Designing for Urban Microclimates: Towards A Generative Performance-based Approach to Wind Flow Optimization

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This paper presents the foundations of a multidisciplinary design optimisation method that addresses the problem of competing wind flow profiles within urban microclimates. The simultaneous integration of architectural and urban design parameters and their aerodynamic constraints are investigated. Differences in the height of tall buildings, which define the urban canopy layer are accounted for. The formulation that supports the simulation of aerodynamic forces at the architectural and urban scales includes multidisciplinary parameter specification of 2D and 3D building geometry, spatial morphology, spatial topology, wind flow settings, and wind flow compliance. The MDO framework and its development are discussed relative to their generative performance-based capacity and innovative approach to multidisciplinary wind flow optimization

Keywords: *Urban microclimate, Multidisciplinary design optimisation, Generative performance-based design, Systems level perspective*

INTRODUCTION

Globally the growth of high-density cities is on the rise (Ng 2011), placing more pressure on the provision of adequate air ventilation in these spaces. Further, over 310 million people live in cities with a high probability of extreme wind events such as tropical cyclones and by 2050 these numbers are predicted to more than double (Lall and Deichmann 2012). The urban climatic issues of providing adequate urban ventilation whilst mitigating against the hazardous impacts of extreme wind events in city environments is therefore of topical concern to building designers, urban planners and governments alike. This paper puts forward a notion that the relative lack of consideration of these interdependent microclimatic issues is due to the complexity of designing at a systems level. That is, at a level that accounts for the nature of aerodynamic behaviours at both architectural and urban scales.

Consequently, the authors focus on the multidisciplinary design optimisation (MDO) problem of competing wind flow profiles that exist at various scales within urban microclimates, where a microclimate is defined as the climate that prevails at the micro-scale level and that differs from the surrounding area (Erell et al. 2012). Relative to wind flow, the microclimates of small or restricted areas of high-density urban environments can be conceived relative to both architectural and urban scales. At the architectural scale, microclimatic wind flow profiles are typically modelled relative to 2D and 3D building features such as niches, under-crofts, openings, courtyards, and awnings. At the urban scale, microclimatic wind flow profiles are modelled relative to 2D and

3D spatial features, (i.e the spaces between groups of buildings), such as street canyons, parks and the 'canopy' of building heights across a city block. From this perspective, this paper presents a framework for the development of a MDO method that accounts for the aerodynamic forces acting upon 2D and 3D spatial features of individual and groups of tall buildings. In addressing this MDO problem, the framework seeks to bridge the architectural and urban design scales, and therefore takes a systems level approach to the optimisation of 2D and 3D architectural and urban design solutions.

The paper proceeds with a review of related literature focusing on the main types of wind flow studies and MDO techniques, including generative techniques before then identifying the research gap relative to the dependencies between the architectural and urban scales. Section 3 presents the framework for developing an MDO methodology for a generative performance-based approach to wind flow optimization. Section 4 closes the paper with a discussion on future work and how MDO can be used to support complexity and a systems level approach to the design of 'favourable wind' conditions in high-density cities at both the building and city scales.

RELATED LITERATURE

In considering the MDO of satisfying competing wind flow profiles across architectural and urban scales, three fields of design science research are of interest: (i) optimisation of building shape and form, (ii) optimisation of spatial morphology and topology, and (iii) multi-objective optimisation and MDO methods.

Optimisation of Building Geometry in Architectural Scale

Numerous research studies on the aerodynamic optimization of building morphology have been undertaken over the past 50 years. Davenport's (1971) investigation of the shape effects of building forms documents some of the earliest work that utilises aerodynamic model tests of tall building structures. The research work that followed Davenport's pioneering research focused on the effects of a five general characteristics of building morphology aimed at reducing aerodynamic forces. They include optimising for the effects of: (i) building corner modifications (see e.g Dutton and Isyumov 1990); (ii) tapering and stepping (see e.g Kim and Kanda 2010a, Kim and Kanda 2010b); (iii) openings and slots (e.g see Isyumov et al. 1989); (iv) twisting (Xie et al. 2014); and (v) building configurations and composite models, (see e.g Tanaka et al. 2013), which explore different building plan shape boundaries (square, circular, rectangular and elliptic), together with different corner modifications, tilts, tapers, helical twists, and openings.

The aerodynamic optimization of building morphology can be classified into two categories, namely aerodynamic modification and aerodynamic design. Aerodynamic modification is an approach taken in a situation when a building's aerodynamic mitigations are necessary but where only limited shape changes are permitted in order to keep the building's overall design unaffected. Corner modifications, such as chamfering, slotting and roundness are common approaches. However, given the confinement in this category and applicable/feasible aerodynamic modifications, the level of improvement may not be sufficient to meet all design objectives in some cases. Structural measures or supplemental damping devices may have to be introduced for further improvement. Aerodynamic design on the other hand is an approach that integrates architectural design with aerodynamic considerations in early design stage. Much more aerodynamic options are therefore available and the outcomes are more efficient and effective. However, the challenge with this category is to quantitatively assess the level of effectiveness of various aerodynamic options, so that an optimized balance can be reached between the costs and benefits. Traditionally this requires comprehensive tests on various configurations.

Although aerodynamic shape plays an important role in tall building design, its optimization cannot be reached without compromising other design aspects, which limit the number of available options. As a result, a major challenge in aerodynamic building design optimization is not to look for the best aerodynamic shape, but to achieve the best balance between aerodynamic efficiency and other design aspects, including aesthetics, cost and urban planning regulations. The various difficulties in the aerodynamic optimization of building morphology surround the compromise between aerodynamic constraints with other (potentially competing) architectural design variables. This leads to a compromise between the benefits and costs of aerodynamic optimization (Xie 2014). Assessments of aerodynamic effectiveness of building shape variables such as tapering, stepping and twisting must be capable of being measured in the conceptual design stages so as to be able to assess these compromises effectively, including their potential to minimise across-wind responses, maximise possible reductions of wind load, and reach an equalisation of responses for different wind directions. Such information provides a valuable guideline in building optimization studies when a compromise between various design aspects is desired. Reasonable assessments of the effectiveness of various aerodynamic options in the early design stage can then be made so that the potential pros and cons can be evaluated in the decision-making process with regard to other design criteria

Optimisation of Spatial Morphology and Topology in Urban Scale

The spaces and open areas between buildings, such as streets, parks and city block courtyards are some of the most important urban elements where wind flow, population and traffic density fluctuate significantly depending on the surrounding building forms, and human exposure to good or low quality air conditions (and hazardous substances) can be expected to reflect such fluctuations (Selberg 1996). As a result, wind flow regimes and wind related problems (e.g due to hazardous winds or traffic-related emissions) have aroused much attention. Urban design guidelines and planning strategies have as a result been developed for cities subject to low and/or high wind conditions. Urban design guidelines and planning strategies that target wind flow are generally aimed at increasing "comfort levels" by achieving more "favourable" wind flow profiles. Typically, they have two main objectives namely, to: (i) maximise of urban air ventilation in case of stagnant wind flow conditions (ii) mitigate against hazardous wind flow profiles in the case of high wind conditions.

However, in spite of growing research and urban design and planning guidelines, many metropolises still suffer from poor ventilation and air quality problems due to improper urban planning. Unstructured planning of urban canopies is common in areas of rapid urbanization (Chan and Ellen 2001, Chan and Au 2003). Therefore, research is aimed at furthering an understanding of the effects of street geometry on the local atmospheric environment. The objective of many research studies in this area is to simulate the effects of urban morphology and topology relative to wind flow in the context of pollutant dispersion (e.g Xia and Leung 2001, Assimakopoulos and Ap Simon 2003) and coastal conditions impacting on wind flow profiles and the "wall effect" (Ng et al. 2011), which increases the hazardous conditions for pedestrians in street canyons with different layouts. The identification of critical building configurations that enhance ventilation and thus provide better conditions for positive air flows have been the focus of these studies. The influence of the ratio between leeward building height and canyon width and the ratio between leeward building height and windward building height are shown to be the most significant criteria by these studies.

Accurate prediction of wind flow profiles within street canyons can help urban planners to take into account urban geometry with optimal natural ventilation and comfort. As two of the most important parameters that dominate fluctuations in wind flow regimes urban environments, is the effects of building and street layout, which extends building geometry and architectural morphology into the domain of street canyon dimensions. These effects have been extensively studied mainly with wind-tunnel experiments (e.g Kastner-Klein and Fedorovich 2001), and numerical models (e.g Chan and Dong 2002). Oke (1998), has also studied the flows and the pollutant dispersion within a street, and summarized the flow regimes according to the ratio of the building height and the street width. However, most of the previous research works were considered where the two sides of buildings have an identical height. In the actual street, the typical case is that the buildings at both sides of a street are asymmetrical in the height layout. Xia and Leung (2001), and Assimakopoulos and Ap Simon (2003) have addressed this gap by conducting investigations on the effects of asymmetrical street layout on pollutant dispersion. A study conducted by (Moya et al. 2015) on the inner city of Melbourne a number of architecture design strategies are investigated relative to their potential to reduce the negative effects of high winds at the pedestrian level. The study utilises CFD as its main analysis technique to measure and predict wind velocity. The study shows that the average wind velocity at 2m high is 3.7m/s, but due to the channel effect created by adjacent buildings, wind velocity through the passages reaches 4.4m/s. As a result, there is a concomitant increase in the discomfort of inhabitants. Moya's (2015) study demonstrates the effects of adding architecture features (such as windbreaks) to existing buildings and the level of wind deflection and velocity reduction that can result.

Multi-Objective Optimisation and MDO Methods

By nature, design is a multidisciplinary process and design problem solving is a co-evolution of the problem and solution spaces (Maher and Tang 2003). As an evolutionary process, it is akin to a balancing act between competing objectives all vying for the greatest influence (Gerber and Lin 2014). With the advancement of technology and the increase in information fidelity and availability, the process of design has become more complex as opposed to less. Consequently, multidisciplinary design considerations have become more and more unavoidable. To manage complexity, and the increase in competing objectives, a systematic problem solving technique is needed. MDO methods have been explored by various researchers as an approach to tackle and manage these problems.

MDO refers to methods to solve design problems which have several objective functions and incorporate a number of disciplines, the normative case for design (Coello et al. 2007). MDO relies on numerical optimization techniques required to design systems involving multiple disciplines or components (Martins and Lambe 2013). As defined by Poloni and Pediroda (1997), MDO is therefore achieved through "the art of finding the best compromise". Previous building design precedents have investigated the application of multi-objective genetic algorithms (MOGA) for identifying the optimal in the trade-offs between quantitative cost related and environmental performance variables in the optimisation of designs. For example, Flager et al. (2009) adopted a MDO method to perform a study on a simple classroom design, focusing on the optimisation of structural and energy performance. Magnier et al. (2010) used a MOO algorithm to optimise the energy consumption and thermal comfort of a residential building. The "CATBOT" project is based on MDO methods that link complex geometry to structural analysis (Keough and Benjamin 2010). In the HDS Beagle project, an MDO tool was developed by Gerber and Lin (2014), which associates parametric modelling, and a GA-based multi-objective optimisation (MOO) algorithm focusing on energy use intensity, financial performance net present value and spatial programming compliance. The HDS Beagle tool provides an integrated platform for enabling rapid iteration and trade-off analysis across the domains of design, energy use intensity, and finance (Gerber and Lin 2014).

These previous research efforts illustrate the effectiveness of MDO in identifying higher performance solution sets among multiple competing criteria. However, an important limitation of these applications to consider surrounds their singular domain emphasis, which focuses on either structural performance, detailed mechanical systems, or simplified geometric application settings. As well, the application of preliminary energy performance feedback to support complex geometry has not been fully understood and therefore developed. Our review of the literature highlights this significant gap given the need for integrating architectural and urban variables and measures into the design simulation of geometry and spatial relationships for optimal wind flow.

TOWARDS A MDO METHODOLOGY

During the conceptual design process, it is important for both architectural design and urban planning disciplines to identify wind flow conditions at the earliest possible stage of their respective processes. It is generally established that the performance of a new building will be impacted by the design decisions made during the early conceptual design stages. In the case of architectural and urban design performance relative to their competing wind flow profiles, it is no different. However for urban design professionals, it is not typically possible to explore the impact of wind flow profiles across a new city block or precinct at a sufficient level of detail during the conceptual design phase due to the lack of information about the physical features of the buildings that they will contain. Thus, whilst related disciplines, architectural and urban design have established differences in terms of their foci, scale, goals and constraints as well as the guidelines and standards that support decision-making. From this perspective, a focus on the goals and constraints of one discipline (e.g architecture) during the conceptual design process may ultimately result in a lack of attention of another related discipline's (e.g urban planning, Kroo, 1997). Designing for the satisfying of competing wind flow profiles across the urban canopy layer of a high-density environment characterised by tall buildings, such a singular discipline-based focus can result in adverse effects at the building and/or city scale.

The formulation of a MDO method relative to wind flow in high-density urban environments requires the integration of the three disciplines of aerodynamics, architectural, and urban design, which all play an important role in defining and achieving the multi-objective function. In this section, the authors describe how MDO can be used to enable the simultaneous design of "best compromised" architectural and urban forms via the analysis of wind flow profiles at different levels of the urban canopy layer (Voogt 2004), see Figure 1. The criteria of a multi-objective function are therefore investigated relative to satisfying wind flow profiles generated at different levels of the urban canopy. The framework includes design parameters for simulation that include variables describing building geometry, and urban spatial morphology and topology. A number of wind flow compliance parameters are considered including wind velocity, pressure, turbulence, flow regime, and amount of energy

MDO for Aerodynamic Architecture and Urban Design

The complex dependencies between architectural and urban design forms and their impact on wind flow is ill-understood in terms of how to optimise wind flow profiles across the urban canopy layer. An understanding of the behaviour and relationship between wind flow around buildings versus cities is lacking. However, the relationship between the geometric and spatial features that exist across these two different scales is a complex one. There are mixed dependencies between architectural and urban elements with different structural qualities and behaviours. At the building scale, design guidelines and standards that reference to wind conditions direct design decisions towards optimising for structural wind resistance and passive cooling. At the urban scale, planning guidelines are typically directed towards optimising for 'good' or 'best' wind ventilation throughout a city, precinct, neighbourhood, block, or street. The lack of understanding between the dependencies between the architectural on ur-

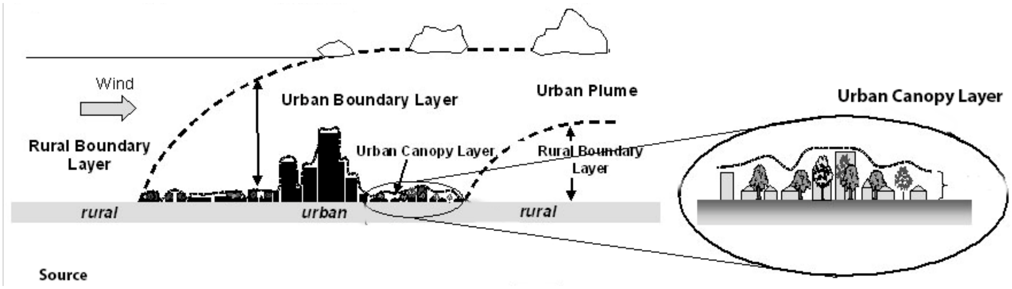


Figure 1
Main components of urban atmosphere (source: Voogt, 2004). Two-layer classification of architectural and urban MDO.

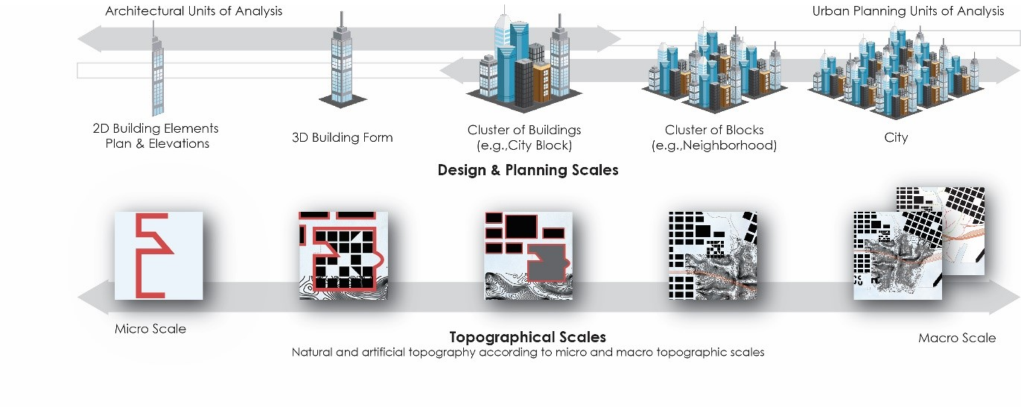
ban scales may ultimately result in poor design performance in terms of how the physical features of each scale impact on the wind flow profiles intended to be realised by the building design and or urban plan.

Considering the different spatial scales within the urban microclimate, wind conditions can be modelled and measured relative to four levels of physical features relating to a building or a city's: (i) geographical location, (ii) land topography, (iii) (urban) spatial morphology and topology and (iv) building geometry. Two main types of wind conditions can adversely impact on both the architectural and urban scales: (a) stagnant-to-low wind flow and (b) high-to-extreme wind flow. In the case of stagnant-to-low wind flow, wind velocity and permeability increases the risk of airborne diseases and pollution. Studies of these conditions have aimed at improving wind flow and developing urban planning guidelines to promote ventilation. These studies generally focus on the interactions between building forms relative to a defined 'grid' of buildings. The unit of analysis and definition of the urban microclimate focuses on the relationship between building- and urban morphology. In the case of high-to-extreme wind flow, wind velocity and permeability increase the risk of building damage. Research studies in this regard have focused on the interface between urban morphology, urban topography and urban topography. Broadly, these research investigations are aimed at understanding how high wind conditions can be mitigated and controlled. The unit of analysis and definition of the urban microclimate focuses on the relationship between a city block, or a small cluster of city blocks (neighbourhoods) and the wider city topology and or the natural topography

The different scales of the physical features of these research studies reflect not only differences in the units of analysis but also how different architectural and urban features impact on wind flow. Figure 1 illustrates this scale, which defines an architectural-urban spectrum that accounts for 2D and 3D features that define the building façade, building envelop, city block, a cluster of city blocks, neighbourhoods, precincts, and the city as a whole.

The gap in understanding wind flow profiles relative to the dependencies between the scales of architectural and urban physical features reflects the disconnect between the architectural and urban planning disciplines. This 'disconnect' is to the detriment of meaningful design for urban microclimates and for achieving the positive effects of wind flow within and around buildings and cities. The approach of this research therefore acknowledges the need to investigate the mixed dependencies between the architectural and urban scales so as to identify the relationships between beneficial wind flow profiles, the physical features that can support them across scales and the resulting design qualities that define the 'urban microclimate'

Figure 2
Spectrum of design and planning across scales of urban microclimate relative to architectural and urban disciplines.



Framework of a Generative MDO Simulation Sequence for Wind Flow

In order to deal with a complex design problem and several design objectives, this PhD research project proposes an integrated approach to coupling parametric modelling techniques with MDO techniques. The framework combines architectural-urban-topography parameters in one platform for performance-driven optimization for wind flow condition. The structure of the proposed framework is based on five stages, with a series of steps across them; these stages are carried out in sequential a manner as shown in Figure 3.

Synthesis module: Using a generative parametric approach, generate all possible design solutions using architectural and urban design variables within a single geometric model so as to manipulate the values of geometric, morphologic and topologic design parameters, and the relationship between the different parameters.

Analysis module: Direct translation of building geometry, spatial morphology and topology together with related wind flow parameter settings into the wind flow simulation engine that utilises CFD to test solutions. As a result, analysable wind flow profiles can be obtained directly from the model without additional modification of geometry before analysis results are then transferred to the Evaluation module

Evaluation module: Refers to overall results of the design analysis. It compares the outcome results from analysis module with design constraints to filters out design solutions. Evaluation module discards all solutions that do not meet building and city compliance constraints. It ranks the remains of design solutions according to their performance based on wind flow criteria defined at different levels within the urban canopy layer, e.g., at the pedestrian level, at ≤100, ≤200, etc.

Sub-Routine - **External Constraints module:** Consists of other architectural and urban design constraints such as building regulations and codes, and zoning ordinance. These constraints granted from outside sources such as city councils and other related authorities.

Optimization module: This module works as a space search mechanism, searching for the optimum design alternatives within the domain of feasible and performance solutions. The aim of the optimization module is to evaluate and choose the fittest of the available and feasible alternative designs based on its performance. However, if the optimized design solution does not fit the performance criteria, a designer can implement changes in the initial design parameters using the synthesis module based on the simulation results.

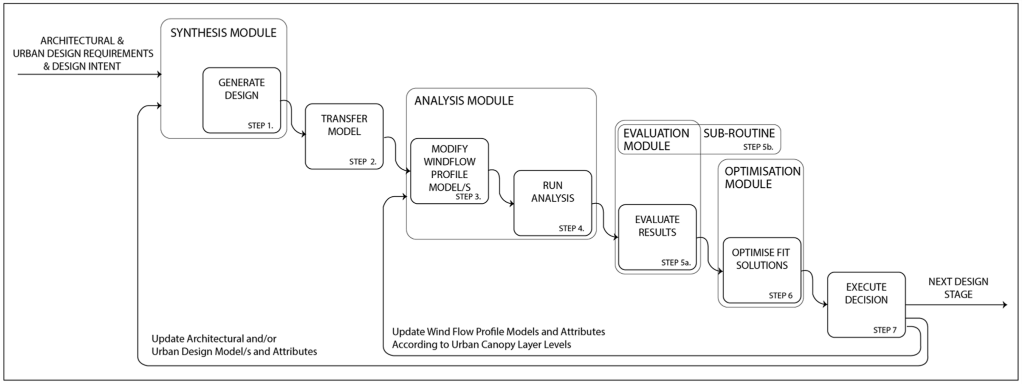


Figure 3
The seven step process for integrating architecture and urban design with wind flow simulation.

MDO Problem Formulation and Parametrization

During the early stage of the design process, the overall building or urban design both play a vital role on the final design performance. Design decisions are not typically aiming to satisfy a single objective rather, it aims at searching for best design solution that compromises between competing objectives. It requires finding alternative design solutions and analysing their performance impacts upfront. However, designers in the early stage of the design process deal with different domains that they may not have experience in. Limitations surrounding experience levels and the fidelity of information may therefore affect the design decisions. In response, a variety of design disciplines have adopted a parametric design approach so as to work within a process that includes a performance analysis feedback loop that supports early design decision-making. Utilising parametric design in the early stage of design process supports the exploration of a larger solution space due to the number of alternative solutions generated via the manipulation of the values of design parameters. It enables the exploration of both architectural and urban design performance, providing an analysis feedback that contributes to the designer's decisions about a complex problem. In addition, it strengthens the flexibility of the design process.

The approach requires the specification of a parametric rig upfront so as to be able to generate a large pool of architectural and urban design solutions, i.e. two layers within the solution space of alternatives. To automatically generate such a solution space, it is necessary to first formally define the design problem into a series of design objective functions, variables, and constraints. These definitions are then used to generate an associative parametric design model, which implicitly describes a bounded and a topologically fixed solution space. The definition of multiple objective functions provide the basis for specifying design parameters and constraints at different levels of the urban canopy layer using corresponding wind flow measures. The specification of these internal layers depends on the city and building profiles relative to existing heights. Consequently, there will be a trade-off between the different objective functions and wind flow profile optimization relative to maximization of air ventilation versus minimisation of hazardous wind conditions. Design variables defined as the parameters that the designer controls influence the design constraints and objective function and are evaluated in the analysis phase; where design constraints are the functions that must be satisfied during the optimization process. In order to create a flexible yet defined design workflow, there are a total of five categories of design variables, including: (i) building geometry parameters, (ii) spatial morphology parameters, (iii) spatial topology parameters, (iv) wind flow setting parameters, and (v) building and city compliance parameters.

Building geometry parameters - From the perspective of architectural design, the units of analysis correspond to the 2D and 3D geometric elements that drive the generation of form. Five parameters controlling building geometry can be identified relative to their influence on wind flow, namely: (i) 2D building footprint or shape boundary, (ii) 3D building profile or form, (iii) maximum building height, (iv) building perforations, and (v) building orientation. Within these parameter categories, controls for manipulating the following four operations are specified: (a) building corner modifications, (b) tapering and stepping, (c) openings and slots, and (d) twisting. The building footprint is used to define the basic 2D building plan so as to be able to explore polygonal (triangular, square, pentagon, hexagon, octagonal, combined between two or more shapes), elliptical or combined shapes. 3D building profiles define the 3D form of building, which enables the different operations (extrusion, twisting, tapering, setback, rounded corners, etc.) to be manipulated. Building height falls into three categories including low-rise buildings with a height from 0 to 10m, mid-rise buildings with a height varying between 10 to 15m, and high-rise buildings that are more than 15m in height. Building perforations enable the exploration of buildings to be able to mitigate against strong aerodynamic forces (especially for tall buildings) and this will also depend on the location, dimension and quantity of openings. Finally, the building orientation can vary 0 to 360 degrees.

Spatial morphology and topology parameters - In the case of urban design, there are a range of parameters that can be used to define urban morphology which reflect the same type of geometric attributes that apply at the architectural scale. They include five main parameters and different configurations of them, including the: (1) city block's footprint, (2) city block's height, (3) city block form, (4) city block perforations, and (5) city block orientation. A further six parameters can be identified relative to urban topographic and geographic conditions that can influence wind flow. These six parameters include the: (1) density of city blocks and buildings, (2) configuration of city blocks, (3) extent of open spaces between city blocks, (4) orientation of city blocks, streets and grids, (5) topography or terrain of the urban environment, and (6) its geospatial location. These parameters provide the basis for controls of the main spatial topographic conditions that influence wind flow. The density of city blocks and buildings can be defined relative to the distribution of population density in an urban city block to classify high density (≥ 60 dwellings per acre), medium-density (30-60 dwelling per hectare) or low density (≤30 dwelling per hectare. The configuration of city blocks and extent of open spaces between city blocks are dependent on the ratio of building mass versus open space and can be described in relation to their 'mean wind incidence'. The orientation of city blocks, streets and city grids and the urban terrain define parameters that describe the geospatial topology in terms of whether it is complex or simple. The location of the city provides a definition relative to coastal or non-coastal conditions.

Wind flow setting parameters- Pedestrian wind comfort and safety are important requirements by many cities government in urban areas. Thus, several city governments require studies of pedestrian wind safety for before adding new buildings. These studies combining statistical meteorological data, aerodynamic information and criteria for wind comfort and wind safety. In the architectural design and urban planning domains it is critical to measure wind velocity, wind pressure, wind turbulence, identify wind flow profiles and measure the amount of wind flow across city block in early stage of design process. A parametric approach to wind flow across the architectural and urban design scales offers an innovative model to MDO of wind flow by merging the definition of both problem and solution in the same method through manipulation of the variables of different conditions and measures. However, in order to utilise parametric models to generate alternatives, it is necessary to define the competing wind flow problems in a series of building and urban design objectives, variables, and constraints and identify the maximum and minimum ranges of wind flow across all levels of the urban canopy layer so as to identify compliance parameters. Thus, it is essential to identify the prevailing wind flow conditions in early stages of the design process relative to whether the building or the area of the urban environment is subject to high-to-extreme wind flow or stagnant-to-low wind flow. High-to-extreme wind flow conditions define as wind velocity equal or exceed of 5m/sec (Penwarden 1973), where stagnant-to-low wind flow conditions define as wind velocity equal or lower than 1.6m/sec (Penwarden, 1973).

Wind flow compliance parameters - Refers to the result of overall building and/or urban wind flow performance, which includes multiple analysis calculations applied relative to the specified wind flow requirements that may be calculated at the individual building level and/or clusters of buildings. Analysis is also applied across the different levels of the urban canopy layer. The disturbance that a building creates from winds at the pedestrian level is due to two separate types of pressures and will be different to the disturbance at 100m, 200m, 300m, etc. (Erell et al. 2012). Different types of wind flow profiles resulting from the disturbance that a building creates will therefore result from the simulation. The first is wind flow caused by pressure distribution on the windward face of buildings, which increases with height and is related to the amount of local dynamic wind pressure. The second type caused by the pressure differences between the low-pressure wake regions on the building's leeward and side faces, and the pressure regions at the base on windward face. In the case of two or more buildings located in close proximity to each other, wind flows may be significantly deformed and cause a much more complex effect than is usual, resulting in higher dynamic pressures and motions, especially on neighbouring downstream buildings and it also generate vortices (Tominaga et al. 2008). Wind flow compliance parameters are therefore based on numerical techniques that measure modifications in wind conditions resulting from design solutions. Wind flow compliance parameters can be defined relative to five variables including wind: (1) velocity, (2) pressure, (3) turbulence, (4) flow regime, and (5) energy. Buildings permit wind flow around and above their surface.

In the measurement of wind velocity, pressure and turbulence, two approaches are commonly utilised, namely Zonal method and Numerical method. These methods typically use primitive governing equations call Reynolds-averaged Navier-Stokes (RANS) equations that includes 'Zonal' and 'Numerical' methods (Reynolds 1895). The Zonal method calculates inter-zonal airflow using the Bernoulli equation (Chen and Patel 1988). However this method is impractical to couple with computational design tools. Numerical methods are therefore more common and are typically based on computational fluid dynamics (or CFD) measures. CFD is used to predict and measure wind velocity, wind pressure and wind turbulence. The advantages of numerical simulation surround the efficiencies of simulation including the high speeds, low costs and maximisation of testing flexibility to accommodate changes in building configurations (Stathopoulos and Baskaran 1996). CFD is an efficient measurement method cross-different spatial scales relative to architectural-urban-geographic scale. In the case of identifying wind flow profiles within a city, a common method is known as the buildings plan area fraction. Building plan area fraction indicates the potential flow regime in in 2D (X, Y) within a city based on Equation (1) below:

$$\lambda p = \frac{Ap}{At} \tag{1}$$

Where building plan area fraction (λp) is defined as the ratio of the plan area of buildings (Ap) to the total surface area of the study region (At). This technique related to the city surface roughness (zo), as the density of buildings (plan area fraction) increases so does the city roughness. Three flow regimes develop in idealized urban street canyons: (1) isolated flow, (2) wake interference flow, and (3) skimming flow. The isolated flow regime occurs when elements are spaced relatively far apart ($0 < \lambda p < 0.1$), the wake interference flow occurs when elements are spaced at a medium density level ($0.1 < \lambda p < 0.6$), and the skimming flow regime occurs for high-density building arrangements ($\lambda p > 0.6$).

In the case of measure the amount of the wind flow cross a city block, a typical technique utilised is the 'building frontal index', which identifies the building skin facing and blocking the wind flow. This measure is related to the city surface roughness (zo) in 2D (XZ and/or YZ) based on Equation (2) below.

$$\lambda f(\theta) = \frac{Aproj}{At} \qquad (2)$$

where building frontal index (λf) defined as the total area of buildings projected into the plane normal to the approaching wind direction (Aproj) divided by the plan area of the study site.

Consequently, different methods for measuring wind conditions across the different spatial scales of architectural and urban design can be utilised relative to the different parameters specified within building geometry and spatial morphology and topography. These measurement methods are essential for optimizing wind flow in different spatial scales within a city. For example, at pedestrian level being equal to 2.5m/s during periods of low wind flow, whilst during periods of extreme or hazardous levels of wind flow, the objective function to be achieved should be equal to no more than 5m/s.

FUTURE WORK

This paper presents an investigation of the complexity of architectural and urban design relative to competing wind flow profiles and the advantages of adopting a multidisciplinary design optimization approach in the early design stages based on a parametric design approach to performance simulation. The lack of dependencies between the three domains of architecture, urban design, and aerodynamics was discussed relative to the related literature. We then defined an integrated framework for MDO focusing on the relationship between geometric and spatial features that exist across the different scales of an urban microclimate. The dependencies between architectural and urban elements and their impact on wind flow was explored in the specification of system parameters relative to building geometry, spatial morphology, spatial topology, wind flow settings, and wind flow compliance parameters across the urban canopy layer.

In future work, this PhD research project will develop the framework into detail a methodology for MDO and carry out a series of studies at varying levels of complexity. The implementation of the framework and its validation will test the design parameters and constraints so as to identify those that are significant in that they have the largest impact on wind flow conditions based on design performance.

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