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Performance-based Design of Tall Building Envelopes using Competing Wind Load and Wind Flow Criteria

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Abstract

This paper investigates performance-based tall building design and the development of an architectural and urban design method that focus on the effects of wind loads on- and wind flows around tall buildings. The paper provides an overview of related buildings codes and city development design guidelines that define the requirements of structural façade wind loading and urban ventilation. A review of performance-based design methods for the generation, analysis and optimization of buildings is also presented. Within this frame, an approach to performance-based tall building envelope design is proposed. The approach is aimed at addressing wind loading and wind impact requirements based on generative parametric modelling and performance analysis that integrates physical parameters at the architectural and urban scales and performance criteria can support filtering and optimization relative to prevailing wind conditions.

Keywords: Performance-Based Design; Optimizing Wind Flow Profile;

1. Introduction

Tall building design strategies have been given increasing attention over the last two decades. Conventional tall building design methods typically focus on single-objective design optimisation techniques and/or produce a small number of design alternatives that explore wind loading and wind flows. An integrated method that addresses performance-based design simulation and optimization of wind loads *on*- and wind flows *around*- the envelope of tall buildings is therefore lacking. Building codes and city development design guidelines for tall buildings specify requirements for structural wind loads acting on tall buildings (building codes) and wind flow impacts arising from tall buildings (design guidelines), e.g., at the pedestrian level. As separate compliance processes, building codes and design guidelines each define distinct criteria, calculation methods and testing procedures for assessing wind loads and flows for design compliance. Building codes and guidelines generally define the required performance via the specification of minimum structural performance requirements under wind load and maximum (and in some cases minimum) 'acceptable levels' of velocity and turbulence around tall buildings relative to the impact of the building envelope on wind flow at the pedestrian level. However, in meeting these requirements separately the interdependencies between architectural and urban scales are ignored. It also, neglects the importance of addressing design criteria surrounding wind flow in the early conceptual stages of design. Understanding the nature of aerodynamic behaviour at both architectural and urban scales is an important aspect of tall building design (Khallaf & Jupp 2016). However, the evaluation of the design relative to building wind loads and urban wind flows is separate from each other. Further, assessing how design requirements are fulfilled relies on the insight of the designer who can focus only on a limited range of performance criteria. Traditional tall building design methods are increasingly facing the difficulties of meeting the requirements of multiple disciplines that can be addressed using performance-based design methods. The application of these methods are especially complex when considered in the context of the competing wind load and wind flow criteria occurring at the architectural and urban scales.

This paper explores the notion of performance-based simulation and optimization of tall building envelope design for competing wind profiles, namely structural wind load and urban wind flow. The overall aim of the research is to develop a method for optimizing tall building envelope alternatives during the early conceptual design stages according to competing design criteria defined at both architectural and urban scales. Optimization is therefore achieved using realistic and reliable information of the probable performance of tall building envelops relative to structural wind loads and urban wind flows. In its purest form, performance-based design entails the development of a preliminary design, mathematical modelling of the design, and simulation of the design's response to various wind flow conditions and comparison of the predicted performance of these events with the performance objectives adopted as the design criteria. If the performance predicted in the simulations is found to meet the stated objectives the design is acceptable, if not the design must be revised and the simulations repeated until acceptable performance is predicted. This approach aims to provide a method of designing tall building envelops for specific intended wind load and flow performance that can be used in the early design stages, thereby mitigating the risk of costly design changes in the detailed design stages when compliance against building codes and design guidelines is typically sought. In the context of this research problem the intended performance of a tall building envelope design may be initially found to be superior or inferior to the required design behavior defined within building codes and design guidelines. Further, it also provides a method to benchmark existing buildings relative to the requirements of building codes and design guidelines so as to assess the actual performance achieved.

This research project sits within a growing field of research that is attempting to advance the current paradigm of performance-optimized building design by developing techniques that account for both the architectural and the urban level; moving from building information modelling to city information modelling. Computational fluid dynamics and generative performance-based design simulation and optimization techniques provide two foundational computational design methods of this research. The paper proceeds by presenting the research objectives and method. The authors then present the results of the two literature studies. The first presents an analysis of relevant building codes and city development design guidelines related to the design of tall buildings focusing on structural wind loads and urban wind flows. The second review surveys recent work on performance-based building design and urban planning methods focusing on techniques developed for performance-based simulation of environmental criteria, with some examples of designing for aerodynamic behaviors. The paper identifies gaps in current approaches and presents a framework that identifies the design criteria for a tall building envelope design method such that solutions can be generated, analyzed and optimized to achieve performance objectives related to satisfying competing wind flow profiles. The authors then discuss performance-based simulation and optimization for combined wind load and wind flow analysis for tall building envelope design relative to design iteration and exploration in the early conceptual design stages. The paper closes with conclusions and future work.

2. Research Aim and Method

The shape of the envelope of a tall building has significant influence on its structural wind load and urban wind flow performance. In designing a tall building envelope the provision for its structural performance, together with how it encourages positive wind flow at the pedestrian level whilst mitigating against negative wind impacts is of topical concern to building designers, engineers, urban planners and governments alike. The authors make two claims regarding the challenges that designers face when designing tall building envelops relative to wind load and flow. The first is that there is a relative lack of consideration of the interdependencies between different types of aerodynamic behaviours due to the complexity of designing at a systems level. That is, at a level that accounts for the dynamic interactions of wind at both the building and urban scales. The second issue surrounds the lack of performance-based simulation and optimization methods that take into account wind load and wind flow compliance criteria defined within relevant building codes and city development design guidelines.

The objective of the paper is to investigate formal regulatory requirements at the building and urban scale, and identify existing computational approaches to wind flow design. This paper therefore uses a literature study to explore these challenges, where a sample of building codes and city development design guidelines are reviewed before presenting related literature on performance-based design. The literature study aims to be broad but not exhaustive. It includes a sample of building codes and a number of Australian city design development guidelines, as well as academic articles which have been located using electronic databases, (e.g., Academic Search Complete, Science Direct, Web of Science, etc.) and Google Scholar. Special attention was paid to academic architecture, urban design and planning journals as well as those specializing in structural wind load analysis and computational fluid dynamics. Two different search types were therefore made according to the dual objectives of the research project, namely: (1) *building codes and city development design guidelines* and (2) *performance-based simulation and optimization*. Papers containing editorials, non–research cases, conceptual articles, and reflective reports (i.e., those that an "I" perspective), were excluded.

3. Background: Understanding wind load and wind flow compliance criteria for tall building design

High density cities can be considered as a matrix of wind obstacles, comprising buildings of different size and forms, arranged at varying angles with different distances between them. Such cities can suffer from poor ventilation and air quality problems, whilst others are subject to strong (sometimes extreme) wind conditions due to their geographical location or improper urban planning. In the case of poor ventilation or stagnant air flow, research shows that the health of a city's inhabitants can be at risk due to the lack of dispersion of airborne pollutants (Assimakopoulos & Ap Simon 2003). On the other hand, strong winds can have negative, long lasting effects on cities, their society, the environment, and economy; as is the case in cities such as New Orleans (Kurban & Kato, 2009). As a result, building codes and city development design guidelines target improving the performance of wind loads *on* buildings and wind flow *around* buildings. To specify structural wind loads and acceptable wind flows precisely for every possible tall building shape in the context of its surrounding environment would result in provisions so complex as to be of limited use to designers. Therefore the specification of building codes and city development design guidelines involve some compromise.

3.1. Building codes and structural wind load requirements

One of the main intents of the wind loading provisions in building codes such as Part 2 of the Australia Standard AS 1170.1-1989 and Australian and New Zealand AS/NZS 1170-2, is to specify the minimum design loads on structures such as tall buildings. Tall building envelops are sensitive to a number of wind load factors, including the wind speed and wind turbulence approaching the site, the building height and geometry, and the influence of nearby buildings on the local wind flow patterns. Building codes usually provide loads along the wind direction for common shapes in open and suburban terrain. An exception is the AS/NZ 2002 code which provides provisions for the cross-wind direction as well. The cross-wind motion is mainly caused by fluctuations in the separating shear layers. Torsional motion can be caused due to imbalance in the instantaneous pressure distribution on each face of the building either due to oblique wind directions, unsteadiness in the approaching flow, partial sheltering and interference from surrounding buildings or due to the building's own shape and dynamic structural properties (Dagnew *et al.* 2009). Studies show that in tall building designs, the crosswind and torsional response may exceed the along wind response in terms of both its limit state and serviceability requirements (Kareem, 1985). Nevertheless, many standards, such as the AS/NZS 1170-2 and US standard ASCE07-05, only provide procedures for evaluation of *along-wind* effects. For complex cases, these standards refer to physical model testing using a boundary layer wind tunnel, or BLWT, facility. The approach taken by some codes in predicting structural and wind loads on tall building envelops is to provide simple formulae that include a measure of conservatism, as might be expected based on the approach taken in deriving the formulae. Williams *et al.* (2003) assert that for small projects (e.g., ≤10 stories) with fairly simple geometries, code formulae are probably of sufficient accuracy for design purposes and conservative results may not have a major cost impact. However codes such as the ASCE 7-05 and AS/NZ 1170-2 recognize that for structures with more complex geometry detailed studies using wind tunnel tests are required since they yield more precise definitions of design loads, and more economical and risk consistent structural designs than code calculation methods. Two Israel standards cover building and urban scales, namely the SI 414 (1982), which is aimed at characterizing wind loads for tall buildings and the SI 5281-3 aimed at optimizing favorable wind at the urban scale. Each standard requires solutions to be design that are suitable to the location, protecting against strong wind flows whilst encouraging air ventilation. Both standards require analysis of the wind regime using CFD testing.

3.2. City development design guideline requirements

Similar requirements are also typically requested by city based development design guidelines for assessing wind impacts of the design on pedestrians at street level. The design of tall buildings can impact on wind flows of the microclimate. A wind impact statement is therefore most often required, which must demonstrate via testing the impact that the design will have on the surrounding public realm. For tall building design proposals (typically ≥10 stories), the results of a full wind tunnel test using a BLWT facility is typically required as part of the development application. Generally, submissions must identify and analyze the effects of wind conditions on pedestrians within the site, on the street at footpath and other surrounding areas. A comparative analysis of the current situation against the likely impacts created by the new development is also required; where impacts are shown to be detrimental to current conditions measures to reduce these impacts must be documented.

The City of Sydney Development Control Plan (DCP, 2012) requires a wind effects report based on wind tunnel testing, which compares and analyses current versus proposed wind conditions, where high wind effects at the pedestrian level must be minimized. These provisions apply to buildings that are above 45m. Similarly, the R-Codes of Western Australia (WA 2015) require that high-rise buildings are set back from the site boundary so as to assist in reducing wind impacts. The Perth's Planning Scheme (City of Perth 2013) requires a wind impact statement based on the results of full wind tunnel testing for new buildings that above 10m. Similarly, Melbourne's Planning Scheme (City of Melbourne 2016) requires analytical wind study for new buildings but this scheme does not specify the assessment method. The City of Wellington is an example of a coastal urban environment affected by high winds. The average annual wind speed is 22km/h causing discomfort to pedestrians and impacting on their safety. Due to the high velocity of winds, the City Council of Wellington has developed its own 'Wind Design Guideline' (Wellington Council 2000) to support the design of new building proposals. The guidelines provide a variety of design principles that help to reduce the impact of high winds. The guidelines refer mostly to a building design's positioning and setback. Principles for mitigating wind flow range from maintaining regular building heights to keeping façades with large surfaces from facing prevailing winds. The City Council of Wellington requires wind tunnel testing for tall buildings so as to be able to assess measurements of the wind velocity and their effects at the pedestrian prior to construction. The guidelines focused on the relationship between architectural and urban scales. The City of Toronto (2013) guidelines for tall buildings requires a pedestrian level wind study to demonstrate the positive effect of the tall building's wind impacts at the pedestrian level. The analytical study involves building's location, orientation, and the shape. In addition, it requires permanent canopies and overhangs to provide wind and weather protection. The canopy height must not exceed 6m with a preferred width of 3m.

Enhancing air quality can be facilitated in cities via the application of design guidelines that comprise of such principles as: non-uniformity of roof heights, avoidance of flat roofs, wider street canyons, shortening the length of streets and creating street intersections and avoiding long, continuous building facades at street level. The Hong Kong

Government has invested in research aimed at improving air quality. The final report of the "Team Clean" initiative (HKSAR 2003) resulted in the introduction of Air Ventilation Assessment (AVA) system. The AVA system includes technical methods for assessment and guidelines for city development promoting better air ventilation. The guidelines were developed after conducting studies into urban design policies, as well as personal, building and community hygiene. As one of the most densely populated cities in the world, Hong Kong is also vulnerable to stagnant wind flow conditions. Low levels of wind flow and permeability carries a high risk of airborne diseases. To improve air movement, recommendations range from creating open and linked spaces in street junctions, as well as maintaining low-rise buildings along prevailing wind directions to create voids at the podium (HKSAR 2003). The guidelines specify minimum and maximum acceptable levels of wind velocity and turbulence, and control the detailing of ground level building forms, set-backs and their connections. In study undertaken by Ng *et al.*, (2011) on some of the effects of the recommendations of the AVA system on Hong Kong, including the "wall effect" (created by the buildings along the coastline) CFD and frontal area index techniques have been used analyze its impact on the velocity of wind flow across a city block. The results highlight the relationship between building facades and the distribution of wind flow. The study successful demonstrated the effectiveness of the AVA system guidelines applied to the design of new buildings on Hong Kong's coastline.

The building codes and city development design guidelines reviewed in this section are compared in Table 1 relative to their type, focus of analysis, and analysis technique. As can be seen, although there are a number of variations relative to the scale or level of analysis, building codes and city development design guidelines typically require wind tunnel or CFD testing aimed at mitigating negative wind impacts caused by tall buildings.

Table 1. Building Codes City Design Development Guidelines

Building Code / City Design Development Guideline	Building Scale Wind Load	Urban Scale		Suggested Design Principles	Assessment Method/ Tool
		Encourage Wind Flow	Mitigate Wind Flow		
1. AS/NZ-2002 (Aust. & NZ).	✓			None Provided	Wind Tunnel Testing
2. ASCE07-05 (United States)	✓			None Provided	Wind Tunnel Testing
3. SI 5281 (Israel)	✓	✓	✓	None Provided	CFD
4. City of Sydney DCP			✓	None Provided	Wind Tunnel / CFD Testing
5. City of Perth Planning Scheme			✓	None Provided	N/A
6. Western Australia R-Codes	✓		✓	Building setbacks from street Architectural features to reduce wind velocity	N/A
7. City of Melbourne Planning Scheme	✓		✓	Building setback from street	N/A
8. Hong Kong AVA system	✓	✓		Creating open spaces in street junctions and linking open spaces Maintaining low-rise building along prevailing wind directions Widening minor roads Varying building height Staggering building arrangements Voids on ground floor of buildings	N/A
9. City of Willington Planning Scheme	✓		✓	Architectural features to reduce wind velocity Building setback from street Clustering buildings to mitigate wind velocity and turbulence Building porosity	Wind Tunnel Testing
10. City of Toronto	✓		✓	Optimize location, orientation and form	N/A

3.3. Design principles supported by building codes and development guidelines

Design principles for controlling wind flow have been developed to provide adequate ventilation, protection, and comfort via the design of the tall building envelope and assessment of the building's relationship with surrounding forms. The desired result of wind flow design principles is to promote 'favorable' aerodynamic characteristics -

avoiding unhealthy stagnant air traps, which reduce airflow altogether; or uncomfortable street canyon effects, which channel and increase wind velocity and turbulence. While it is generally understood the performance intent of these design principles is to reduce wind impacts that are detrimental to a city's inhabitants, the level of performance required is only qualitatively stated. What 'favorable', 'acceptable', 'discomfort', 'unpleasant' or 'detrimental' mean in the context of a city's development design guideline is generally not quantitatively specified, despite the requirement of wind tunnel testing. These terms have however been quantitatively defined. Capeluto *et al.* (2003) define 'favorable' wind conditions as moderate winds of 2m/sec, and Penwarden (1973) provide a definition of 'discomfort' as the mean wind speed of 5 m/sec, which marks the onset of discomfort for pedestrians. Speeds greater than 10 m/sec represent 'unpleasant' wind conditions, and speeds greater than 20 m/sec are defined as dangerous for pedestrians (Penwarden 1973). Design principles that are typically described in city development design guidelines relate to four aspects of tall building design, namely (i) the detailing of ground level building form, (ii) the addition of architectural features to reduce or buffer wind flows, (iii) building set-backs, and (iv) adjacency relationships that promote optimal wind conditions. Compliance testing of tall building designs against the requirements of building codes and design guidelines are most often not undertaken until the later design stages, when important decisions have already been made. Changes to the design of the envelope can be costly at this later stage. Further, current building codes and design guidelines are do not adequately address the interface between designing for the wind loads acting on a tall building's envelope and designing for wind flows around a tall building's envelope at pedestrian level.

4. Performance-based simulation and optimization

During the early stages of the design process, decision-making is not typically aimed at satisfying a single objective, rather it is aimed at searching through a range of potential design alternatives that 'satisfice' (Simon 1956) design requirements and constraints; often between competing requirements represented by a number of different disciplines. Relative to the different types of wind load and wind flow requirements, this requires finding alternative design solutions that satisfy both building codes relative to structural design load requirements and city development design guidelines relative to urban wind flow requirements. As discussed in Section 3, whilst most wind load requirements specified in building codes share common standards due to the nature of structural and physical properties, design guidelines vary from one region to another according to environmental conditions, including an area's vulnerability to natural wind hazards (tornados, typhoons, cyclones, etc.). When making design decisions about the envelope of a tall building in terms of its form, mass and height the nature of surrounding wind conditions must first be identified. However, analyzing and filtering design alternatives against specific wind load and wind flow performance criteria so as to meet competing design requirements in the early stages of the design process is a difficult task. In response, the application of performance-based simulation and optimization provides the necessary decision support.

The development and application of performance-based design systems has grown in the past few decades. As early as the mid-nineties, performance-based engineering (PBE) was used in structural engineering applications to reduce the likelihood of structural collapse. For example Shea *et al.* (2005) develop a design optimization method based on a generative structural design system that utilizes parametric modelling and performance-based design. The method is used to design long-span roof systems, where a combination of structural grammars, performance evaluation and stochastic optimization are implemented. Structural grammars enable the generation of new structural truss members, and performance evaluation includes structural analysis, performance metrics and stochastic optimization by simulated annealing. The method demonstrates a number of synergies between associative modelling and generative systems moving towards integrated performance-based generative design. The method enables designers to explore parametric variations of design scenarios and evaluate the structural impact of alternative forms.

In the architectural domain, Oxman (2008) describes performance-based as the exploitation of building performance simulation for the modification of geometrical form for optimizing a candidate design. The benefit of a performance-based simulation is based on the support of analytical filtering and/or evaluation of building prototypes during the early stages of design. This enables rapid design feedback and supports continual modification. A range of applications have been developed in performance-based building simulation and it has established itself as a method for achieving designs able to rationally meet the requirements of a sustainable and a safe built environment (Spence & Kareem 2014). The approach permits the design of buildings with a realistic and reliable understanding of the probable performance in a variety of conditions, such as competing wind flow profiles.

4.1. Performance-based simulation and optimization

Performance-based simulation in wind engineering has seen increasing adoption during the assessment of risk in facilities subject to natural hazards (Huang *et al.* 2015). Jain *et al.* (2001) present a procedure for the calculation of wind load on tall buildings located in the strong wind region using performance-based wind design. The study demonstrated that the wind speeds in the building codes of the United States (e.g., UBC, ASCE 7-95) are not sensitive to site specific conditions and have a large degree of uncertainty. The study, therefore, proposed a site-specific performance-based design method using wind speeds in the simulation of tall building designs. Jian *et al.* (2001) linked the value of their method with the cost savings for the building owner. A method for 'Performance-based Wind Engineering', or PBWE, was first developed by Paulotto *et al.* (2004). The method focuses on the performance of tall buildings subjected to extreme wind conditions. The method defines two performance levels: high and low. High-performance relates to a definition of pedestrian comfort / discomfort levels and is based on alterations to the wind field at street level. Low-performance considers the building's structural loading and the probability of failure and collapse. Spence & Gioffrè (2012) propose a 'Reliability-Based Design Optimization' (RBDO) framework, which is based on a directional fragility model that combines the directional building aerodynamics and climatological information, and is aimed at optimizing large-scale design problems that are characterized by several global component-wise probabilistic constraints. Granadeiro *et al.* (2012) present a methodology to assist design decisions regarding the building envelope shape considering its implications on energy performance. Their methodology involves a flexible design system, to generate alternative envelope shape designs, with integrated energy simulation, to calculate the energy demand of each design. Shape grammars are used to encode architectural design systems, given their ability to encode compositional design principles. Their downside is the complexity in developing computer implementations. The methodology converts a grammar into a parametric design system and is illustrated with an application to the grammar for Frank Lloyd Wright's prairie houses.

5. Framework of performance-optimized wind design for urban microclimate

Generally, building codes and development guidelines define the required performance using specifications of minimum structural wind load requirements and maximum acceptable levels of velocity and turbulence around tall buildings relative to the impact on pedestrians at street level. Due to their separate functions, building codes pertaining to wind loading and city development design guidelines pertaining to wind impacts do not sufficiently address the interaction between the structural/ architectural design parameters and the urban design parameters. Further, as discussed in Section 3, code-compliance testing of tall building designs are most often not undertaken until after important design decisions about the façade have been made and at a stage where design changes and rework can be costly. Design workflows for testing performance of the envelope design and pedestrian impact are most often based on prescriptive methods that are unable to optimize to the desired performance at both the building and urban scale. Considering the impact decisions made at the conceptual stage on the success of tall building design solutions, performance improvements to the building's envelope need to be made in the early design stages when building's form, mass, orientation, materials, building systems and related product properties are proposed (Turrin *et al.* 2011). Further, conventional building envelope design methods typically produce a small number of design alternatives (Fisher *et al*. 2012). In response, the authors propose an integrated framework for performance-based design of tall building envelope solutions. In controlling wind load and flow, the positive and negative impacts of wind depends on the relationships between a variety of elements, including geometric attributes describing the building (location, envelope, form, height, porosity, etc.), urban environment (building proximity, street width, open spaces, etc.) and wind variables according to structural loads acting on the façade and wind flows relative to neighboring buildings. The framework is therefore based on different wind load and wind flow criteria and accounts structural building and urban parameters as shown in Table 2.

The method is based on generative parametric modelling and a two-stage performance analysis that enables the gap between building and urban scales to be bridged. The approach is therefore able to support the simulation and optimization of wind loads *on*- and wind flows *surrounding* tall buildings. The framework is based on three modules and seven steps as shown in Figure 1. Details of each module are explained below.

Table 2. Design Parameters and Performance Criteria for Tall building Envelope Design

Type	Parameters	Value
Building	Building Location	Coastal, Inland, latitudes, longitudes
	Building Orientation	0 to 360°
	Chamfered corners	9% to 16% of the building breath
	Corner Cut & Corner Recession	5% to 10% of the building breath
	Rounded corner	>10% of the building breadth
	Elliptical cross section	Floating value
	Tapering	2.5% to 15% from the ground to the highest point of the building
	Openings	1.5 to 25% building width
	Building Height	>45m
Urban	Urban Density	≤12:1
	Street width and length(m)	Street Width 7.2m to 16.6m, Street length 100m to 200m
	Building Block width and length	Width 70m, Length 100m to 200m
	Urban Porosity	N/A
	Building Separation	8m to 16m
Wind	Velocity	1.5m/s to 2.5m/s
	Turbulence (TKE)	Floating Value
	External Pressure Coefficients	≤ +0.48 Kn/m2

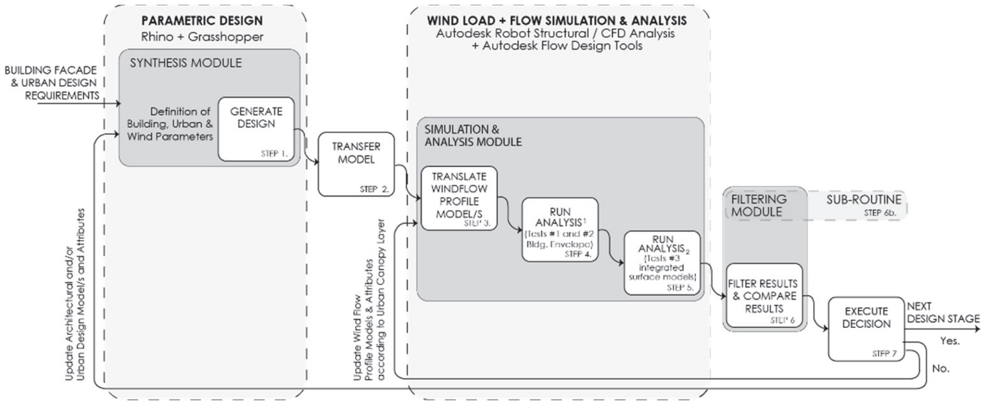

Fig 1. Three modules using a seven step process for integrating architecture and urban design with wind flow performance design.

Synthesis Module - Define parameters and constraints: To ensure a common understanding of tall building envelope design across different platforms (parametric design, performance), a collection of key performance parameters are identified and defined in line with its corresponding geometrical and urban constraints. Due to the breadth of performance-based design knowledge, the proposed system must be defined in a way that is both specific and comprehensive. The working system boundary is defined based on three groups of parameters, as shown above in Table 2. The three categories of parameters are identified as critical components for the proposed performance-oriented parametric system, namely, performance parameters (for wind load and wind flow) and geometric parameters (defining the building envelop and urban environment). By assigning different values to the geometric parameters, the values of the above performance factors are accordingly adjusted in parallel with the geometrical change of the tall building envelope. The change of performance factors can be visualized within the system, which assists designers to make possible the interaction between design selections and their impact on wind load at the building scale and wind flow at the urban scale. Grasshopper is selected as the parametric modelling tool due to the capacity of flexible modelling rendering and design work flow when integrated with Rhino. A governing model is therefore established based on the main parameters influencing the performance of the building relative to wind load and wind flow, namely (1) building orientation, form, height and building porosity, and (2) urban density, building distance, building configuration, street width and length and urban porosity. The model is a surface-based model composed of geometric primitives (points, polygons and surface).

Simulation and Analysis Module: The aim of the synthesis module is to explore the various possibilities of linkage and interaction between building and urban parameters though a series of tests. This stage is therefore principally about taking the parameters defined in the previous module (see Table 2) and relating them to the model. The flexible relations between geometries, wind load and wind flow performance can then be analyzed. A relational diagram is applied in mapping the relationships between the different parameters. The analysis workflow enables the manipulation of both geometrical parameters and performance variables with feedback data visualization and result comparison. Autodesk Robot Structural/ CFD Analysis and Autodesk Flow Design are selected as the performance simulation tools. The rationale for their selection is due to the wide range of simulation tasks and work flow based on their share proprietary platform. Furthermore they are broadly used both in research and practice.

- *Single discipline simulation and analysis*: A series of tests are undertaken in this stage to explore various aspects of the governing model. The first test comprises two forms of analysis, where various combinations of parameter setting and their interrelationship are examined in these tests. The tall building envelope (a single discipline problem) is the basis of analysis using basic wind loading criteria: Test #1 - explores visual feedback of performance factors triggered by changes to wind load parameters. Test #2 - explores direct visual interaction between geometry and performance. Expected changes of performance results are triggered by various geometrical adjustments to the external envelope. Test #2 is based on the same governing model as in Test #1.
- *Multi-disciplinary simulation and analysis*: This second stage of testing is the core component of the overall research. It focuses on the full range of performance requirements (Table 2) to consider the geometry of the building envelope and urban environment in terms of wind performance. Simulations are run for prevailing winds relative to seasonal variations (summer, autumn, winter and spring). At the urban scale, the objectives of optimization may be different relative to seasonal wind speeds and directions. For example, in autumn/ winter, it may be aimed at minimizing wind velocity, turbulence, pressure and wake; in spring/ summer, wind velocity may need to be maximized to encourage adequate levels of ventilation, whilst the incidence of turbulence and wake should be minimized. These conflicting objectives pose challenges for design exploration. The combination of monthly prevailing wind speeds and direction distributions can be set as performance goals for generating collections of corresponding geometric iterations of the tall building envelope. Galapagos, a plug-in of Rhino Grasshopper, is adopted as a bi-directional approach to multi-objective problem solving. Test #3 is therefore based on the parametric "governing model" from the previous tests, with the goal to develop a processing model, moving from a single objective function (wind load) to a multiple objective function to deal with the competing objectives of urban wind flow.

Filtering module: Refers to overall results of simulation and analysis, comparing results from the previous module with design constraints to filter design solutions. The module ranks solutions according to performance criteria defined at three different levels within the UCL: at pedestrian level (1.75-2m), at podium level (6-15m) and above (16-45m). A ***Sub-Routine - External Constraints module*** extends the Filtering Module so as to consider other architectural and urban design constraints. A real-time feedback loop between adjustable geometric properties of the tall building envelope and its corresponding wind performance closes this unified system. The framework therefore also assists designers understanding the nature of wind load and wind flow behaviors at both building and urban scales. The approach is intended to optimize the design solution to one that satisfies competing criteria whilst meeting building standards and city development guidelines.

6. Conclusion

This paper presented a review of building codes and city development design guidelines pertaining to the design of tall building envelopes for wind loads and urban wind flow requirements. A brief review of related studies investigating the role of performance-based design was then presented. Based on the literature surveyed, the paper highlighted the lack of performance-based simulation and optimization approaches that take into account building and urban scales relative to wind load and wind flow performance criteria. In addition, a gap in understanding of the dynamic nature of the design parameters and competing performance objectives surrounding the building scale and the urban scale was identified. The authors then proposed a framework based on building and urban parameters and wind performance criteria. The framework seeks to bridge the gap relative to dependencies between the two scales and supports the filtration and optimization of tall building envelopes. The benefit of using the framework surround the performance-based feedback which is valuable to decision-making in the early stages of design.

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