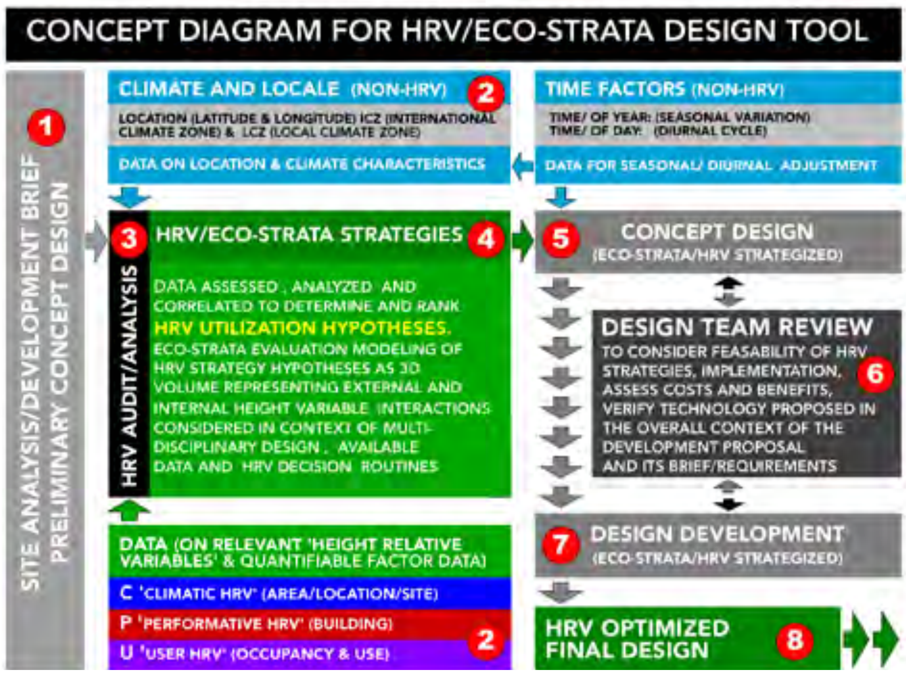

Figure 8. Concept diagram for HRV/eco-strata design tool.

clarify; in the actual event, location and climate will often be decisive. Atmospheric differentiation generally will not be observed below 200 meters, and this height generally exceeds the average in urban areas; consequently 200-meter buildings may be within both the UCL and the UBL and would form a logical bottom threshold for a model intended to demonstrate climatic variation. Using an above-average height also implies buildings more likely to include mixed uses, which in turn may foster energy-saving initiatives such as balancing usage and demand peaks (Li, Shen & Qian 2015). Although taller buildings tend to be higher in energy intensity, the exposure of their extended environmental interface offers scope for an improved passive/productive energy paradigm, particularly as completions in the 200-meter plus category increase (CTBUH 2018).

HRV/Eco-strata Prospects

It is intended that HRVs and "eco-strata" will contribute a different perspective to the design of tall buildings, leading to a difference in the perception of "tall," whereby an inner-urban tall building will be regarded as occupying multiple environments along its height, and functioning at multiple scales. Tall urban buildings are influenced by a hierarchy of effects, from those affecting individual items such as walls, to area phenomena such as locality-specific UHI, and regional effects, all of which may impact on vertical variation. Add to this height-relevant non-climatic considerations of a building's utility, occupation, and use, and the scene is set for a high-rise that may truly reflect all those differences in its design along its height. ■

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