Tall Building Design Exploration: Designing for Wind Resilience

PhD Thesis

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Date: 2019

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Mohamed Ibrahim Khallaf declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the Design, Architecture and Building/Faculty of Built Environment at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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This research is been supported by an Australian Government Research Training Program Scholarship.

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Signature: Signature removed prior to publication.

Date:2019

Acknowledgements

I would like to express my deepest gratitude and appreciation to my principal supervisor, Associate Professor Julie Jupp, as well as my co-supervisor, Associate Professor Sumita Ghosh, for their considerable effort in supporting me throughout my PhD. Working with them has been a rewarding and enjoyable experience.

I am indebted to Prof. Heather Macdonald and Associate Professor Leena Thomas for their valuable criticism and encouragement at various stages of this thesis. In addition, I would like to thank Associate Professor Daniel Lee for helping me to develop my technical skills in the aerodynamic field. Also, I would like to express my warm appreciation to Professor Charles Rice, Dr Michael Er and Associate Professor Johnny Wong for their support in the last stage of my PhD journey.

I will never be able to find words to thank my mother, wife and daughter for their endless love and sacrifice. They have tolerated a hard time and shared all burdens with me. I dedicate this thesis to them.

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DEFINITIONS OF KEY TERMS AND LIST OF ABBREVIATIONS

Within this research, several key terms and abbreviations may have different interpretations in different contexts. This following section explains these terms as they have been applied in this research.

Air Ventilation Assessment (AVA): A system that includes technical methods for assessment and guidelines for city development promoting better air ventilation.

CFZ: A file format that supports Computational Fluid Dynamic software

Computational Fluid Dynamic (CFD): A numerical simulation method that offers a powerful tool for wind engineering

Design Performance (DP): Assessment of a design's capability according to specified performance criteria.

Design Solution (DS): A geometric model generated and/or optimised from a parametric system. This may also be referred to as a solution.

Development Control Plan (DCP): Provides detailed planning and design guidelines to support the planning controls in cities.

Finite Difference Method (FDM): is a computational method that divides the geometric model into small, interconnected computational Quadrilateral elements in 2D, and into hexahedral elements in 3D.

Finite Element Method (FEM): is a computational method that discretises and subdivides a geometry model into small finite-sized elements of geometrically.

Finite Volume Method (FVM): It discretises the governing equations by dividing the physical space of the geometric model into a number of computational arbitrary Polyhedral in a form of control volumes.

Floor Area Ratio (FAR): Is the ratio of a building's total floor area (gross floor area) to the size of the piece of land upon which it is built.

Generative Design (GD): A design process wherein a flexible model can be varied to produce alternative design solutions.

Innovative Design (ID): Non-routine design that proceeds within a well-defined state space of potential designs by manipulating the applicable ranges of values for design variables.

Leadership in Energy and Environmental Design (LEED): is a green building rating system in the world.

Living System (LS): Consists of eight levels of living systems, each of which is composed of 20 critical subsystems that carry out essential life processes.

Parametric Design (PD): A mode of design practice that utilises a computational parametric design environment.

Performance Driven System (PDS): A parametric system that is driven by performance criteria to explore to a selected performance criterion.

Parametric System (PS): A set of parametric models that are integrated to operate as a whole. This may also be referred to as a design system.

Perfromance-Based Wind Engineering (PBWE): A method focuses on the performance of tall buildings subjected to extreme wind conditions.

Reliability-Based Design Optimisation (RBDO): A framework is based on a directional fragility model that combines the directional building aerodynamics and climatological information.

Council on Tall Buildings and Urban Habitat (CTBUH): The world's leading resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities.

Abstract

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 wind conditions due to their geographical location or improper urban planning. Further, the design of tall buildings plays an important role in the urban microclimate. Tall buildings design envelopes can affect urban microclimate wind flows by increasing or decreasing the wind flow of the surrounding area. Typically, conventional tall building design methods focus on single-objective design exploration techniques and/or produce a small number of design alternatives that explore wind loading and wind flows.

The aim of this research, therefore, is to provide support to planning and building standards authorities to bridge the gap between building code and city design guidelines at the architecture scale and urban scale by developing a computational design method that is able to mitigate the negative impact of wind flow caused by tall building in dense cities. This research extends concepts from generative architectural design into the domain of urban design, focusing on generating a design method to explore the effects of wind load and wind flow caused by tall building envelopes within high-density city fabric. The research presents a novel approach to predicting and providing instantaneous wind pressure data on facades of tall buildings, as well as wind flow data from the surrounding area in early stages of the design process. This performance-based design approach combines building and urban parameters to control the effect of winds on tall buildings at the pedestrian, podium and upper levels of tall buildings. This approach is based on the theoretical foundations of designing for urban resilience, highlighting the different objectives of this approach relative to existing tall building design standards and urban city planning guidelines.

This research provides an overview of related formal regulatory requirements of the building scale and urban scale, including buildings codes and city development design guidelines. In addition, performance-based design methods for generating, analysing and exploring buildings are investigated. The dissertation explores existing performance-based tall building design and the development of an architectural and urban design method that focuses on the effects of wind loads on and wind flows around tall buildings.

Publications

1- **Khallaf, M., & Jupp, J. (2017b). Tall Building Design Exploration: Designing For Wind Resilience**. in *AUBEA 2017:* " *AUBEA 2017*. RMIT University, 2017.

2- **Khallaf, M., & Jupp, J. (2017a). Performance-based Design of Tall Building Envelopes using Competing Wind Load and Wind Flow Criteria**. *Procedia engineering*, *180*, 99-109.

3- **Khallaf, M. & Jupp, J. (2016). Designing for Urban Microclimates: Towards Multidisciplinary Optimisation of Wind Flow for Architectural and Urban Design**, In name of editor (Ed.), *eCAADE* . Publisher: place of publication.

Chapter One

Introduction

This chapter presents an introduction to the area of inquiry and the problem addressed in this thesis. The aim, objectives and the methodology of this research are presented. The chapter ends with an overview of this thesis.

According to the World Urbanisation Prospect (2014), 54 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 66 per cent by 2050 (World Urbanisation Prospect, 2014). This growth in global urban population density makes cities vulnerable to disruptions caused by natural disasters (Melkunaite & Guay, 2016). The rapid expansion in building infrastructure in hazard-prone areas can damage the urban ecosystem, placing a burden on social and economic structures (Melkunaite & Guay, 2016). The urban climatic issues of providing adequate urban ventilation whilst mitigating against the hazardous impacts of extreme wind events in city environments are therefore of topical concern to building designers, urban planners and governments alike (Khallaf & Jupp, 2016). Cities can suffer from poor ventilation, and air quality problems, whilst others are subject to strong wind conditions due to their geographical location or improper urban planning. Strong and stagnant wind conditions can have negative, long-lasting effects on cities, their society, the environment, and economy; as is the case in cities such as New Orleans and Hong Kong (Kurban & Kato, 2009; Ng et al, 2005). In 2005, high-speed winds and storm surges struck New Orleans caused a sever damaging in the city infrastructure, houses, and businesses (Kurban & Kato, 2009). Whilst, stagnant wind conditions in Hong Kong has caused outdoor urban thermal comfort problems, worsened urban air pollution by restricting dispersion in street canyon, and increased high concentrations of pollutants, such as Nitrogen dioxide (Ng et al, 2004)

Increases in urban population size have led to an increase in the demand for tall buildings (Ilgen, 2006). Large clusters of tall building structures in highly populated cities create a matrix of wind obstacles, resulting in stagnant and high wind conditions for urban inhabitants. Thus, in the expansion of sustainable urban planning strategy and building design practices for high-density cities, a significant issue is the need to reduce wind-related hazards caused by climate change. In addition, there is a need to reduce the effect of environmental conditions on tall buildings in cities by improving air ventilation in stagnant wind conditions while easing the effects of strong or extreme aerodynamic forces.

Increasingly, designers are implementing generative techniques to enhance the design process with analytical, evaluative and generative logics (Coorey, 2014). The generative architectural design concepts first expressed by Frazer in *An Evolutionary Architecture* (Frazer, 1995), which subsequently were formulated as a theoretical framework, have been utilised widely and adapted by parametric designers for generative and evolutionary design computation (Janssen, 2004). Most recently, researchers have demonstrated successful iterative processes of generation, development, analysis, and design exploration using parametric systems to achieve many building design objectives (for example, see Frazer & Janssen, 2006; Drogemuller & Frazer, 2008; Ayoub, 2012; Coorey & Jupp, 2013, 2014).

This PhD research project combines generative architectural design and urban design with a focus on inner-city environments and the effects of wind loads and wind flow. In the context of this thesis, the urban microclimate is defined as a complex system, or "living system", using Miller's (1995) terminology, which is discussed in Section 2.2.3. The "living system" approach to the planning and design of urban city spaces generates questions about the urban morphology of an innovative, resilient, and regenerative city. What design characteristics are needed in cities subject to different wind conditions, such as stagnant wind conditions with wind speeds below 2.7 metres per second/s, or strong wind conditions with wind speeds exceeding 5.5 metres per second/s? In adopting this approach, this research project differentiates between the evolution of a city in the sense of urban development and adaptation over time, and evolution in the more formal sense of a computational generative system that can be utilised as an architectural-urban design tool (Frazer, 2011) for existing urban environments and new city developments.

1.1 Research Problem

Increased climate hazards coupled with rapid urbanisation are likely to put increased strain on the capacity of local governments (Tanner *et al*., 2009). Strong and extreme wind events can have long-lasting effects on cities, including their societies, environments, and economies. In addition, low air ventilation can contribute to the spread of diseases and pollution. Research studies have shown that the positive or negative effects of wind on cities *depends* on the relationships between geographic elements (such as topography, climate, location), urban elements (such as building proximity, street layout, infrastructure, vehicular flow) and building elements (such as building envelope, form, orientation, height and width).

Consequently, if design changes to urban morphology occur on a large enough spatial scale, wind flow can be modified and controlled. This PhD research project has extended ideas of generative architectural design into the domain of evolutionary urban design, focusing on generating parametric design techniques to explore the effects of tall building design on wind flow in high-density city environments and helping to enhance the process of designing tall buildings for wind resilience. This research has demonstrated ways to maintain comfortable and safe pedestrian-level wind conditions that are appropriate for the season and the intended use of the pedestrian area.

1.2 Aim and Objectives

In the development and promotion of sustainable urban design strategy and building design practices, a significant issue for many high-density cities, which often are located on coastlines, is the need to find ways to improve air ventilation and positive pedestrian airflow conditions while lessening the effects of strong aerodynamic forces.

However, in the last decade, the relationship between city morphology (particularly high-rise building forms) and wind velocity has been documented (Collier, 2006). The area of vertical building surfaces facing high winds, the proximity of buildings and the vertical temperature gradient[1] closest to the surface have been shown to influence wind speed, with negative effects resulting in "wind tunnels" in urban street canyons (Voogt & Grimmond, 2000). In the case of strong wind events, the effects of urban morphology can have long-lasting effects on cities, including their society, environment, and economy. Research has shown that the effects of changes in urban building "roughness"[2] manifest as changes in wind field distribution, such that increased or reduced drag and turbulence in cities can create a deeper or shallower zone of frictional influence, within which wind speeds are significantly reduced or increased. The positive or negative effects of wind on cities, therefore, depend on the relationships between geographic elements (such as topography, climate, location), urban elements (such as building proximity, street layout, infrastructure, vehicular flow) and building elements (such as building envelope,

[1] A physical quantity that describes at what rate the temperature changes most rapidly around a particular location in the vertical dimension.

[2] An uneven flow of air caused by irregularities in the surface over which the flow takes place.

form, orientation, height and width). Consequently, if design changes to the urban morphology occur on a large enough spatial scale, wind flow can be modified and controlled (Hunt *et al*., 2004).

The research focuses on wind-related hazard caused by tall building design. The research attempts to answer the research question, what would be an effective tall building design approach that able to mitigate the impacts of strong wind condition while encouraging the wind flow in case of stagnant wind condition at two inter-related scales: the building scale and urban city scale in dense cities.

The aim of this research, therefore, is to develop a computational design method that is able to mitigate the negative impact of wind flow caused by tall building in dense urban environments and to bridge the gap between building codes and city design guidelines relative to wind flow. This will extend the iterative processes of analysis and exploration into the realm of architecture design, urban design, adaptation and evolution, with the principal environmental driver being the exploration of aerodynamic forces in built-up city environments. Computational fluid dynamics and generative architecture design exploration together provided a unifying concept that was employed to develop an integrated modelling and simulation environment for wind load and wind flow, which was capable of generating alternative design options to achieve resilient and sustainable urban morphology. The following objectives were considered necessary to achieve this aim:

1. Investigate formal regulatory requirements at the urban scale and building scale related to the control and mitigation of wind flow in urban city environments.
2. Identify existing computational approaches to controlling and mitigating wind load and wind flow for urban design and tall building design.
3. Develop and test the generative performance-based simulation and exploration method via a series of pilot studies.
4. Verify the computational method by implementing the approach on a case study based on the existing conditions in an urban city environment.
5. Examine the method developed relative to its ability to support guidelines and policies for implementing the concept of urban resilience.

1.3 Methodology

This research involved the investigation and development of an advanced performance-based design focused on high-density cities that are vulnerable to wind-related hazards. Various research methods are used widely in design, engineering and computer science. **A research method**

developed in the field of information systems was chosen because it addressed the issues involved in developing computational systems. Nunamaker and Chen (1990), who noted the usefulness of systems development as a research strategy, originally described this research approach. The approach involves a series of stages through which a system develops from a conceptual framework into a prototype to be evaluated. The five stages of this research process are:

1. Construction of a conceptual framework
2. Development of a system architecture
3. Analysis and design of the system
4. Building on the prototype system
5. Observation and evaluation of the system.

In using this research methodology, researchers must justify the significance of the research questions pursued. An ideal research problem is one that is new, creative, and important in the field. When the proposed solution of the research problem cannot be proven mathematically and tested empirically, or if it proposes a new way of doing things, researchers may elect to develop a system to demonstrate the validity of the solution, based on the suggested new methods, techniques or design.

This approach is equivalent to a proof-by-demonstration (Nunamaker & Chen, 1990). In order to test the feasibility of the proposed method, a series of experiments were designed and conducted (see pilot studies presented Chapter Four and a detailed case study in Chapter Five). In testing a generative parametric method that could facilitate the re-planning, re-design and re-development of cities relative to the exploration of wind flow, this research project compared the range of design alternatives generated using the following constraint types and conditions:

- Existing planning regulations and guidelines
- Existing topographic conditions and urban morphology
- Local climatic data and meteorological trends
- Fast fluid dynamics simulation schemes.

1.4 Overview

This PhD thesis is divided into seven chapters as illustrated in Figure 1.1:

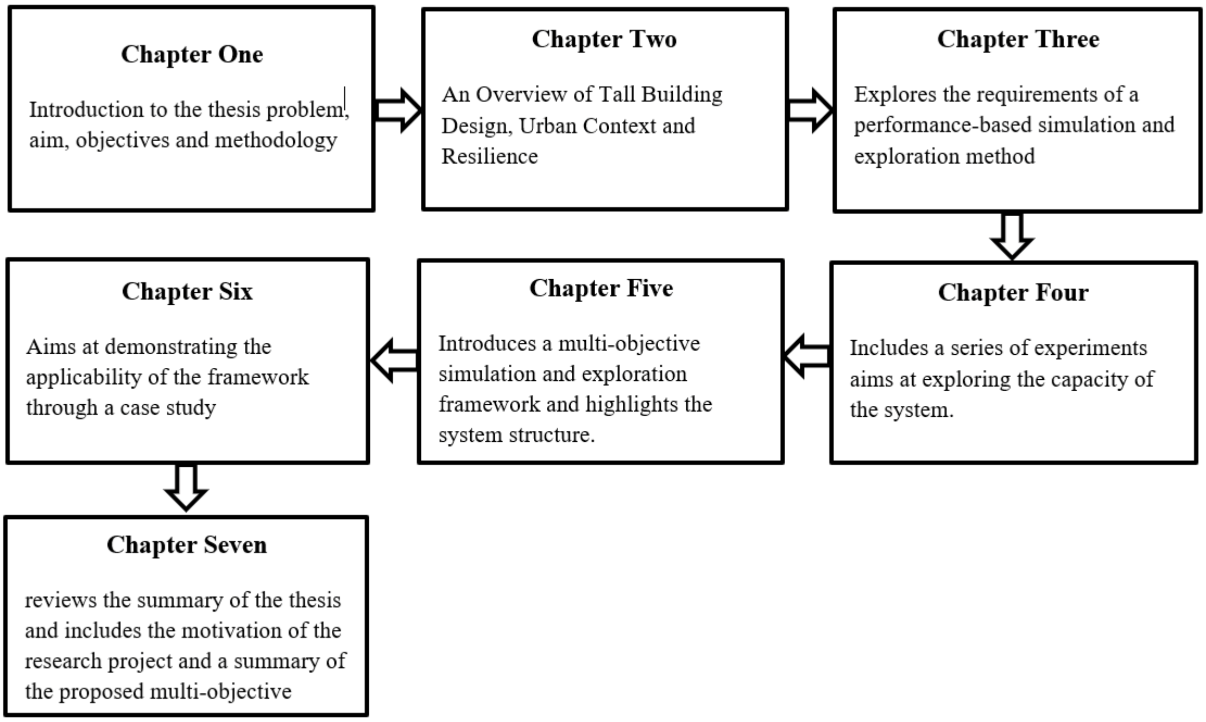


Figure 1.1 A Flow Diagram Illustrates The Thesis Structure.

Chapter One presents an introduction to the area of inquiry and the problem addressed in this thesis. In addition, the chapter presents the aim, objectives and the methodology

In **Chapter Two**, literature from complementary areas of inquiry is reviewed. The literature is from fields including tall buildings, urban resilience, understanding cities, and performance-based design. In addition, existing computational approaches for controlling and mitigating wind load and wind flow for urban design and tall building design are identified in this chapter. Next, the chapter highlights the limitations of previous studies on wind-related hazards and presents the aim of this research.

In **Chapter Three**, the requirements are explored of a performance-based simulation and exploration design method that is capable of integrating various urban and building parameters. The approach investigates the capabilities of a parametric modelling approach that utilises computational fluid dynamics. In addition, investigations are presented regarding building codes and city development design guidelines pertaining to the design of tall building envelopes for wind loads and urban wind flow requirements.

In **Chapter Four**, the development of the performance-based simulation and exploration method used in this research is introduced. Experiments conducted in the course of this research, and which aimed to explore the system's capacity to manage and control different parameters at a multi-dimensional scale, are presented. In this chapter, testing in the pilot studies of the method, efficiency, and effectiveness of each module of the computational method through two levels of complexity is reported. The overall computational method based on the objective criteria of each pilot study is assessed in order to determine the limits of each module and of the overall system.

In **Chapter Five**, the multi-objective simulation and exploration method used in this research is introduced, including the system structure. A generative approach and computational fluid dynamics technique were used to support the flexibility and interdependencies between the framework's modules. The chapter then presents the workflow of the system and the anatomy of each module of the system.

In **Chapter Six**, the applicability of the method is verified and demonstrated through a case study that was based in Melbourne, Australia. In this chapter, the multi-objective simulation and exploration method is tested and verified through comparison of an existing building generated by conventional tall building design methods and an alternative solution, which was generated by a multi-objective simulation and exploration method. The models' design performance is compared in term of wind parameters at three levels: the pedestrian and podium zone, the second zone, and the third zone. This follows an assessment of the quality of both buildings against wind load and wind flow performance criteria, which highlights the limitations and strengths of both buildings' envelope design.

In **Chapter Seven**, the research project is summarised, including the purpose of the multi-objective simulation and exploration system. In addition, the method's potential contribution to design computing, building codes and city design guidelines, and urban resilience is discussed. Furthermore, the main limitations of this research are discussed, along with suggestions for future research.

Chapter Two

An Overview of Tall Building Design, Urban Context and Resilience

This chapter presents a review of the literature from a number of complementary areas of inquiry. The literature is relevant to tall buildings, urban resilience, and performance-based generative design. This chapter aims to highlight the research gap regarding dependencies between tall building design, urban context and resilience.

2.1 Tall Buildings

Tall buildings, which are developed as a response to population growth, rapid urbanisation, and economic cycles, are essential to modern city development (Ayoub, 2012). Tall buildings, which are usually designed for office or commercial use, are among the most distinguished space definitions in architectural history (Ilgin, 2006). Tall buildings tend to be aesthetically powerful, iconic and visible. However, their cost of construction is higher and they are more difficult to design than other buildings (Lee, 2011). In addition, tall buildings reduce habitability and pedestrian comfort in surrounding areas, increase wind-induced noise, and exert an interference effect on neighbouring buildings (Lee, 2011) in this section, the definition of a tall building is reviewed, along with approaches to tall building design and the interface between the tall building and urban context.

2.1.1 Definitions of Tall Buildings

The number of tall buildings globally has risen significantly in the last decade (Ayoub, 2012). The increasing number of tall buildings is due to several factors, including growth in urban populations and land costs, and aesthetic features of tall buildings (Ayoub, 2012). The Council on Tall Buildings and Urban Habitat have proposed international criteria for defining tall buildings, including height relative to context, proportion, and building technologies related to height. According to the first criterion, a tall building is considerably higher than its surrounding buildings. For example, a 14-story building may not be considered tall in a high-rise city such as Chicago or Hong Kong. However, in a regional European city or a suburb, 14-stories may be distinctly taller than the urban average. The second criterion considers that the building should be slender enough so that it gives the appearance of a tall building, especially against a low urban background.

The third criterion suggests that a building may be considered tall if it features technologies attributed to tallness, such as specific vertical transport systems and structural systems that are efficient against lateral forces. For example, Beedle (1971) describes a tall building as a multi-story building that can be defined by the need for extra operation and technical measures due to its actual height, instead of by its overall height or number of stories. Ali and Armstrong (1995) define a tall building as a multi-story building that is constructed by a structural frame, features high-speed elevators, and combines extraordinary height with ordinary room spaces.

In addition, the definition of tall building varies in different disciplinary contexts. The structural design point of view defines a building as tall when its structural analyses and design are in some way affected by lateral loads, particularly by sway caused by such loads (Taranath, 1998). On the other hand, the architectural perspective defines a building as a tall when tallness becomes a concern affecting planning, aesthetics, and the environment (Ilgin, 2006). In sum, there is no absolute or universally accepted definition of what constitutes a tall building (Al-Kodmany, 2018). Therefore, this research defines a tall building as a multi-story building that is considerably higher than the surrounding buildings and cause a wind-related hazard that affect the surrounding environment.

2.2 Approaches to Tall Building Design

Tall building design strategies have received increasing attention in the last two decades (Khallaf & Jupp, 2016b). Designers of tall buildings rely on regulatory standards, parameters, and constraints based on specific design problems and general guidelines (Ayoub, 2012). Ilgin (2006) provides considerations for designing tall buildings, including cultural, political and social factors, sustainability, and safety. However, Ilgin (2006) does not explain how to integrate these considerations into the process of designing a tall building or outline a design process for tall buildings.

Moughtin *et al*. (2003) argue that designing a building involves a cyclical series of linked phases, as shown in Figure 2.1. The design process includes: the Goals Phase, where goals and objectives are outlined; the Survey Phase, where information relevant to the design is gathered; the Analysis Phase, where information gathered is analysed; the Alteration Phase, where ideas are generated, the Evaluation Phase, where solution is developed and alternatives generated; and, the Plan Phase, where decisions are made depending upon the evaluation.

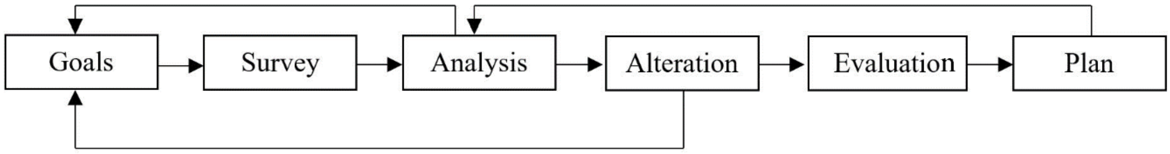


Figure 2.1 The building design process (Moughtin *et al.*, 2003)

However, conventional tall building design methods typically focus on single-objective design exploration techniques and/or produce only a small number of design alternatives (Khallaf & Jupp, 2016b). Touloupaki and Theodosiou (2017) describe conventional building design as combining certain measures and decisions recalled from the architect's memory based on their aspirations and the client's requirements regarding a project. The conventional building design method includes four phases, as shown in Figure 2.2.

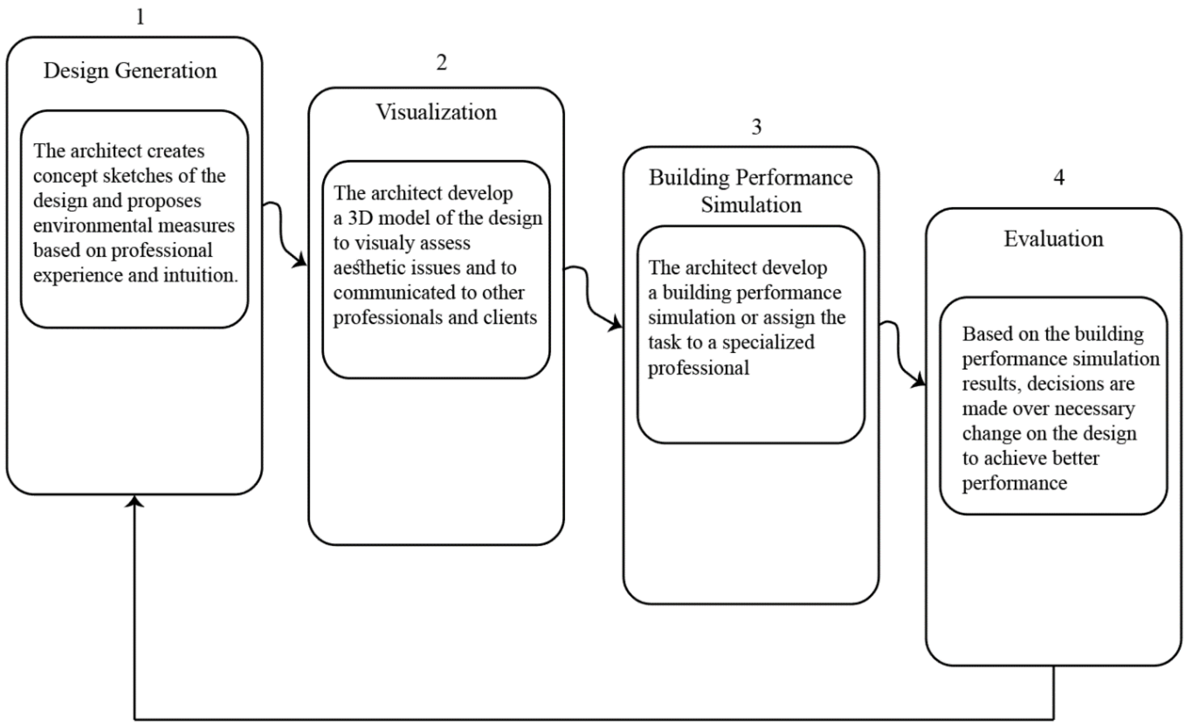


Figure 2.2 The conventional building design process (Touloupaki & Theodosiou, 2017)

This design process includes: Design Generation, where the architect creates concept sketches of the design and proposes environmental measures based on professional experience and intuition; Visualisation, where the architect develops a three dimensional model of the design to visually assess aesthetic issues and to communicate the design to other professionals and clients; Building

Performance Simulation, where the architect develops a performance simulation model (or assigns this task to another professional); and Evaluation, where necessary changes to the design are made based on the result of the previous phase. This design process has a limited capacity to generate or explore design alternatives that can satisfy different objectives. Altogether, in the early stages of conventional design processes, decision-making typically is aimed at satisfying a single objective to find the best solution, rather than assessing potential design alternatives that meet design requirements and constraints such as building code, city design, and environmental performance guidelines, or socioeconomic, cost and life-cycle considerations.

2.2.1 Urban Context

Understanding urban context is important for finding approaches to tap into the potential of cities and reroute their development pathways towards sustainability and resilience (Frantzeskaki, 2018). Carmona *et al*. (2010) argue that urban context goes beyond the immediate site surrounding a development, instead encompassing the whole city and perhaps the surrounding region. Madanipour (2006) highlighted the need to consider the role of urban design in evolving urban contexts. However, Delmas (2018) noted the limited consideration of the urban context in typical design processes, in particular for a tall building. This has led to a stand-alone building design with negative effects on urban environment performance. The design of tall buildings, for example, can cause wind phenomena including downwash, channel effects, and turbulence, with direct negative impacts on pedestrians in urban contexts.

Urban design denotes different meanings in different disciplines and fields of study. Lang (2017) defines urban design as designing a four-dimensional, socio-physical vision for a city. Davies (2000) defined urban design as creating a vision for an area and deploying skills and resources to realise that vision. Carmona (2014) describes the urban design as a hybrid discipline that draws its legitimising theories from diverse intellectual roots including sociology, anthropology, psychology, political science, economics, ecology, physical and health sciences, urban geography, and the arts. Carmona *et al*., (2010) highlighted the difference between urban design as direct and indirect design. Direct design can be described as place-making or place design through a design process. Indirect design involves place-shaping through establishing policy, making investment decisions, and managing spaces.

Generally, urban design aims to make urban areas functional, attractive, and sustainable (Boeing, 2014). However, in addition to managing multifaceted externalities, urban design plays an important role in shaping sustainable futures cities. The Commission for Architecture and the Built

Environment of England (2010) emphasises the potential positive social and economic outcomes of urban design, contending that strategic design might enhance ecological decision-making. For example, Metro Vancouver (2011) has launched five goals to guide future growth in the city's region for 2040. The goals include: creating a compact area; supporting a sustainable economy; protecting the environment and responding to climate change impacts; developing complete communities, and supporting sustainable transportation choices. Related strategies and policies explain how each goal can be achieved. Focusing on responding to climate change, the strategy emphasises enhancing air quality by directing urban development in ways that encourage efficient built form.

Based on the different definitions and aims of urban design, in this research the author defines urban design as a hybrid discipline that include place-making through a design process and place-shaping through establishing design policies. The aim of the urban design is to enhance ecological decision-making for an area or city.

2.2.2 Interface Between Tall Building Design and the Urban Context

Yuan (2018) highlighted the need to expand understanding of the effects of urban scale and building scale on wind environment due to the strong relationship between both designs. In addition, Ilgin (2007) pointed out that the shape of a building may create inhospitable or even dangerous wind environmental conditions for pedestrians at street level. Moreover, the addition of new buildings to an existing environment can affect the liveability of outdoor open spaces, the performance of the surrounding buildings, and city-wide conditions (Delmas, 2018). Further, Ayoub (2012) emphasises that the design of tall buildings affects pedestrian views, pedestrian permeability and overshadowing, and must be integrated with the surrounding context and comply with different site climates. Thus, bringing an understanding of design approaches to the urban design context may contribute to addressing the system approach to wind design.

There is a wide range of approaches to urban design, which can be classified into traditional and computational approaches. Traditional approaches (informational approaches, behavioural and social approaches, and environmental and policy approaches) generally are aimed at increasing physical activity in urban areas (Heath *et al*., 2006). Punter (2007) identifies two systems for urban planning that affect the urban design, including regulatory systems and discretionary systems. The regulatory system is based on administrative law and a written constitution. It delivers clear development rights and floor space limits, and often building envelope controls. This system is based on dimensional controls, which are used to interpret planning or zoning regulations. The discretionary system does not spell out the full basis of decision making in advance. However, the plan sets some basis, largely around location and land use, for decisions. Tiesdell and Adams (2011) have described a “tools approach” to urban design, whereby a variety of regulatory and discretionary instruments, mechanisms and actions are employed judiciously during the planning process to generate better design outcomes. However, the traditional approach has limited capacity to analyse and evaluate the performance of urban design solutions.

On the other hand, computational approaches for urban design, such as shape grammar and parametric design, have emerged in recent years (see Vidmar, 2013; Stenio, 2010; Gil *et al*., 2010). Steino *et al*., (2005) emphasise the benefits of utilising a computational approach, including informative and effective rendering of the design process. In addition, the computational approach has the capacity to overcome several problems of closed design systems and facilitate participation in less time (Steino *et al*., 2005). Beirão (2012) highlighted the computational approach’s capacity to provide a dynamic design environment and explore different solutions by changing parameters and the primitive input geometries. Capeluto (2003) underlined the benefits of utilising a computational approach, including generating design solutions and evaluating and analysing design performance.

2.2.3 The City as a Complex System

In order to improve cities and building design practices for high-density cities, an understanding of the city as a complex system is required to improve or adapt existing system components or design new components within the city (Miller, 1978). Cities have been understood as static systems for many years. Only in the last two decades has the focus changed from an aggregate equilibrium system to an evolving system with a structure that emerges from the bottom up (Batty, 2008). Further, cities have their basis in the regular ordering of size and shape across many spatial scales, whether these scales are urban or architectural. Batty (2008) confirms that cities are the preeminent example of complex systems that have the opportunity to manage their resilience towards sustainability through processes of transformation (Olazabal, 2017).

Manesh and Tadi (2011) explain how to plan and design new elements in the city context such that the new elements improve the energy performance and sustainability of the entire neighbourhood. In the study, complex system theory is utilised to characterise the distinct features of the urban morphology. The authors describe a complex system as a system composed of many heterogeneous agents which are interconnected nonlinearly, such as people, transport and open spaces. The authors emphasise that the potential to study urban issues while considering the city as a complex system provides an ability to address urban issues such as sustainability (Manesh & Tadi, 2011).

Further, Manesh and Tadi (2011) highlight that even minor changes to the existing urban fabric will emerge in the performance of the entire final system. To prove this claim, the authors investigated refurbishing courtyard spaces in residential blocks. Their objective was to enhance the energy performance of the entire residential block. The usage of poor constructional technology and location causes building exposure to unwelcomed solar radiation, increasing the energy consumption of the existing building. Adding a new building adjacent to the existing building to prevent unwanted solar radiation helped to reduce the existing building's energy consumption, reducing energy consumption across the whole block. From the complex system perspective, adding one new agent—the new residential building—assisted the existing agent to perform better.

From this point of view, the city as a system contains a variety of heterogeneous agents. Their relationships define and constrain a city's ability to adapt to multi-hazard threats, such as climate change and wind-related hazards. Those heterogeneous agents are connected in different ways. Thus, a change in the structure or performance of one of the agents may result in changes in others' performance.

In the context of the city, this research considers a heterogeneous agent as building and urban context. In addition, the relationship between agents is considered as regulatory codes and guidelines. Consequently, an understanding of the characteristics of complex systems is required to develop a design method that connects building design and the urban context at two spatial scales to enhance the resilience of cities to wind-related hazards.

2.2.4 Resilience

In developing and promoting sustainable urban planning strategies and building design practices, the concept of resilience has become a central aspect of modern cities. Over 310 million people worldwide live in cities with a high probability of natural disasters, including hurricanes and tropical cyclones. By 2050, these numbers are predicted to more than double (Lall & Deichmann, 2012), underscoring the need to enhance the resilience of cities.

2.2.5 Definition

The term 'resilience' has been defined and used with different meanings in different disciplines and fields of study. One commonly agreed on definition 'resilience' describes resilience as the capability to prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to public safety, health, economy, while protecting the security of an urban area (Wilbanks, 2007). The approach taken by this research reflects this definition, emphasising the effects of wind flow on urban environments. In this thesis, therefore, the primary focus is on urban resilience relative to the threats of wind-related hazards.

2.2.6 Theories of Urban Resilience

Building on environmental and social sciences research, Leichenko (2011) investigated urban resilience from the perspective of the effects of climate change. Leichenko (2011) framed urban resilience as the ability of a city or urban system to withstand a range of shocks and stresses. Leichenko (2011) highlighted broad agreement on resilience among different fields of research regarding the need for cities to prepare for the effects of climate change and implement strategies for urban resilience to address a wider range of environmentally-driven stresses and shocks. Leichenko (2011) argued that various disciplines' efforts to promote urban development, sustainability, and resilience to climate change should be synthesised.

Similarly, Jabareen (2013) investigated resilient cities, focusing on climate change and environmental risk. This research considered urban resilience as a complex and multidisciplinary phenomenon focusing on a single or small number of contributing factors, which results in partial or inaccurate conclusions and misrepresentation of the multiple causes of the phenomenon. Jabareen (2013) defined a city's resilience by the overall abilities of its governance, physical, economic and social systems and entities to learn, prepare in advance, plan for uncertainties, resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner. Jabareen (2013) proposed a Resilient City Planning Framework aiming at outlining what cities and their urban communities should do in order to move towards resilience in the future. Jabareen's (2013) framework is based on four principle ideas, namely:

(i) A vulnerability analysis matrix, aimed at identifying and analysing types, demography, intensity, scope, and spatial distribution of environmental risk, natural disasters, and future uncertainties in cities.

(ii) Urban governance, focusing on the governance culture, processes, arena and roles of the resilient city.

(iii) Prevention measures, aimed at preventing environmental hazards and effects of climate change, and

(iv) Uncertainty-oriented planning, focusing on an assessment of environmental risks and hazards that are difficult to predict but must be considered in city planning and risk management, rather than adaptations to conventional planning approaches.

In the literature review for this research, a taxonomy of urban resilience was identified across environmental and social science domains. This taxonomy divides urban resilience into four categories:

(i) Urban ecological resilience, o the ability of a city or urban system to absorb disturbance while retaining identity, structure and key processes (Alliance, 2007).
(ii) Promotion of resilience through urban governance and institutions or focusing on how different types of institutional arrangements affect the resilience of local environments (Ostrom, 2010).
(iii) Urban hazards and disaster risk reduction, or the capacity of cities, infrastructure systems, and urban populations and communities to recover quickly and effectively from natural and human-made hazards, such as hurricanes and international terrorism (Coaffee, 2008).
(iv) The resilience of urban and regional economies, focusing on the evolution of urban and regional economic and industrial systems (Pendall, 2009).

For this research project, the third category of this urban resilience taxonomy was employed, along with Jabareen's (2013) fourth principle, whereby urban resilience is defined as a system's capabilities for responding to uncertainty and change in climate conditions.

The scope of actions considered by these approaches to urban resilience range from the development of building codes and standards to land use, planning, and property acquisition. In addition to various urban planning interventions, the design method is proposed, which typically is aimed at eliminating the long-term risk of hazardous environmental phenomena due to the effects of sudden changes in climatic conditions. For example, Eraydin (2012), proposed a resilience planning paradigm based on three dynamic assets of urban systems: adaptive capacity (aimed at reducing vulnerability and sustaining ecosystems for urban areas under threat from hazards caused by climate change), self-organisation (a process of internal organisation within a system that requires no guidance or management by an outside source), and transformability (the capacity to create a fundamentally new system when ecological, economic or social conditions make the existing system untenable). Similarly, Chelleri (2015) argued that sustainable transformation should be the long-term objective of urban design, operationalised through the management of different scales and approaches to resilience. The approaches should focus on resilience against broader scale shocks and stresses, as well as cascading impacts across multiple scales, including situations where trade-offs in resilience may occur.

2.2.7 Urban Resilience and Wind

In the development and promotion of sustainable urban planning strategy and building design practices, the concept of resilience has become a central aspect of modern cities. Residents of many cities are vulnerable to extreme natural hazards, such as storms, floods, fire and drought, all of which are exacerbated by climate change and cause significant economic damage and loss of human life (Cariñanos *et al*., 2018).

Focusing on wind-related hazards related to urban hazards and disaster risk reduction, researchers have found that unplanned urbanisation in cities to accommodate population growth has contributed to the daily exposure of urban communities to environmental risks that threaten their health and well-being (Cariñanos *et al*., 2018). It is essential to understand the definition, behaviour and cause of wind in cities in order to predict and assess the impact of negative wind on a city's fabric.

Wind is generated by the differential heating and pressure of the Earth's atmosphere creating wind flow. Wind flow can be defined as understanding the motion of air around objects, which helps to calculate wind velocity, turbulence and pressure around objects. Wind load can be defined as understanding wind pressures throughout the surface area of objects such as buildings, which helps design cladding systems (Anderson, 2001).

Focusing on tall buildings, the effects of wind speed are demonstrated relative to the performance of individual tall buildings, small clusters of tall buildings (city blocks) and large clusters of tall buildings that comprise entire cities (Collier, 2006). The area of vertical building surfaces facing high winds, the proximity of buildings to each other, and the vertical temperature gradient close to a building's surface have been shown to influence wind speed. The negative effects of these conditions result in "wind tunnels", creating urban street canyons (Voogt & Grimmond, 2000) or in stagnant wind conditions that create health hazards due to airborne diseases.

In the expansion of sustainable urban planning strategy and building design practices for high-density cities, a significant issue is the need to find ways to improve air ventilation and pedestrian wind conditions while mitigating against the effects of strong or extreme aerodynamic forces. By providing adequate urban ventilation while mitigating the hazardous impacts of extreme wind events in city environments, urban climatic issues are of topical concern to building designers, urban planners, and governments. Urban area design aims at supporting the comfort, health, and safety of residents and users. Wind comfort and safety are essential requirements for pedestrians in urban areas, creating a challenge for urban designers, planners, and architects to achieve these requirements.

However, coastal urban areas are most vulnerable to severe winds, due to low wind friction. Therefore, residents and users of coastal areas may be exposed to higher levels of wind-related risk factors. Often, high wind speeds in coastal urban areas are associated with major hurricanes and storms that cause devastating damage to property, injuries and loss of life (for example, Typhoon Mireille, which struck Japan in 1991 and Hurricane Katrina, which struck New Orleans in 2005). High-speed winds and storm surges can damage roads, bridges, houses, and businesses, affecting cities economically, socially and environmentally. Tamura (2009) showed that insurance companies in Japan paid around six billion United States dollars in property damage caused by Typhoon Mireille's strong winds.

Kurban and Kato (2009) aimed to develop an empirical method to measure the vulnerability of various population groups during a disaster. The degree of vulnerability depended on the nature of the disaster. The authors created a Vulnerability Index (UVI) to evaluate the social and economic vulnerability of major cities in the United States. The study proved that coastal urban areas were more vulnerable to severe winds than other urban areas, experiencing a higher rate of loss as a result, as shown in Figure 2.3.

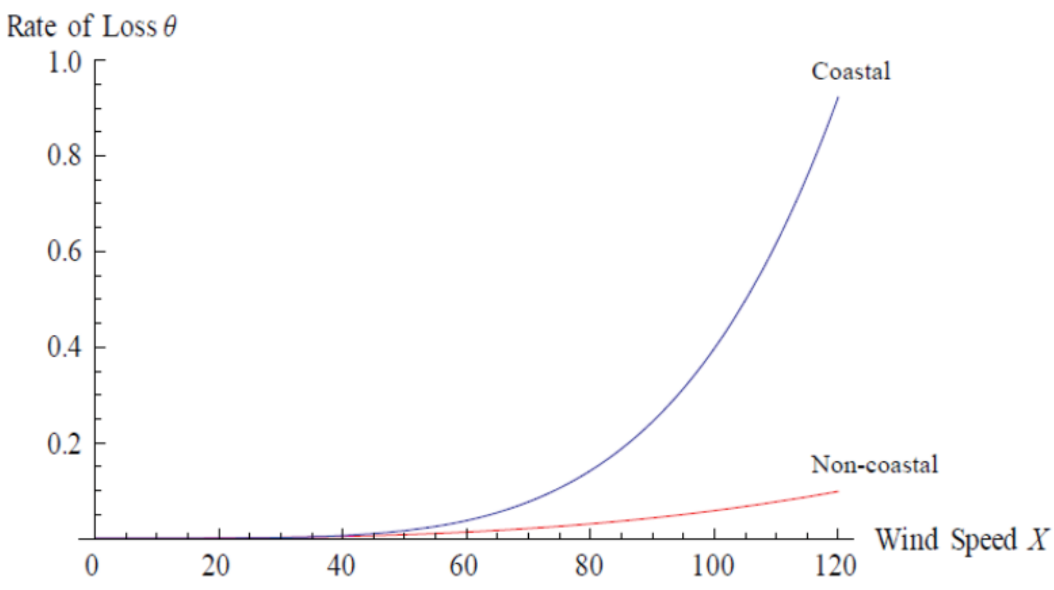


Figure 2.3 Wind speed in miles per hour and loss rate (Kurban & Kato, 2009)

Capeluto *et al*. (2003) described their research group's attempt to create standards and guidelines for wind design during the early stages of the design process. The standards and guidelines aimed at protecting "favourable wind conditions", existing levels of pedestrian traffic and existing neighbourhoods before adding any new structures. Capeluto *et al*. (2003) defined favourable wind conditions as moderate winds of two metres per second. The case study involved a series of experiments that utilised computational fluid dynamics (CFD) as a measure and evaluation tool to inform design decision-making relative to the optimum height of the proposed building. The study's result showed a strong relationship between wind velocity and building height. However, the relationships between wind velocity, and building parameters, city morphology, and topology that define wind conditions were ignored in the experiment.

The importance of understanding the relationship between urban morphology and favourable wind conditions in high-density cities provides an opportunity to avoid serious urban air pollution episodes to improve the quality of life in urban environments in general (Hang *et al*., 2009). Hang *et al*. (2009) proposed an approach to model the effects of wind conditions in cities by accounting for building elements as obstacles characterised by a variety of morphological characteristics (overall city form, building area density and street configuration) that affect the velocity and the direction of wind flow around and inside cities.

In a series of experiments that tested physical three-dimensional models of urban environments in Japan, Kubota *et al*. (2008) highlighted the strong relationship between the gross building coverage ratio and wind velocity ratio. The authors modelled building densities of various residential neighbourhoods in Japan, using wind tunnel tests as the main evaluation tool. The results showed that increases in the gross building coverage ratio led to decreases in wind velocity.

Wind flow can have positive features in an urban environment, such as providing a comfortable indoor or outdoor environment. In addition, it can facilitate the conservation of energy through passive cooling or natural ventilation (Yan, 2004). However, high wind conditions may cause discomfort at the pedestrian level and devastating effects on buildings and humans. Therefore, urban area design requires integrating meteorological statistical data, aerodynamic information and wind performance criteria early in the design process to achieve a comfortable indoor or outdoor environment. Meteorological data is information gathered by meteorological stations, while aerodynamic information includes information regarding changes in wind flow statics due to terrain, local urban design, and building configuration.

Rodrigues *et al*. (2015) aimed at mitigating wind-related hazards caused by strong winds at the pedestrian level, utilising CFD as their main simulation and evaluation tool. Their experiment consisted of a square section of nine buildings of width B and height H aligned into three rows. Each row contained three buildings oriented to the mean wind speed. Spaces between the buildings were the same distance, as shown in Figure 2.4.

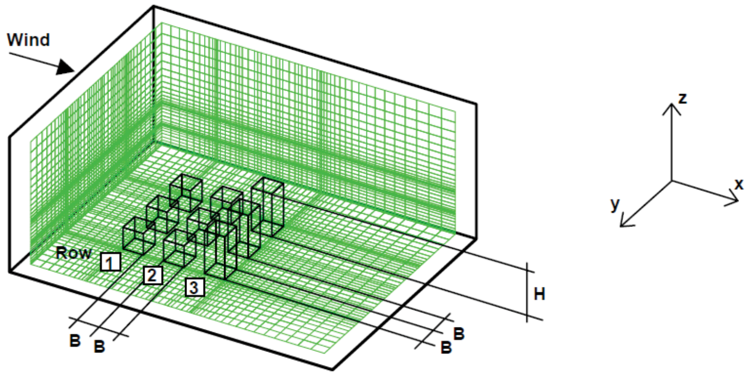


Figure 2.4 Physical model and grid solution (Rodrigues *et al*., 2015)

Results showed a linear relationship between channel effect and building height and width. Consequently, the authors recommended reducing building height and building width to mitigate the high wind velocity caused by the channel effect. In addition, the experiment showed that the downwash effect caused by tall buildings increased wind velocity at the pedestrian level. Therefore, the authors recommended that tall buildings and small buildings should not be attached. The authors illustrated the effect of building parameters (height and width) and urban layout on wind flow at the pedestrian level. However, the experiment did not reveal the effects of building form and orientation on wind velocity at the pedestrian level.

Moya *et al*. (2015) investigated the potential of design strategies to reduce the negative effects of high winds at the pedestrian level in inner-city Melbourne. The authors utilised CFD to measure and predict wind velocity. The study showed an average wind velocity of 3.7 metres per second at heights of two metres. However, wind velocity increased through the passages due to the channel effect caused by adjacent buildings, reaching speeds of 4.4 metres per second and increasing inhabitants' discomfort. In addition, the study demonstrated the level of wind deflection and velocity reduction that can result from adding architecture features (such as windbreaks) to existing structures.

Due to the hazardous effect of strong winds at the pedestrian level, many city authorities require studies of pedestrian wind comfort and wind safety for proposed new structures. These studies include aerodynamic information and wind comfort and safety criteria. The Planning and Building Department in Mississauga City, Canada, attempts to maintain comfortable wind conditions at the pedestrian level by requesting reports that consider the potential effects of proposed new structures on the local microclimate during the early stages of the planning and design process. This allows sufficient time to consider appropriate wind control and mitigation strategies, including significant changes to the site and building design. Prior to the construction of new designs in Mississauga, the Planning and Building Department requires a qualitative and/or quantities assessment that includes information on building height, the number of the buildings, site location and the size of the site area. Qualitative assessments may be based on professional observation and evaluation using CFD or wind tunnel studies. Wind tunnel tests are based on measured data from physical scale models that are tested using a boundary layer wind simulation facility. In addition, the Department has developed wind comfort criteria, as shown in Table 2.1.

Table 2.1. Pedestrian Wind Comfort Criteria (Planning and Building Department of Mississauga City, year)

Comfort Category	**GEM Speed (m/s)**	**Description**
Sitting	≤ 2.7	Calm or light breezes desired for outdoor restaurants and seating areas where one can read a paper without having it blown away.
Standing	≤ 4.1	Gentle breezes suitable for main building entrances and bus stops.
Walking	≤ 5.5	Relatively high speeds that can be tolerated if one's objective is to walk, run or cycle without lingering.
Uncomfortable	> 5.5	Strong winds of this magnitude are considered a nuisance for most activities, and wind mitigation typically is recommended.

Consequently, the Department recommends the following strategies to mitigate strong winds, including:

1. Incorporating podiums, tower setbacks, notches and/or colonnades,
2. Strategic use of canopies, windscreens, landscaping, planters, public art and or/ other features that prove to be effective for mitigating problematic wind condition, and
3. Modification of pedestrian usage.

However, the Department focuses on each proposed building's scale and use of architecture features (such as a niche, windscreens, or windbreaks), not considering urban scale and urban parameters.

To date, researchers studying wind flow in city environments have focused on the relationship between wind velocity and building parameters (one or two parameters) such as building heights, building width and/ or the space between the buildings. In addition, researchers have not considered cities as complex systems, in which any change in one building's wind performance may affect other buildings. Researchers to date, therefore, have neglected the interface between buildings scale and urban scale. This gap in the literature in tall building design is an obstacle to achieving acceptable wind comfort around buildings in most urban areas.

2.2.8 Designing for Wind Flow and Wind Load

Spaces and open areas between buildings, such as streets, parks, and city block courtyards are among the most important urban elements (Xiaomin *et al*., 2006). Wind flow varies depending on building forms, open areas of the city, and linkages between open spaces, meaning human exposure to good or low-quality of air conditions depends on city design (Ng, 2009). As a result, wind flow regimes and wind-related hazards (for example, due to hazardous winds or traffic-related emissions) have captured much attention.

As a result, urban design guidelines and planning strategies have been developed for cities subject to low and/or high wind conditions. These strategies generally aim at increasing pedestrian comfort levels by achieving more favourable wind flow profiles. Typically, these strategies have two main objectives: maximising urban air ventilation in case of stagnant wind flow conditions and mitigating against hazardous wind flow profiles in the case of high wind conditions.

However, despite growing research and urban design and planning guidelines, many metropolises suffer from poor ventilation and air quality problems due to improper urban planning. Unstructured planning of urban canopies is common in areas of rapid urbanisation (Chan & Ellen, 2001; Chan & Au, 2003). The objective of many researchers in this field is to simulate the effects of urban morphology and topology relative to wind flow in the context of pollutant dispersion (for example, Xia & Leung, 2001, Assimakopoulos & Ap Simon, 2003) and coastal conditions impacting on wind flow profiles and the "wall effect" (Ng *et al*., 2011), which increases hazardous conditions for pedestrians in street canyons with different layouts. The focus of studies to date has been the identification of critical building configurations that enhance ventilation to provide better conditions for positive air flows. These studies have shown that the most significant parameters are the influence of the ratio between leeward building height and canyon width and the ratio between leeward building height and windward building height.

Accurate prediction of wind flow profiles within street canyons will assist urban planners to consider urban geometry with optimal natural ventilation and comfort. The effects of building and street layout largely dictate fluctuations in wind flow regimes in urban environments, extending building geometry and architectural morphology into the domain of street canyon dimensions. These effects have been studied extensively, mainly in wind tunnel experiments (for example, Kastner-Klein & Fedorovich, 2001), and numerical models (Chan & Dong, 2002). Miao (2014) studied flows and traffic exhaust dispersion in urban street canyons with different configurations to develop urban planning strategies to ease air pollution and pollutant dispersion within a street. The study result showed that building width and height could affect pollution levels inside a street canyon dramatically.

However, most previous research has considered the effect on wind flow of buildings of identical height. In the actual street, the typical case is that buildings on either side of a street are asymmetrical in height layout. Xia and Leung (2001) and Assimakopoulos and Ap Simon (2003) addressed this gap by conducting investigations on the effects of asymmetrical street layout on pollutant dispersion.

2.2.9 Approaches to Wind Testing

In determining the effects of wind flow and wind load for urban design and building design, two main approaches include physical model approaches, such as wind tunnel testing, and numerical model approaches, such as CFD. However, most physical models offer low fidelity. In contrast, numerical models—including CFD—tend to offer high fidelity (Alfaris, 2009)

Wind Tunnel Testing relies on physical model testing that incorporates particular site conditions. It measures wind flow around the physical model and wind load on the physical façade using a boundary layer wind simulation facility. The process of predicting wind flow and wind load through this method is complex due to the model's size, shape, and openings. Therefore, the accuracy of this method is insufficient. In addition, the cost of carrying out this method is high, and it is incapable of integration into computational design methods for simulation analysis to test and inform design decision making early in the design process. Thus, the method has limited utility in computational design.

CFD is a numerical simulation method that offers a powerful tool for wind engineering. Increasingly, CFD is used to assess the risk associated with buildings subject to natural wind-related hazards (Huang *et al*., 2015; Khallaf & Jupp, 2016b). CFD is the typical method for analysing and predicting urban microclimate. The method demands highly detailed analysis, complex calculations and knowledge of specific software (Tsitoura, 2017). CFD can integrate design and analysis in a virtual environment, supporting the application of fluid dynamics theory regardless of complexity (Wahrhaftig & Silva, 2018). CFD is used to predict and measure wind velocity, wind pressure and wind turbulence. In the past 50 years, CFD has undergone a successful transition from an emerging field into an increasingly established field of urban physics research, practice and design (Bolcken, 2015). Ramponi *et al*. (2015) note that advantages of utilising CFD include: providing whole-flow field data on the relevant parameters in every point of the computational domain, utilising CFD to provide full-scale testing to avoid the incompatible similarity requirements in reduced-scale testing, such as wind tunnel test requirements, and full control over boundary conditions, facilitating efficient parametric studies.

In addition, CFD can combine meteorological data and aerodynamic information in small-scale or large-scale designs, such as buildings, neighbourhoods, and cities. It provides numerical and graphical data of wind flow representation at any point on horizontal and vertical meteorological scales. This provides designers and engineers with information that facilitates decision making (Paydarfar, 2001). Further, CFD has been shown to produce highly reliable estimates of physical forces of flow, supporting the cost-effective and timely exploration of design alternatives (Wahrhaftig & Silva, 2018).

2.3 Performance-Based Generative Design

The development and application of performance-based design systems have grown in recent decades. A performance-based generative design method integrates many disciplines of different scale. As early as the mid-nineties, performance-based engineering was used in structural engineering applications to reduce the likelihood of structural collapse. For example, Shea *et al*., (2005) developed a design method based on a generative structural design system, utilising parametric modelling and performance-based design. The method was used to design long-span roof systems through implementing a combination of structural grammars, performance evaluation, and stochastic optimisation. Structural grammars enable the generation of new structural truss members. Performance evaluation includes structural analysis, performance metrics and stochastic optimisation by simulated annealing. This method demonstrates many 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.

2.3.1 Definition

In the architectural domain, Oxman (2008) describes the performance-based design as the exploitation of building performance simulation for the modification of the geometrical form for optimising a candidate design. The benefit of a performance-based simulation is based on the support of analytical filtering and/or evaluation of building prototypes early in the design process. This enables rapid design feedback, supporting continual modification. Many applications have been developed in performance-based building simulation, which has established itself as a method for achieving designs that rationally meet the requirements of a sustainable and a safe built environment (Spence & Kareem, 2014).

2.3.2 Aerodynamic Design Approaches to Tall Building Design

Although the fact that the shape of the building is primarily driven by the site conditions, economical aspects, architectural and engineering determinants, the aerodynamic treatments of the shape of the tall building is also needed to be considered (Sharma *et al*., 2018). Numerous research studies on the aerodynamic design of building morphology have been undertaken over the past 50 years. The aerodynamic exploration of building morphology can be classified into two approaches, namely aerodynamic modification, and aerodynamic design. The 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 to keep the building's overall design unaffected. 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 general characteristics of building morphology aimed at reducing aerodynamic forces. They include optimising the effects of (i) building corner modifications (e.g. Dutton & Isyumov 1990); (ii) tapering and stepping (e.g., see Kim & Kanda 2010a, Kim & Kanda 2010b); (iii) openings and slots (e.g., Isyumov *et al*., 1989); (iv) twisting (Xie *et al*., 2014); and (v) building configurations and composite models, (e.g., Tanaka *et al*., 2012; 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. Figure 2.5 shows the plan view of the different characteristics of building morphology.

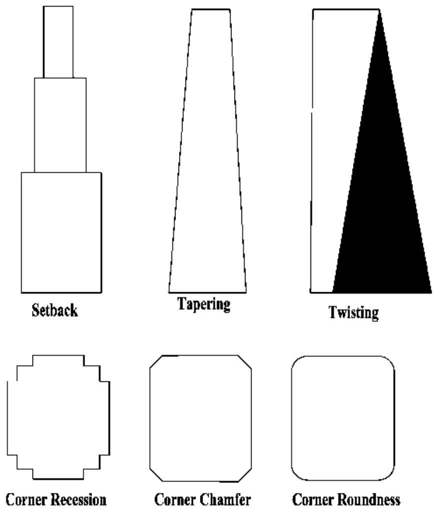


Figure 2.5 Plan view of different characteristics of tall building morphology

Corner modifications are one of the most common strategies that have been used in the last decades in the practice. The strategy aims at mitigating the negative wind impact of the building structure

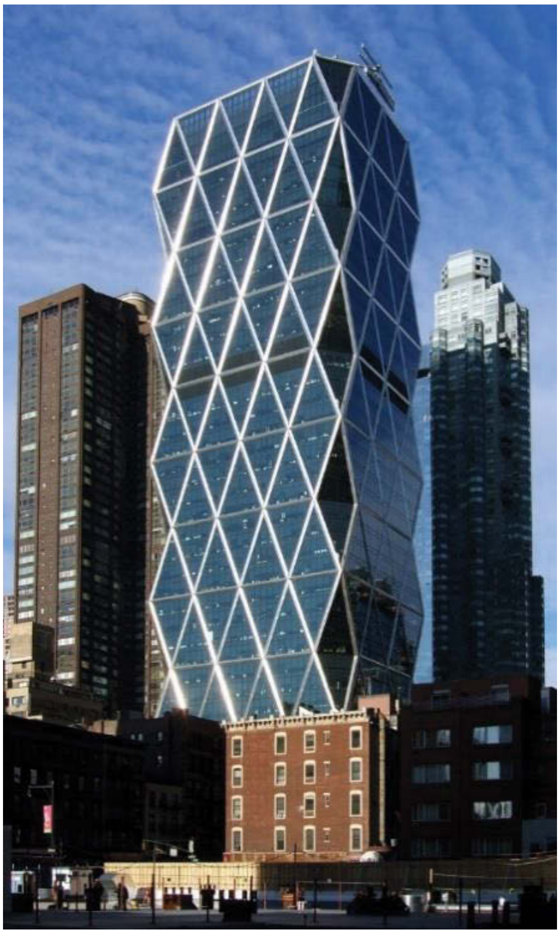


Figure 2.6 Hearst Tower by CTBUH.

Figure 2.7 Chamfered Corner by CTBUH.

and façade. It includes (i) Chamfering corner (ii) Roundness corner (iii) Recessed corners and, (iii) Double step recessed corners. Hearst Tower building (Figure 2.5) is 182-meter tall building in New York certified as the first LEED gold built in 2006 (Rafiei & Adeli, 2016). Due to the high wind condition in New York City, and the height of the building, the designer utilised this chamfer corner approach to minimise and disrupting the formation of the vortices caused by the wind flow as shown in Figure 2.7.

Shun Hing Square building (Figure 2.8) is another example of using corner modification approach in urban areas that exposed to high wind flow. The building height is 384 meters located in Shenzhen, China. The designer has utilised roundness corner strategy to mitigate the wind excitation cause by the wind flow Figure 2.9. Corner roundness modification is a more effective mean to reduce the Wind-Induced Responses on tall buildings as compared to chamfered or recessed corner modifications (Ayoub, 2012).

Figure 2.8 Shun Hing Square by CTBUH.

Figure 2.9 Rounded Corner by CTBUH

Stepping shape and recessed is another aerodynamic approach that assists designers to mitigate the impact of the wind velocity in an urban area that subjects to high wind condition. Taipei's 101 building, at 508 meters (Figure 2.10) is a good example of adopting two aerodynamic approaches include stepping and recessed corners. Stepping and double recessed corner are used on the cross-sectional shape of the building (Figure 2.11) aiming to reduce the aerodynamic force impact on the building façade and structure. The stepping and recessed corners on Taipei 101 reduces crosswind respond and drag, of a 25% reduction in the base moment (Irwin, 2005).

Figure 2.10 Taipei 101building by CTBUH.

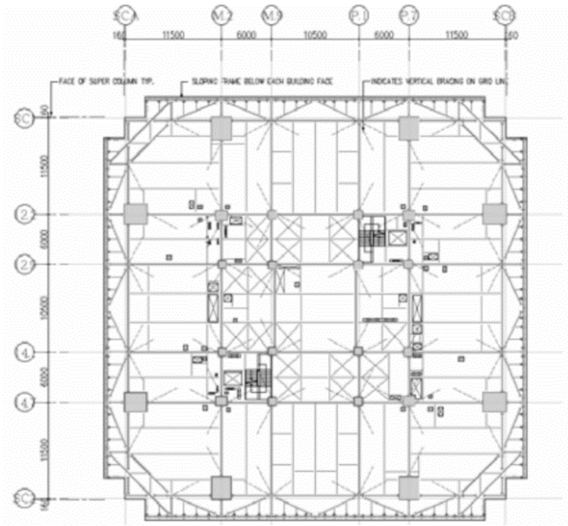


Figure 2.11 Taipei 101 building Plan by CTBUH.

Twisting is an alternative approach to tall building design (Xie *et al*., 2014). A twisted tall building design can reduce the wind impact on the building façade and wind vortices excitation (Ayoub, 2012). Designers utilise this approach to design tall buildings in cities that are vulnerable to high wind conditions. For example, architect Santiago Calatrava adopted this approach in designing HSB Turning Torso (190 meters) in Malmo, Sweden (Figure 2.12) and Chicago Spire (609 meters) in Chicago (Figure 2.13). The design utilised this approach aiming at reducing the vortex shedding induced response to tall buildings and minimising wind loads from the prevailing direction.

Figure 2.12 Turning Torso in Malmo by CTBUH.

Figure 2.13 Chicago Spire in Chicago by CTBUH.

However, aerodynamic modifications approach is able to produce limited design solutions that may not be sufficient to me*et al*l design objectives in some cases. In addition, the approach does not change the cause of vortex caused by the wind impact. The source of a vortex is the shape itself and through the change in the outer architecture of building in such a way that flow of wind around the building is smooth (Sharma *et al*., 2018).

The aerodynamic design, on the other hand, is an approach that integrates architectural design with aerodynamic considerations in the 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 optimised balance can be reached between the costs and benefits. Traditionally this requires comprehensive tests on various configurations.

One of the most common aerodynamic design approaches for designing a tall building is parametric modelling. Parametric modelling is a computational process that works as a generative and as an analytical method for design realisation. In addition, it offers an innovative approach to design exploration by merging the definition of both problem and solution in the same model through manipulation of the variables embedded within the model. Kilian (2006) highlighted that a parametric model approach defines the type of relationships and associations among shapes and geometries, and their components within a computational modelling environment. The benefit of utilising parametric design approach is the generative and performative capacities and both coarse and fine granularity

Canton Tower (Figure 2.14) is one of the tallest building in China that height 604 meters (CTBUH, 2004). The building located at the edge of the most active typhoon prone area in the world (Guo *et al*., 2012). Duo to the geographical location and the height of the building, the designer has adopted the aerodynamic design approach integrating with parametric modelling aiming to produce a design that able to mitigate the impact of the strong wind. The tower consists of two elliptical shapes that twist 45° relative to one another (Figure 2.15), creating a tapered waist that able to reduce the strong wind impact on the building façade and structure. A wind tunnel tests have been conducted to study the effects of the wind flow on the tower façade and structure (Guo *et al*., 2012). However, the wind test is solely based on the analytical and scaled models which lost the accuracy

(Guo at al, 2012). In addition, the wind study neglected the impact of the wind caused by the tower at the pedestrian level.

Figure 2.14 Canton Tower by CTBUH.

Figure 2.15 Twisted Elliptical Shapes by CTBUH

Another practice example of integrating the parametric design approach and aerodynamic design is Shanghai Tower design (Figure 2.16). The building located in Shanghai, China with a height of 632m. Due to its super height, wind load is one of the controlling factors of the architectural and structural design (Zhaoa *et al*., 2011). Utilising parametric modelling and aerodynamic design approach allow highly accurate results and a good correlation between a model and its built form (Xia & Peng, 2012). Further, because of the flexibility and adaptively of the parametric design technique, it offered instant feedback of changing variables and thus generate different design solutions (Xia & Peng, 2012). This allows designers to better understand iterative massing studies while observing the relative impact to the overall performance of the systems involved. Wind tunnel test has been conducted to measure the impact of the wind on the building façade. The studies' result shows that the across wind load can be effectively reduced when design curved façade and spiralling form 120 degree as shown in Figure 2.17 (Zhaoa *et al*., 2011).

The integrating parametric design and aerodynamic design approaches contribute to reduce the correlation of vortex shedding along the building height, and thus reduce the across-wind building response (Zhaoa *et al*., 2011).

Figure 2.16 Shanghai Tower by CTBUH.

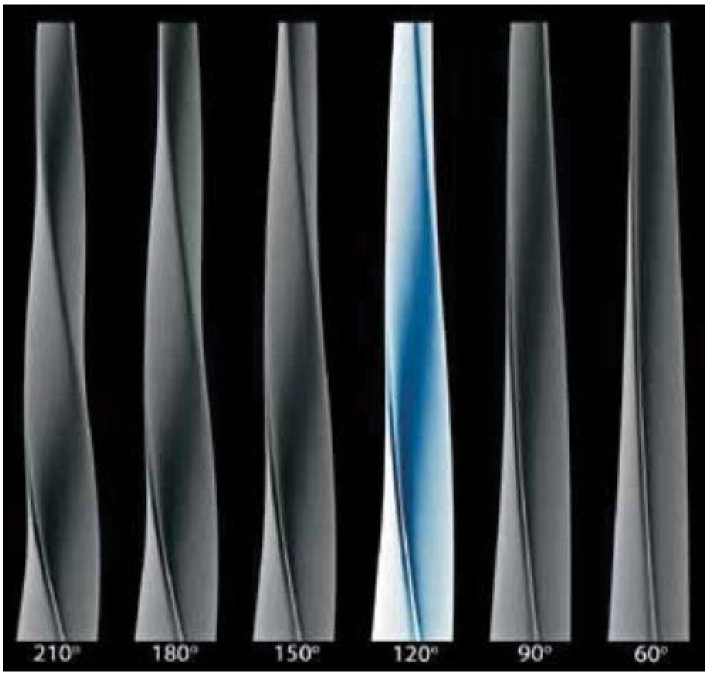


Figure 2.17 Twisted Façade 120 Degree by CTBUH.

However, because of the limitation of wind tunnel test approach as mentioned in Section 2.3.5, it prevents to test multiple design scenarios instantaneously and inform design decision maker in the early stage of the design process.

Although aerodynamic shape plays an important role in tall building design, it cannot be reached without compromising all other design aspects (Xie, 2014). Assessments of aerodynamic the 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. The main challenge in building aerodynamic is to compromise aerodynamic solutions with other architectural design aspects and to compromise between benefits and costs (Xie, 2014). Therefore, it is important to have an assessment of effectiveness of various aerodynamic options in the early design stage so that the potential pros and cons can be evaluated in the decision-making process (Xie, 2014).

2.3.3 Generative Approaches to Urban Design

Generative methods for urban design have been proven to greatly facilitate the process of design exploration (Shi *et al*., 2017). The main motives of utilising generative design approach to urban design field are to take the advantages of the computational capabilities to support designers. It able designers to explore larger design space and evaluate the design generation. Holzer (2008) highlighted the ability of the generative approach in cooperating with the environmental performance-evaluation approach. Since there is a wide range of generative model approach to design, Oxman (2006) identifies three generative, approaches can be utilised for urban design namely the combinatorial approach, a substitution approach and a parametric modelling.

The ***combinational-shape grammar*** model is a set of shape transformation rules-based system that are applied recursively to generate a set of designs (Shi *et al*., 2017). The shape grammar approach is able to create forms by assembling different primitive shapes as shown in Figure 2.18. Shape grammar primarily uses in urban design, painting and sculpture. However, it is difficult to apply shape grammars as a primary design approach to solve large complex scale in two dimensional and three-dimensional problems as urban and cities scales. The main limitation this method is the accuracy of the generated solutions (Koutsourakis, 2009).

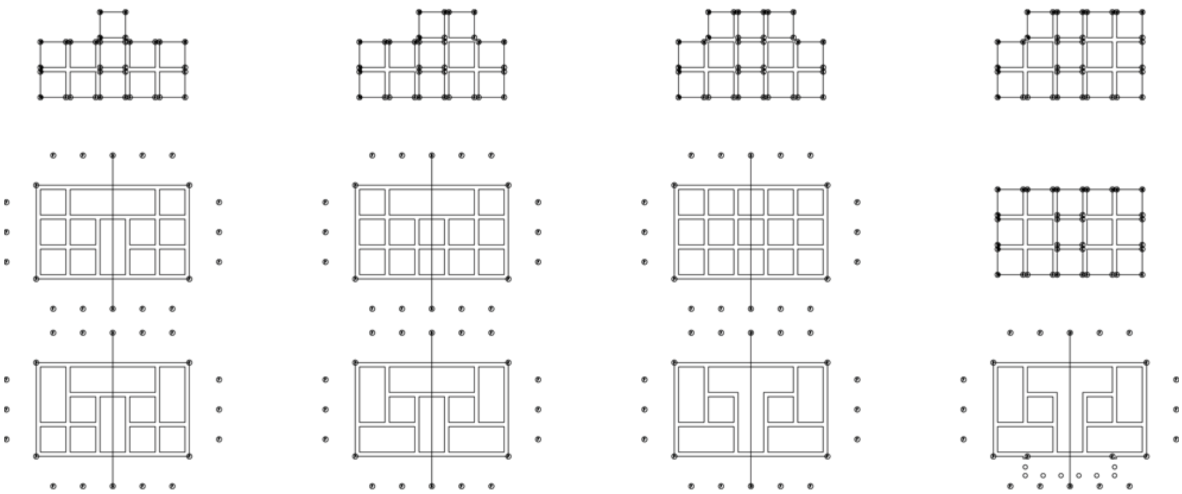


Figure 2.18 Shape grammar assembling elements

The substitutionally ***generative model*** automatically generates forms without being constrained by search space or a specific value. This approach starts with inadequate design knowledge while developing a set of rules such as the l-system as shown in Figure 2.19. The system is a parallel string rewriting. It is a symbolic representation of the formal design - mechanism based on a set of production rules (Parish *et al*., 2001)

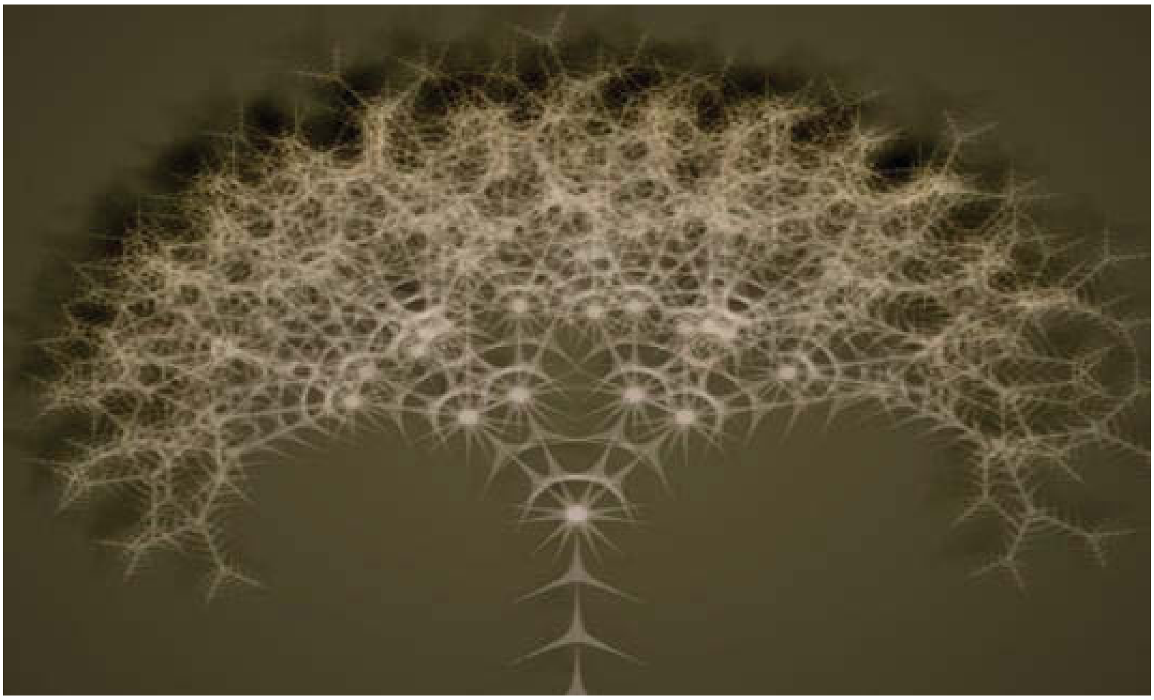


Figure 2.19 L-system approach to urban design

However, is deficient in co-operating with architecture and urban design complex problem due to its inability in conjunction with environmental performance evaluation

Parametric Modelling, as mentioned in Section 2.4.2, offers an innovative approach to design exploration. The benefit of utilising parametric design approach is the generative and performative capacities and both coarse and fine granularity. In addition, parametric modelling has the flexibility to be utilised in both urban design and building design. However, the main limitation of this approach is the prior identification of design parameters, constraints and the relationship between design components that would narrow the search space. Figure 2.20 shows the results of urban design utilising parametric modelling.

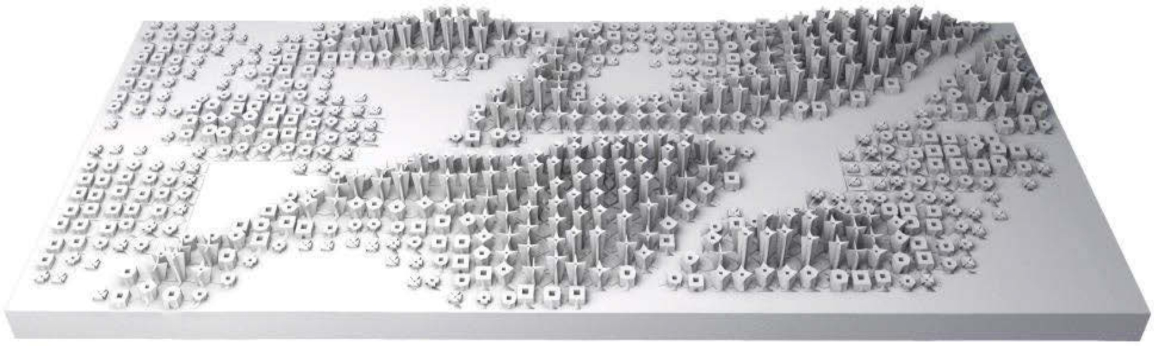


Figure 2.20 Parametric modelling for urban design

Table 2.2 summaries the design aspects of different generative design approaches advantages, and the limitation of each approach including computational approach, substitution approach and parametric approach.

Table 2.2 Design Aspects of Different Generative Design Approach

Generative Approaches	Typical Approach Domain	Advantages	Limitation
Combinational	Painting, Urban Design and Sculpture	Geometric (visually defined)	inaccurate generated solutions
Substitution	Planting, agriculture and Landscape design	generates forms without being constrained by search space or a specific value	Symbolic
Parametric	Urban design, Architecture and Engineering domain	Regular design evaluation and improvement Multiple solutions Optimisation Disruptive innovation	Progress slows down after achieving near optima solutions Designer must define the parameters and constraints before the progress

Drawn from the previous literature, this section determines that parametric design approach has the capability to solve wide range problems in both building scale and urban scale whereas most the other generative approaches have limited flexibility to be utilised in both scales. In addition, the ability of the parametric approach to integrating with environmental performance evaluation.

2.3.4 Towards a Performance-Based Simulation and Exploration Method

Architectural design it is conventionally viewed as a process of repetitive cycles of generation/evaluation/modification until the design objectives are satisfied (Touloupak & Theodosiou, 2017). Following this inefficient workflow, there is practically no way to determine that the proposed solutions are even close to a realistic optimum (Touloupak & Theodosiou, 2017). 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 satisfy design requirements and constraints; often between competing requirements represented by a number of different disciplines. 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, analysing and filtering design alternatives against wind load and wind flow in an urban context so as to meet competing design requirements and mitigate the negative impact of the wind flow in the early stages of the design process is a difficult task. In response, the application of performance-based simulation and exploration approach provides the necessary decision support. The ultimate goal of computational simulation methods should not just be the analysis of prescribed shapes, but the automatic determination of the true optimum shape for the intended application (Burkard, 2000). Though, performance-based simulation in wind engineering has seen limited adoption during the assessment of risk in facilities subject to natural hazards (Huang *et al*., 2015).

Performance-based Wind Engineering or PBWE method was first developed by Paulotto *et al*. (2004). The method focuses on the performance of tall buildings subjected to extreme wind conditions. It defines two performance levels: high and low. High-performance relates to a definition of pedestrian comfort/discomfort levels and 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.

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 approach 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.

Spence & Gioffrè (2012) propose a ‘Reliability-Based Design Optimisation’ (RBDO) framework, which is based on a directional fragility model that combines the directional building aerodynamics and climatological information and is aimed at optimising large-scale design problems that are characterised 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. The 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. Table 2.3 summarises the advantages and the limitation of each design approach.

Table 2.3 A summary of different design approaches

Design Approach	Advantages	Limitation
Touloupak & Theodosiou, (2017)	• Repetitive cycles of generation/evaluation/modification. It able to generate several solutions.	• Very hard to determine that proposed solutions. • Solutions are not a realistic optimum
Paulotto *et al.* (2004).	• Focuses on the performance of tall buildings subjected to extreme wind conditions. • It defines two performance levels: high and low	• Focuses only on the tall building structure, neglecting the tall building design envelop in the early stage of the design process.
Jain *et al.* (2001)	• It is a site-specific performance-based design approach using wind speeds in the simulation of tall building designs.	• Focuses on the building structure neglecting the building envelop design. • Focuses only on the building scale neglecting the urban scale.

	• Linked the value of their method with the cost savings for the building owner.	
Spence & Gioffrè (2012)	• Based on a directional fragility model that combines the directional building aerodynamics and climatological information. • Aims at optimising large-scale design problems.	• Focuses only on the structural building system. • Unable to explore the desired performance at both the building scale and city scale integrating
Granadeiro *et al.* (2012)	• Involving a flexible design system to generate alternative envelope shape designs, with integrated energy simulation, to calculate the energy demand of each design	• The complexity in developing computer implementations • The limitation of the shape grammar that the framework uses as a computational method.

The overall design exploration strategy developed is based on the belief that problem formulation evolves during the process of searching and converging for the fittest (tall building envelop) solution; thus, ultimately leading to a more informed and 'fittest' solution. In this way, design exploration is seen as being both a divergent and convergent process used to evolve and investigate a multidisciplinary design space that utilises wind performance criteria with the intent of design discovery and to inform decision-making trade-offs between the building and urban scales. 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 for wind flow profiles.

2.4 Summary

As cities continue to expand with the uncertainties of climate change and unprecedented urbanisation, the importance of enhancing the resilience of cities is increasing. Based on different definition for the 'resilience' covered in this chapter, this research defines resilience as a system that able to respond to uncertainty and change in climate conditions. Taking the perspective that the city is a "complex system" (Miller, 1978), as discussed in Section 2.2.3, it can be understood that the city as a system consisting of nonlinearly interconnected heterogeneous agents. These agents shape the city's fabric, and they are linked to each other differently, thus, any change in the structure or performance of one the agents may result in changes in others.

Focusing on wind-related hazards, this chapter puts forward the notion that the relative lack of consideration of wind-related hazard 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. As discussed in this chapter, Delmas (2018) highlighted that there is a limited consideration of the urban context in typical design processes, in particular for a tall building design. In addition, previous studies discussed in this chapter demonstrate that tall buildings play an vital role in increasing the wind-related hazards issues by causing a strong or stagnant wind flow to the urban context. Therefore, different approaches of tall building design have been proposed in the past aiming to mitigate the negative impact of wind flow include a conventional design method and performance-based design method. Conventional design method described as a combination of certain decisions recalled from the architect's memory based on his aspirations, while performance-based design method described as the exploitation of building performance simulation for the modification of the geometrical form for enhancing a candidate design.

However, based on the literature surveyed, this chapter highlighted the lack of tall building design process that take into account building and urban scales relative to different wind conditions and wind performance criteria (Khallaf &Jupp, 2016). The design workflow for testing performance of the envelope design and pedestrian impact is most often based on prescriptive methods that are unable to explore the desired performance at both the building scale and city scale integrating. Considering the decisions made at the conceptual stage of 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, building systems and related product properties are proposed (Turrin *et al*., 2011).

Consequently, this research project acknowledges the need of developing a computational design method utilising the performance-based design to support simulation and exploration of tall building design and its impact on the surrounding urban context relative to wind flow. The benefit of developing such a framework surrounds the performance details feedback that is valuable to decision-making in the early stages of design and bridge the gap between building codes and city design guidelines relative to wind flow, thus, achieving positive effects of wind flow around buildings and cities. The existing research efforts into performance-based simulation and exploration, as well as the research gaps, will be further discussed in the next chapter.

Chapter Three

Performance-based simulation and exploration

This chapter explores the requirements of a performance-based simulation and exploration method that is capable of integrating a variety of urban and building parameters. The approach includes five stages carried out sequentially. The stages include synthesis, analysis, evaluation, constraints, and exploration. The framework combines building and urban parameters for performance-driven exploration relative to wind flow condition. The chapter, also, investigates the capabilities of each module.

3.1 Introduction

The primary objective of this research project is to develop and validate a decision-support design method for performance-based simulation and exploration design. Design as exploration is one of the design models that recognise the information required to construct a state space of possible designs that not always available at the outset of the design process (Gero, 1994). In this model, designing involves an exploration of behaviours, possible structures and the means of achieving them (Gero, 1994; Logan & Smithers, 1993).

The research methodology employs computational fluid dynamics as its core simulation technique for the prediction of wind performance at different heights defined by the building's overall geometric form and its relationship with the surrounding building context. 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 exploration of wind loads on- and wind flows surrounding tall buildings. The framework is based on five stages that include synthesis, analysis, evaluation, constraints, and exploration.

Learning from the literature review in the previous chapter, the system must incorporate with multi-design parameters and constraints in a multi-dimensional scale. The development of this system will require identifying the main component of the system include (i) method requirements and (ii) technical requirements.

The method requirements include (i) Performance requirements based on building standards and city guidelines, (ii) Utilising the Computational Fluid Dynamic modelling as a unit of the analysis due to its accuracy and the efficient measurement method cross-different spatial scales relative to building and urban scale, (iii) Utilising a parametric modelling as the generative method due to its capacity to generate vast design space, and (IV) approach to assessment. In addition to the method requirements, technical requirements play an important role to convert the conceptual method into a practical method. Technical requirements include (i) Utilising Autodesk Computational Fluid Dynamic due to the wide range of simulation tasks and workflow based on their share proprietary platform, (ii) Utilising Grasshopper as the parametric modelling tool due to the capacity of flexible modelling rendering and design workflow when integrated with Rhino.

This approach will provide an integrated computational method that combines building parameters and standards with urban parameters and guidelines to generate feasible alternative design solutions that satisfy both building standards and city design guidelines. In addition, it will provide simulation and real-time feedback that enhance design workflow. The workflow and the outputs will help designers and the governments to be prepared for wind-related hazards and minimise the damage to public safety and health of an urban area, thus enhancing urban resilience.

3.2 Building and Urban Performance Requirements

The design of tall buildings can affect 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 analyse the effects of wind conditions on pedestrians within the site, on the street 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 Development Manual for Chicago Plan Commission Projects (DPD, 2012) request a wind impact study analysis for buildings that above 182 meters and/or or adjacent to existing or proposed publicly accessible such as parks, plazas, playgrounds, etc. The aim of the study is to show the impact of the project on surrounding areas at the pedestrian level considering the nearby public spaces. The study should include the potential effects of wind in every direction, and to describe how the design of structure will mitigate the effects of wind.

The City of Sydney Development Control Plan (DCP) (City of Sydney, 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 minimised. 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, 2012) 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 the building's location, orientation, and 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 nonuniformity 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.

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 'favourable' 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 'favourable', '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 in previous research studies. Capeluto *et al.* (2003) define 'favourable' wind conditions as moderate winds of two metres per second, and Penwarden (1973) provides a definition of 'discomfort' as the mean wind speed of five metres per second, which marks the onset of discomfort for pedestrians. Speeds greater than 10 metres per second represent 'unpleasant' wind conditions and speeds greater than 20 metres per second 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 setbacks, and (iv) adjacency relationships that promote optimal wind conditions (Khallaf & Jupp, 2016). Section 3.2.2 will discuss the different principles further.

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 the wind flows around a tall building's envelope at pedestrian level (Khallaf & Jupp, 2017)

3.2.1 Multidisciplinary Design and Wind Performance

During the conceptual design process, it is important for both architectural design and urban design disciplines to identify wind flow conditions at the early stage of the design process. 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 building performance relative to their wind flow profile, it is no different. For urban design professionals, it is not typically possible to explore the impact of wind flow profiles across a new city block or precinct in a sufficient manner during the conceptual phase of the planning process 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 and planning have established differences in terms of their foci, scale, goals, and constraints as well as the guidelines and standards that support decision-making (See following section Table 3.1). 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 to another related discipline's (e.g., urban design or urban planning, (Kroo, 1997). Gandemer (1975) highlighted that wind flow at the pedestrian level around buildings is a result of a complex interaction between wind flow and building parameters (shape, size, height, etc.) therefore, buildings can produce unpleasant high wind speed at a pedestrian level. Capeluto (2003) investigates the impact of building a new business in the heart of Tel Aviv in the area of 250,000 m2 that contain high-rise building of 40 stories. Capeluto (2003) investigation showed the significant future negative wind impact of the tall buildings on the existing low-rise residential buildings and at the pedestrian level. The study found that the new high-rise buildings would act as a high wall that would deprive the sun and winds of the existing buildings and pedestrian whilst it will create a high wind flow in some areas. Therefore, Tel Aviv City Planning Department decided to adopt certain rules for the design of this new business district to ensure sun and winds in the existing residential neighbourhood.

On the other hand, Ng (2009) reported the negative impact of the stagnant wind condition at the pedestrian level in Hong Kong is due to the hilly topography, poor urban planning, and the building design. The tall and bulky high-rise building blocks with very limited open spaces in between, uniform building heights, and large podium structures have led to lower permeability for urban air ventilation at the pedestrian level. A stagnant wind condition in Hong Kong contributed in speared of the severe acute respiratory syndrome (SARS) which led the Hong Kong Government subsequently set up a Governmental Team Clean Committee to investigate possible urban design policies to improve the air ventilation.

Therefore, understanding the nature of aerodynamic behaviour at both architectural and urban scales is an important aspect of tall building design and urban design to prevent the negative impact of strong and stagnant wind condition (Khallaf & Jupp 2016).

3.2.2 Tall Building Design and Structural Wind Load Requirements

One of the main intents of the wind loading provisions in building codes such as the 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 envelopes 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, and The Municipal Code of Chicago (2017) which provides provisions for all wind directions. The cross-wind motion is mainly caused by fluctuations in the separating shear layers. Torsional motion can be caused due to an 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 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., ≤ten stories) with simple geometries, code formulae are probably of sufficient accuracy for design purposes and conservative results may not have a major cost impact. The Municipal Code of Chicago (2017) requires that all tall building's structure and cladding, to be designed and constructed to resist a horizontal wind pressure on all surfaces exposed to the wind, allowing for wind in any direction. In addition, reductions in wind pressure on building facade due to neighbouring structures and terrain shall not be considered.

However, codes such as the AS/NZ 1170-2 recognise 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 aimed at characterising wind loads for tall buildings and the SI 5281-3 (2011) aimed at optimising favourable wind at the urban scale. Each standard requires solutions to be designed that is suitable for the location, protecting against strong wind flows whilst encouraging air ventilation. Both standards require analysis of the wind regime using CFD testing. Table 3.1 (prepared by the author) summarises building codes and city design development guidelines.

Table 3.1 Building Codes and City Design Development Guidelines

Building Code / City Design Development Guidelines	Building Scale Wind Load	Urban Scale		Suggested Design Principles	Assessment Method/ Tool
		Encourage Wind Flow	Mitigate Wind Flow		
AS/NZ-2002 (Aust. & NZ).	✓			None Provided	Wind Tunnel Testing
The Municipal Code of Chicago	✓			None Provided	N/A
Development Manual for Chicago Plan Commission Projects			✓	None Provided	N/A
SI 5281 Tel Aviv City	✓	✓	✓	None Provided	CFD
City of Sydney DCP			✓	None Provided	Wind Tunnel / CFD Testing
City of Perth Planning Scheme			✓	None Provided	N/A
Western Australia R-Codes	✓		✓	Building setbacks from the street Architectural features to reduce wind velocity	N/A
City of Melbourne Planning Scheme	✓		✓	Building setback from the street	N/A
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 the ground floor of buildings	N/A
City of Wellington Planning Scheme	✓		✓	Architectural features to reduce wind velocity Building setback from the street Clustering buildings to mitigate wind velocity and turbulence Building porosity	Wind Tunnel Testing
City of Toronto	✓		✓	Optimise location, orientation, and form	N/A

3.3 Bridging Design Scales for Improving Wind Performance

In the context of designing for beneficial wind flow profiles across the variety of elements and conditions of an urban environment, such a singular discipline-based focus can result in adverse effects at the building and/or city scale. Consequently, an understanding of the relationship between the architectural and urban design qualities and the physical building/city planning features that are responsible for achieving them is lacking. In relation to wind flow, the relationship between design qualities and physical features across the different scales of micro-climate that exist in an urban context is a complex one. There are mixed dependencies between architectural and urban parameters with different scales, values, and qualities.

However, neither the architectural and urban design process is supported to explore wind flow profiles relative to these dependencies. At the building scale, design guidelines and standards that refer to wind conditions direct design decision-making towards optimising for structural wind resistance and passive cooling. At the urban scale, designing guidelines directed towards optimising for 'comfort' wind ventilation throughout a city, precinct, neighbourhood, block, or street. The lack of understanding of the intertwined dependencies between the architectural on urban 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 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 morphology and (iv) building form. Two main types of wind conditions can adversely affect 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 increase 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 structure- 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 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 3.1 illustrates this scale, which defines an architectural-urban spectrum that accounts for 2D and 3D features that define the building façade, building envelope, city block, a cluster of city blocks, neighbourhoods, precincts, and the city as a whole. Table 3.2 shows the different parameters and define the corresponded unit of analysis.

Figure 3.1 The spectrum of design and planning across scales of urban microclimate relative to architectural and urban disciplines

Table 3.2 Unit of Analysis of Different Parameters.

Physical Features	Parameters	Unit of Analysis
Geographical Parameters	• Geographical location, • land topography, • Building density, • City open spaces • City grids and blocks configurations, • City grids and orientations.	Focuses on the relationship between a city block, or a small cluster of city blocks, and the wider city topology and or the natural topography (Geographical scale)
Urban Parameters	• Block height, • Block orientation, • Block morphology and • spaces between the buildings	Focuses on the relationship between a building scale (3D geometric) a small cluster of city blocks (City/Urban Scale)
Architectural parameters	• Building form, • Building orientation, • Building eight, and Building width	The units of analysis correspond to the 2D and 3D geometric elements that drive the generation of the form (Architectural Scale)

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 design/planning disciplines. This 'disconnect' is to the detriment of meaningful design for urban micro-climates and for achieving the positive effects of wind flow within and around buildings and cities. Consequently, this research project investigates urban hazard mitigation from the perspective of tall building design, focusing on mitigating the impacts of strong and extreme winds at two interrelated scales: the building scale and urban city scale. The research claim is therefore that in designing for these two scales simultaneously, the objectives and outcomes of urban resilience can be addressed.

3.3.1 Units of Analysis

Based on the research studies reviewed in the previous chapter, the positive and negative impacts of wind flow of cities depend on the relationships between geographic parameters (topography, climate, location, etc.), urban parameters (block height, orientation, morphology and spaces between the buildings) and building parameters, (building form, orientation, height, and width).

From the perspective of architecture design, the units of analysis correspond to the 2D and 3D geometric elements that drive the generation of form. Five main architectural parameters are identified relative to the design of the building's morphology and its impact on the wind flow around and through its form, namely: (i) building footprint, (ii) building height, (iii) building form, (iv) building perforations, and (v) building orientation as shown in Figure 3.2

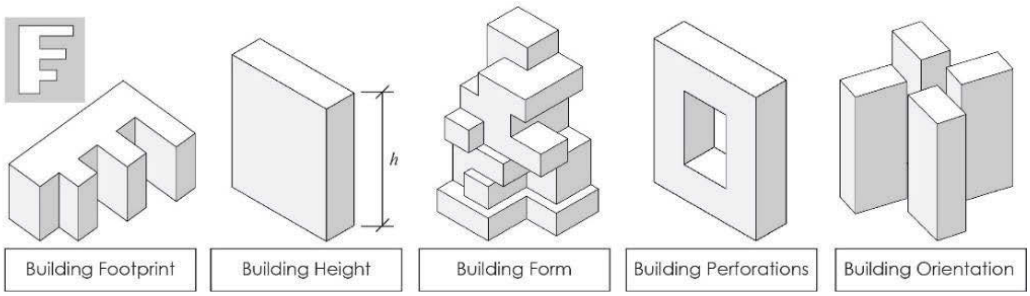


Figure 3.2 Five building morphology parameters influencing wind flow performance at the architectural scale

In the case of urban design, there is a range of parameters that contribute to defining urban morphology that reflects 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)

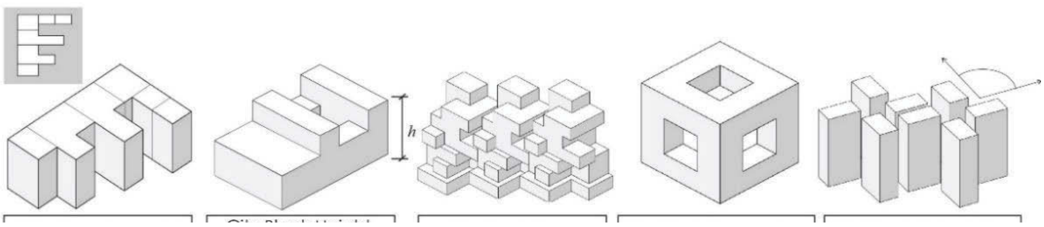


Figure 3.3 Five urban morphology parameters influencing wind flow performance at the urban design scale

city block’s footprint, (2) city block’s height, (3) city block form, (4) city block perforations and (5) city block orientation, as shown in Figure 3.3.

From the perspective of urban planning, six parameters can be identified relative to urban topographic and geographic conditions that can influence wind flow. These six parameters are shown in Figure 3.4 and include the:

1. The density of city blocks and buildings,
2. The configuration of city blocks,
3. The extent of open spaces between city blocks,
4. The orientation of city blocks, streets and grids,
5. City terrain, and
6. City location

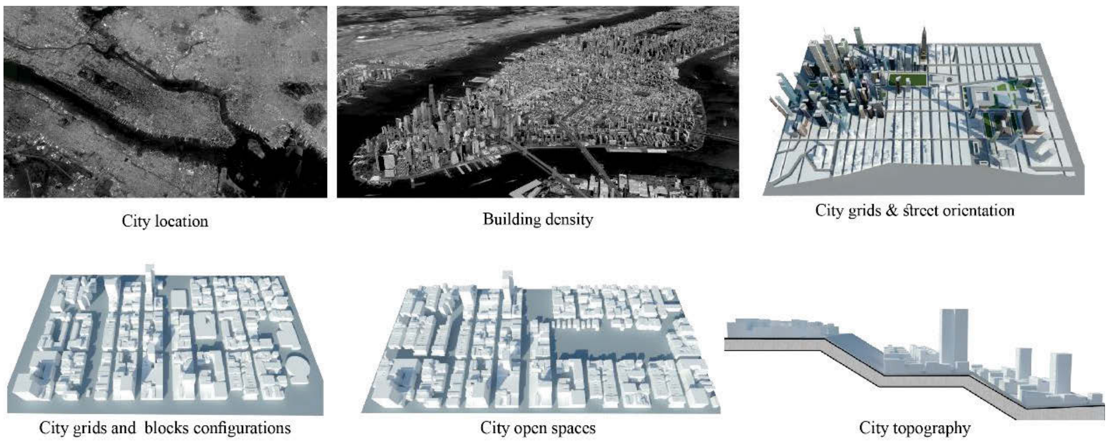


Figure 3.4 Six parameters of urban topology

The urban topology and topography parameters identify the urban topographic and geographic conditions that influence wind flow. It defines: (1) the density of city blocks and buildings, aim at defining the distribution of population density in city block whether high density, medium density or low density. For example, The Planning Strategy for Metropolitan Adelaide describes high density 67 dwellings per hectare, where medium density is 34-67 dwellings per hectare, and low density is 17-33 dwellings per hectare (Government of South Australia, 2006)

Australia (more than 60 dwelling units per acre), mid-density (30 to 60 dwelling per hectare) or low-density (less than 30 dwelling per hectare, (2) The configuration of city blocks, (3) the extent of open spaces between city blocks, depend on the size and orientation of these spaces in relation to the mean wind incidence, (4) the orientation of city blocks, streets and city grids, (5) city terrain, aim at defining the geographic terrain whether complex terrain or simple terrain, however, this definition varies from country to another, (5) city location that aim at defining if the city is coastal or non-coastal.

3.4 Approach to Context Sensitive Building Envelop Generation

As this thesis showed different approaches to tall building design and urban design in Section 2.4.2 and 2.4.3, a variety of design disciplines have adopted a generative parametric design approach so as to work within a process that includes a performance analysis feedback loop that supports early design decision-making (Alfaris, 2009; Coory, 2014; Turrin *et al*., 2014; Khallaf & Jupp, 2017). Parametric models are powerful tools, capable of generating vast design spaces (Alfaris, 2009). In addition, it offers a novel approach to design exploration and optimisation that allows the definition of both problem and solution in the same model (Coorey, 2014). Turrin *et al*., (2014) highlighted the benefits of utilising parametric modelling at the early stage of the design process aiming at converting an abstract definition into measurable criteria. The research introduced design information from numeric evaluations and performance simulations coupled with evolving forms of architectural solutions. The researched aimed at supporting a design exploration that able the designer to intervene in the search process as well as extract knowledge from the generated solutions. The result of the research showed the potential in supporting the generation and exploration of design alternatives without conflicting with design objectives.

Granadeiro *et al*. (2013) presented a methodology that aims at assisting design decisions regarding the building envelope shape considering its effects on energy performance. The primary aim of the proposed design method is to measure the energy demand of each design solution. In order to achieve this aim, the proposed method involved parametric design system to generate alternative envelope shape designs integrated energy simulation. The result of the research showed the benefit of integrating the parametric system into the design process to establish a direct link between design generation and automated energy simulation.

Consequently, utilising parametric design in the early stage of the 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 allows exploring the design performance and providing analysis feedback that contributes to the designer’s decision in a complex design problem. In addition, it strengthens the flexibility of the design process. The parametric generative approach will play a key role in generating different tall buildings envelop alternatives solutions in relation to performance-based design.

3.5 Approach to Assessment of Building Envelop and Urban Interface

Learning from the literature review in the previous section, CFD is an efficient measurement method cross-different spatial scales relative to the architectural-urban-geographic scale. In the case of identifying wind flow profiles within a city. CFD is based on four numerical solution methodologies of different governing equations for solving fluid problems include Spatial Discretisation, Turbulence Modelling, Boundary Conditions, and Mesh Generation.

Spatial Discretisation is a process of converting the geometric model into discrete parts aiming at preparing the geometric model to be suitable for computation numerical analysis. Three different methods of spatial discretisation include Finite Element Method (FEM), Finite Difference Method (FDM), and Finite Volume Method (FVM).

Finite element method is a computational method that discretises and subdivides a geometry model into small finite-sized elements of geometrically simple shapes as shown in Figure3.5. It divides it into computational Triangular elements in 2D and tetrahedral elements in 3D. Consequently, complex geometries and unstructured grids such as CAD geometries can be discretised, and there will be no grid transformations needed (Chung, 2010).

Finite difference method divides the geometric model into small, interconnected computational Quadrilateral elements in 2D, and into hexahedral elements in 3D, as shown in Figure 3.6. This method requires only an orthogonal structured grid; therefore, this method can be applied only to simple forms of geometrical models.

Finite volume method based on either the finite element method or finite difference method. It discretises the governing equations by dividing the physical space of the geometric model into a

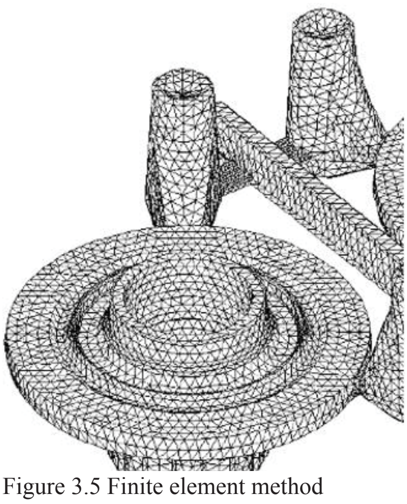


Figure 3.5 Finite element method

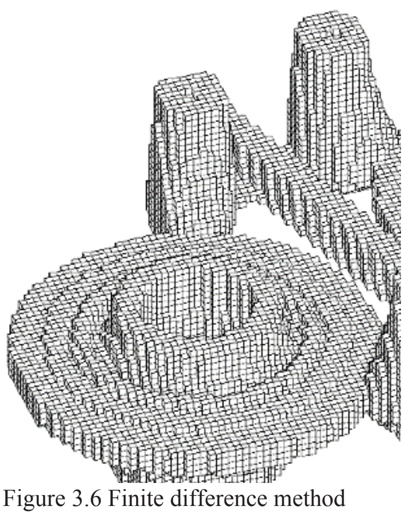


Figure 3.6 Finite difference method

number of computational arbitrary Polyhedral in a form of control volumes. FVM is a flexible and accurate method of discretisation as it can be implemented on structured and unstructured grids.

Turbulence Modelling is the construction and use of a model to predict the effects of a turbulence utilising Navier-Stokes equations. Since there are different types of Turbulence Modellings such as Direct Numerical Simulation and Large-Eddy Simulation, this research will utilise Reynolds-Averaged Navier-Stokes Equations as it highly used in aerodynamic engineering. The advantage of this approach is it requires lower grid points of the geometric model compared to other models. Reynolds-Averaged Navier-Stokes Equations model, therefore, reduces the computational processing.

Boundary Conditions is the initial conditions of the geometric model determining the state of the fluid at the time t=0 (Blazek, 2015).

Mesh Generation aiming to decompose the geometric models into subdomains to enable discretised governing equations to be solved inside each of these subdomains using one of three discretisation methods (FDM, FEM, and FVM).

3.5.1 The process of CFD

CFD involves data processing based on three stages includes: Pre-processing, Solution, Post-Processing as showing in Figure 3.7. Details of the process are explained below.

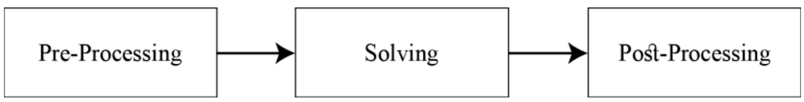


Figure 3.7 CFD: stages of data processing

Pre-processing involves defining the geometry modelling that usually are surface-based models composed of geometric primitives (points, polygons, and surface).

- Setting the boundary condition of the region of the analysis.
- Mesh generation defines the type of mesh (structured or unstructured) that will be utilised in the solving stage. The granularity of the mesh fine or dense mesh affects the level of the results' accuracy and the processing time. Denser mesh provides higher accuracy and higher processing time relative to a fine mesh.
- Selection of the flow type (steady or unsteady, incompressible or compressible, laminar, turbulent)

Solving or processing is the main module of the CFD process; it defines the discretisation method to solve the mathematical governing equations

- Specifying the discretisation method (FDM, FEM, or FVM)
- Solving the mathematical governing equations of the fluid flow to provide numerical values of each cell of the defined mesh. Consequently, the discretisation method (FDM, FEM, or FVM) must be specified in compliance with the used type of mesh (Ayoub, 2012)

Post-Processing evaluates the data generated by the processing stage. It provides the analysis of the results of the solving stage numerically and graphically (2D and 3D). In addition, it displays the defined mesh together with vector plots of the velocity of the fluid flow or contour plots of scalar variables such as wind velocity and wind pressure within the defined boundary condition

Regardless the difficulties of utilising CFD as analysis and simulation tool, adopting CFD in performance-based approach in the early stage of the design process will play an important role as the main driving mechanism to establish controls for analysis and simulation integrates. In addition, it will assist the designers to test and analyse the different design solutions by providing essential analysis data numerically and graphically relative wind performance criteria. Consequently, it will support the flexibility and the interdependencies between analysis and evaluation module in the design process that is essential in a performance-based approach to a complex problem.

3.5.2 An Overview of Available CFD Software Packages

This section illustrates an overview of wind analysis and simulation of different applications. Table 3.3 shows a list of features and capabilities were developed in compliance with CFD that will contribute to select the CFD tool to utilise within this research to achieve the research aim. The features are divided into six attributes include the compatibility with parametric design, the ability to embed 3D modelling tools, the type of the grid, the compatibility with the 2D and 3D dimensions, the discretization method and the turbulence model. The table overviews five professional packages for evaluation, depending upon their popularity among users.

Table 3.3 A General Overview of Wind Analysis and Simulation Application

Application Name	Compatibility with Parametric Design Platforms	Embedded 3D Modelling Tool	Grid Generation Type	Dimensions	Discretization Method	Turbulence Model
ANSYS Fluent Release 132	Yes (Fluent for CATIA)	Yes (Design Modeler)	Structured & Unstructured	2D & 3D	FEM (CFX) and FVM (Fluent)	Zero-, one- and two-equation models: (k-ε), k-ω), RST, LES
Flow-3D Version 103	No	Yes	Structured	2D & 3D	FVM	two-equation models: (k-ε), k-ω), LES
OpenFoam Version 2.0.14	No	No	Unstructured	3D	FVM	Zero-, one- and two-equation models: (k-ε), k-ω), DNS, LES
Autodesk CFD 2017	Yes (All Autodesk software and Rhinoceros)	Yes	Structured & Unstructured	2D & 3D	FEM	Two-equation model (k-ε), LES
Flow Simulation (SolidWorks)	Yes (SoldWorks 3D Design)	Yes	Structured & Unstructured	2D & 3D	FVM	Two-equation model (k-ε)

Based on the comparison in Table 3.2, this section concludes that Autodesk CFD 2017 comprises all the features and capabilities in compliance with CFD. It compatible with parametric design, embedded 3D modelling tool, it able to generate a structured and unstructured mesh. In addition, the application is able to simulate 2D and 3D models utilising the Finite Volume Method (FVM). Therefore, this research will utilise the Autodesk CFD 2017 as a CFD tool to conduct the case study in Chapter Six.

3.6 Toward A Performance-Based Simulation and Exploration Framework

This research discussed the need for developing a performance-based simulation and exploration method aiming at dealing with a complex design problem and several design objectives. In the previous chapters. This chapter describes the first prototype of the proposed framework that utilises the performance-based simulation and exploration method. The framework combines building and urban parameters for performance-driven exploration relative to wind flow condition. The structure of the initially proposed framework is based on five stages carried out in sequential a manner as shown in Figure 3.8.

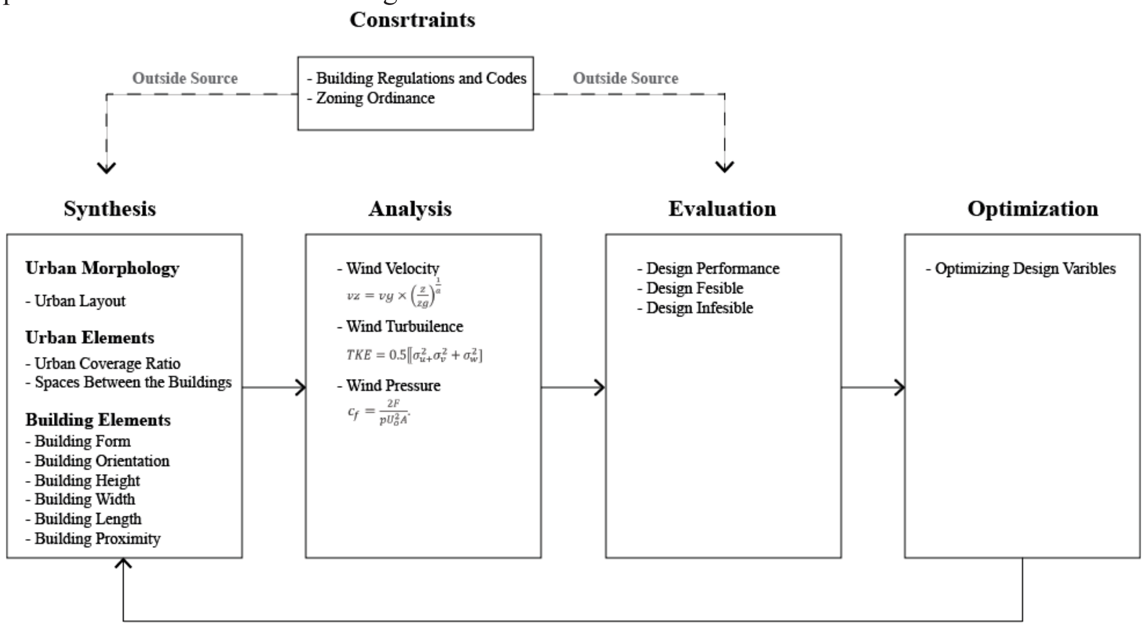


Figure 3.8 Performance exploration framework

3.6.1 Synthesis Module

It abstracts the scheme into a group of design parameters and rules utilising parametric modelling. Design parameters describe the building parameters (building form, orientation, height, width, length and proximity), urban parameters (urban coverage ratio, and the spaces between the building), and urban morphology parameters (urban layout, street width, and street length), whereas design rules describe a design as a series of relationships driven by parameters. Parametric modelling, therefore, enables this module to generate automatically all possible design solutions as design variables and geometric model by manipulating the value of the design parameters and the design rules. Consequently, it's essential for the designer to define the building and urban parameters and rules.

3.6.2 Analysis Module

This module enables the direct translation of the design geometry and related wind flow settings into the wind flow simulation engine. It utilises the CFD modelling to analyse and simulate the design solution characteristics relevant to wind flow condition, using the Reynolds-Averaged Navier-Stokes Equations. As a result, an analysable wind flow model can be obtained directly from the model without additional modification of geometry and therefore transfer the analysis results to the Evaluation module.

3.6.3 Evaluation Module

Evaluation module plays an important role in the in the decision-making. The input to an evaluation module is the results of the analysis module. It refers to the overall results of the design analysis. It compares the outcome results from analysis module with design constraints to filter design solutions. Evaluation module discards all solutions that do not meet building and city compliance constraints. It ranks the feasible design solutions relative to their wind performance according to the performance criteria.

3.6.4 Constraints Module

Consists of urban and building design restrictions such as building standards, city regulations, and other restriction that vary from area to another such as airport building height restrictions. These constraints granted from outside sources such as city councils and other related authorities.

3.6.5 Exploration Module

This module works as a space search mechanism searching for optimum design alternatives within the domain of feasible and performance solutions. The aim of the exploration module is to evaluate and choose the fittest of the available, feasible alternatives designs solution based on the design performance and the performance criteria. However, if the optimised design solution does not fit the performance criteria, a designer can implement changes in the initial design parameters in the synthesis module based on the acquired simulated results, another for cycle run. However, it must note that the objective of this research project is not creating a computational tool; rather; it aims at developing a system that provides functionality and usability.

3.7 Summary

As discussed in Section 2.2.3 that city is considered as a complex system, the chapter investigated the requirements for a performance-based simulation and exploration method that can integrate the heterogeneous gents and the relationship between them across two spatial scales. The requirements include method requirements and technical requirements. Method requirements based on building standards and city guidelines, utilising CFD modelling as a unit of the analysis (Alfaris, 2009; Ayoub, 2012) and utilising a parametric modelling as the generative method (Alfaris, 2009; Coory, 2014; Turrin *et al*., 2014; Khallaf & Jupp, 2017). Whilst technical requirements include utilising Autodesk CFD as the analysis tool, and Rhino/Grasshopper as a generative tool.

Further, the chapter illustrated the importance of utilising CFD as the main wind analysis tools across different design scales (architectural scales and city scale). Furthermore, the chapter identified the process of the CFD simulation that based on five stages include Spatial Discretisation, Turbulence Modelling, Boundary Conditions, and Mesh Generation. In addition, the chapter illustrated different applications for wind analysis and simulation to justify which CFD application to be utilised within this research. The comparison based on six attributes includes the compatibility with parametric design, the ability to embed 3D modelling tools, the type of the grid, the compatibility with the 2D and 3D dimensions, the discretization method and the turbulence model. The comparison included five professional packages for evaluation, based on their popularity among users. The chapter concluded that Autodesk CFD 2017 comprises all the features and capabilities in compliance with CFD. Consequently, the Autodesk CFD 2017 will be used as the main analysis tool to conduct the case study in Chapter Six.

The chapter also investigated related buildings codes and city development design guidelines that define the requirements of structural façade wind loading and urban ventilation. The chapter concluded that the current building codes and design guidelines do not adequately address the interface between designing for wind loads versus designing for wind flows. At building scale, building codes focus on optimising tall building structural wind resistance. While, at the urban scale, urban design guidelines focus on achieving for ‘comfort’ wind ventilation throughout a neighbourhood at the pedestrian level. 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 in this chapter. In addition, the chapter addressed a lack of understanding of the intertwined dependencies between the architectural and urban scales that ultimately result in poor design performance in terms of how the physical features of each scale impact on the wind flow profiles intended by the building design and or urban plan.

Consequently, an approach to performance-based tall building envelope design is proposed. The approach is aimed at addressing wind load and wind flow based on generative parametric modelling and performance analysis that integrates physical parameters at the architectural and urban scales. The performance-based design method is based on five modules include synthesis, analysis, evaluation, constraints and exploration. The approach integrates generative parametric modelling and Computational Fluid Dynamics. Regardless the difficulties of utilising CFD as analysis and simulation tool, it is able to provide analysis data numerically and graphically relative wind load and wind flow that will support the evaluation module in the proposed design method. The next chapter will investigate the capability of the proposed computational framework via two pilot studies.

Chapter Four: Experiments

This chapter presents a two pilot studies that are not aimed at validating the system performance described in the previous chapter, but it aims at exploring the capacity of the system to manage and control different parameters at multi-dimensional scale. This chapter will test the approach, efficiency and effectiveness of each module of the computational method through two different levels of complexity of pilot studies. The criteria of the selection of the pilot studies are based on the different complexity, the number of the parameters, and the technical requirements. The assessment of the modules based on the quantity of generated solutions, quality of the solutions, the quality of the solutions data analysis. In addition, this chapter will assess the overall computational method based on the objective criteria of each pilot study in order to determine the limits of each module and of the overall system.

4.1 Exploration of Multiple Design Variables

This pilot study aims at testing the effectiveness and efficiency of each module of the system prototype through a simple wind flow problem within a fictitious site. The proposed system based on the technical requirements discussed in Section 3.1. It implemented in a prototype using Rhinoceros/Grasshopper as a parametric modelling tool, and Autodesk Flow Design as a CFD analysis tool. The first exploration experiment will explore the ability of the system to solve a simple wind flow problem within a small-scale urban area and the ability to manage multiple design parameters in a 3-dimensional environment with different scales including architectural and urban scales.

It based on a simple problematic wind flow within a small rectangular site of 80 metres by 65 metres as shown in Figure 4.1. The site includes 16 buildings defined by a width of eight metres and a depth of 15 metres, a minimum height of three metres and the maximum height of 52 metres. The problem involves strong winds that approach from the south associated with an average speed of 10 metres per second at the pedestrian level. The objectives in this pilot study are to explore different design solutions to achieve the minimum wind velocity at the pedestrian level, minimum wind pressure at the building façade, and minimum wind turbulence between and around the buildings at the pedestrian level.

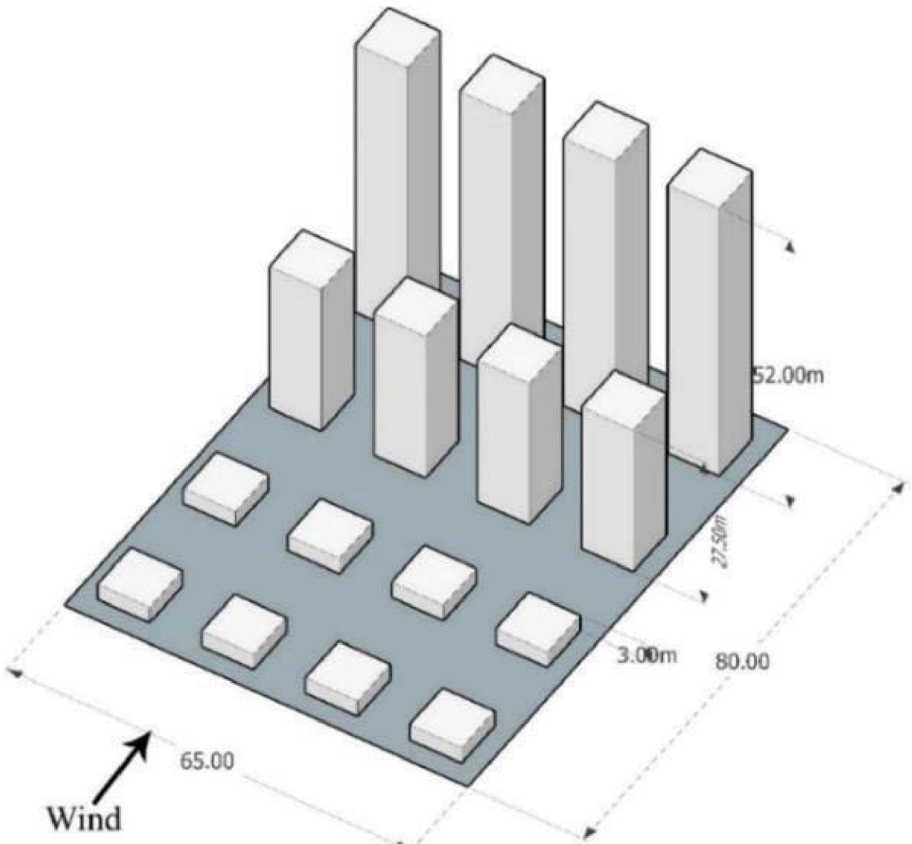


Figure 4.1 The fictitious site

4.1.1 Synthesis Module

The role of the synthesis module is to generate all the possible design solution by assigning different values to the urban and building parameters. This achieved by defining the type of the parameters (variables or constraint), the value of each parameter (see Figure 4.2) and the relationship between the defined parameters as shown in Figure 4.3.

Synthesis

Urban Morphology
- Urban Layout

Urban Elements
- Urban Layout
- Spaces Between the Buildings

Building Elements
- Building Form
- Building Orientation
- Building Height
- Building Width
- Building Length
- Building Proximity

Figure 4.2 Synthesis Module

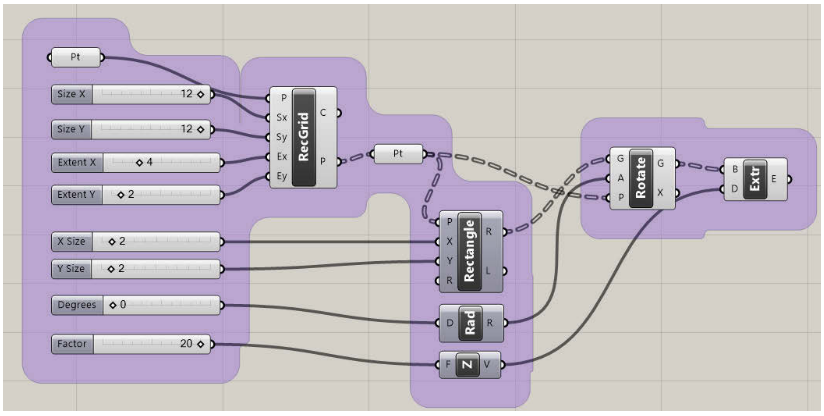


Figure 4.3 Synthesis Parameters and Their Relationships

As the proposed site includes 16 points, each point act as a building centre to control both parameters the building parameters and the urban parameters. 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 height, width, length, and orientation, and (2) buildings separation. Each parameter has a different influence on wind flow profile as shown in Table 4.1.

Table 4.1: Building and Urban Parameters

Parameter Category	Parameters	Value	Type of Value
Building	Height	3m to 52m	Variable
	Width	2m to15m	Variable
	Length	2m to 15m	Variable
	Orientation	0 to 45°	Variable
Urban	Distance from the centre point to another	X= 3.7m to 18.70 Y= 3.7m to 13.50	Variable
Topography	Flat terrain	0	Variable

Once all design parameters and their relationships have defined, the system has the capacity to generate all the possible solution utilising Grasshopper as a bi-directional approach to multi-objective problem-solving. In this pilot study, the framework generated nine different solutions as a surface-based model composed of geometric primitives (points, polygons, and surface) as shown in Figure 4.4.

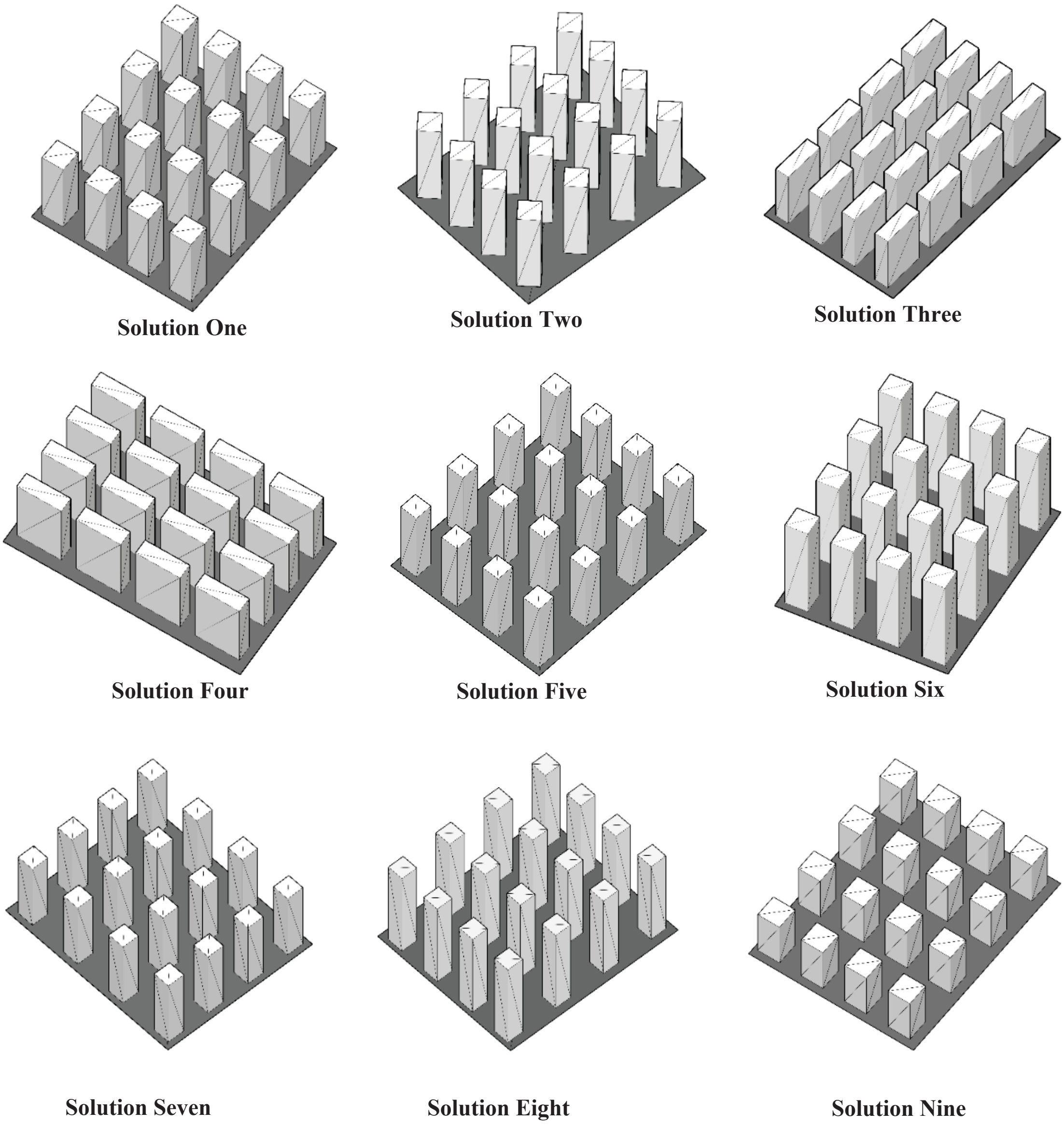
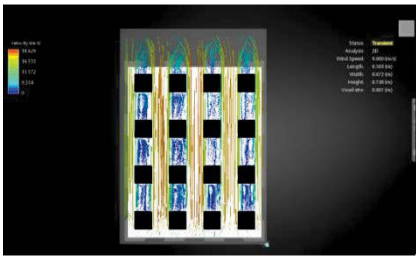
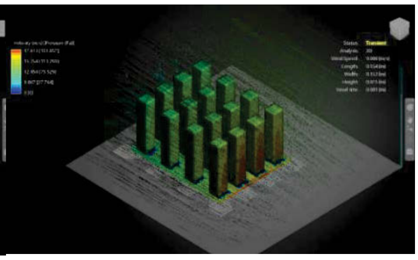
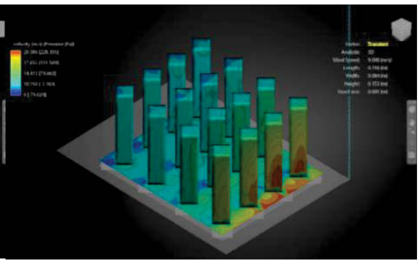
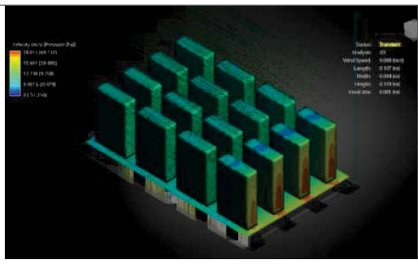
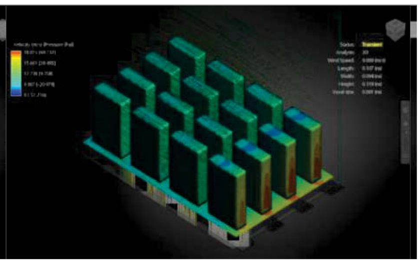
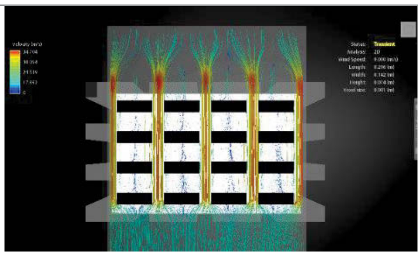
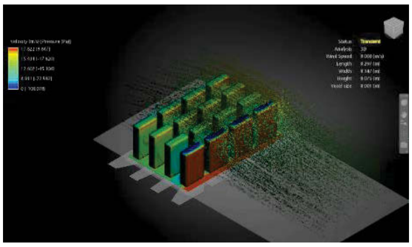


Figure 4.4 Alternative design solutions

4.1.2 Analysis Module

The module aims at testing and analysing the geometry of the building envelope generated by the previous module. It consists of the simulation of the flexible relationships between geometry and wind performance of the outcomes results includes velocity, wind pressure on building façade and wind turbulence. The simulation workflow enables the analysis of the impact of the wind load on and wind flow around of the geometrical parameters with the numerically and graphically of data points. The module involves CFD analysis method that utilises the Reynolds-Averaged Navier-Stokes Equations. Table 4.2 shows the quantitative assessment of the wind performance of the alternative solution.

Table 4.2 Quantitative Assessment of the Wind Performance of the Alternative Solution.

Solutions Number	Velocity and Turbulence	Pressure
Solution: One **Average wind velocity: 9.31m/sec** **Average Wind Turbulence: 17786.301 m^2/s^2** **Average wind Pressure: 151.05pa**		
Solution: Two **Average wind velocity: 14.92m/sec** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 114.17pa**		
Solution: Three **Average wind velocity: 9m/sec** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure:34.5pa**		
Solution: Four **Average wind velocity: 22.61m/sec** **Average wind turbulence 104905.117m^2/s^2** **Average wind pressure: 4.93pa**		

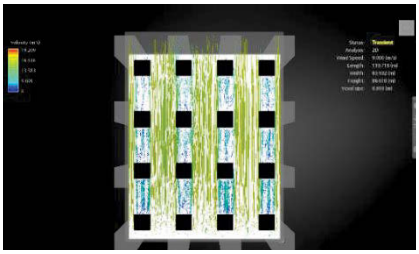
Solution: Five

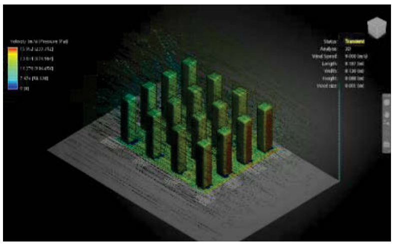
Avg. wind velocity: 9.62m/sec

Avg. wind turbulence

18991.017 m^2/s^2

Avg. pressure:116.65pa



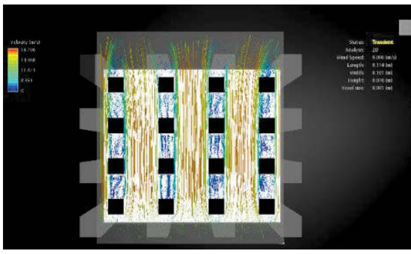


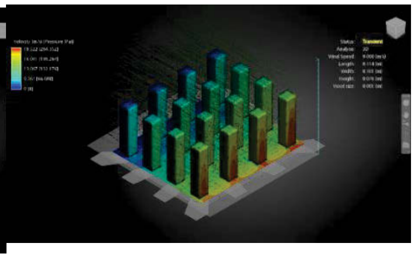
Solution: Six

Avg. wind velocity: 9.6m/sec

Avg. wind turbulence: 18912.272m^2/s^2

Avg. wind pressure: 132.15pa





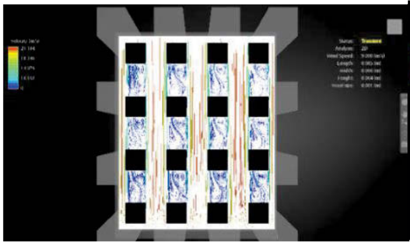
Solution: Seven

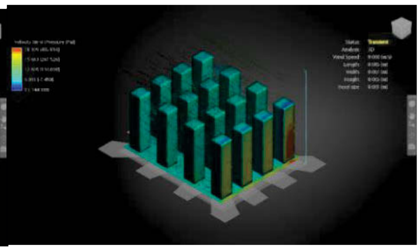
Avg. wind velocity:

10.90m/sec

Avg. wind turbulence 33007.10 m2/s2

Avg. wind Pressure:202.50pa





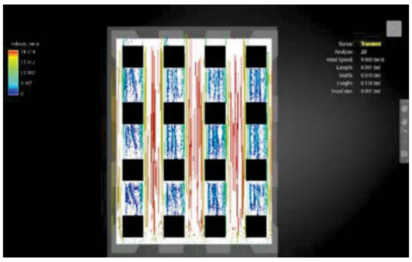
Solution: Eight

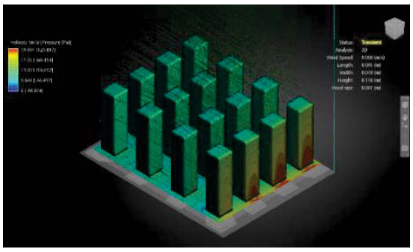
Avg. wind velocity: 10.90m/sec

Avg. wind turbulence

17493.61m2/s2

Avg. wind pressure: 60.44pa



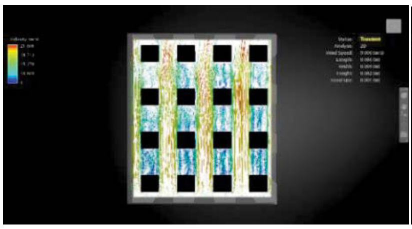


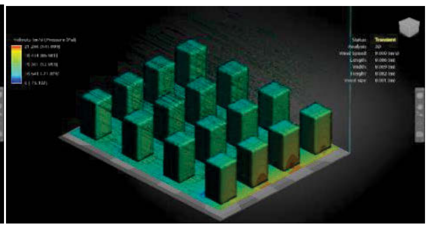
Solution: Nine

Avg. wind velocity: 11.64m/sec

Avg. wind turbulence 2171.613m2/s2

Avg. wind pressure: 70.5pa





4.1.3 Evaluation Module

Evaluation module provides a quantitative assessment to assist the decision-maker in identifying the optimum performing design solutions relative to the objective function. As shown in Figure 4.5, the evaluation module includes two main stages namely constraints stage and a performance stage. Constraints stage compares the alternative solutions with the design constraints (e.g. Building codes and city development guidelines) to identify the feasible solutions that meet the design constraints and discard the infeasible solutions that violate the design constraints.

Performance stage evaluates and ranks the feasible solutions relative to the wind performance criteria. As this pilot study aims at exploring the capacity of the framework to manage multiple design variables and to test the ability of the system to solve a simple wind flow problem within a small-scale, it has not included design constraints. Therefore, all the design solutions considered as feasible designs and the system escalated them to the exploration module.

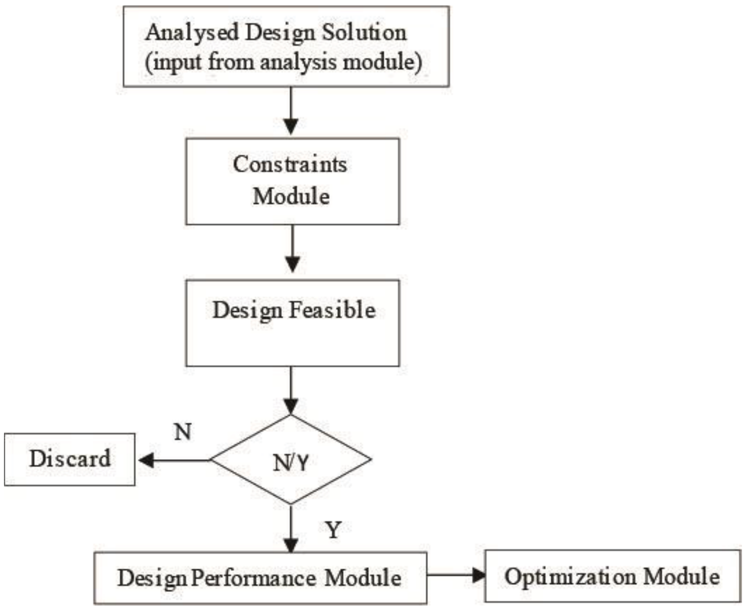


Figure 4.5 Evaluation flow chart

4.1.4 Exploration Module

It works as a search space mechanism searching for the optimum design solution among the feasible design solutions that match or near to the objective function and wind performance criteria. As mentioned in Section 4.2.1, the objective functions produce a design solution that able to achieve (i) a minimum wind velocity at pedestrian level and, (ii) a minimum wind pressure of the building facade and wind turbulence between and around the buildings at the pedestrian level.

In this experiment, the third design solution has ranked as the optimum solution among other alternatives. It achieved the minimum average wind velocity of nine metres per second, average wind pressure of 34 pa and average turbulence of1 6621.91 m2/s2 as shown in Table 4.3. The design parameters include: building height of 38.41 metres, building width of eight metres, building length of 15 metres, orientation is zero degrees, the distance between buildings in the X direction is 13.50 metres and 8.45 metres in the Y direction, as shown in Table 4.4.

Table 4.3 Optimal Design Solutions

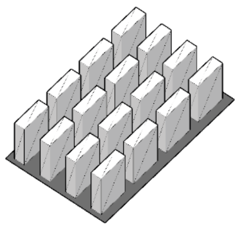
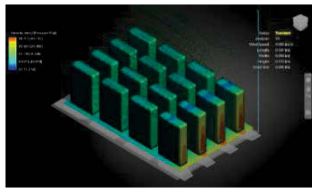
Solutions Number	Design	Velocity and Turbulence	Pressure
Solution: Three			

Table 4.4 Fittest Design Solutions

Parameter Category	Parameters	Value
Building	Height	38.41
	Width	8.4m
	Length	25m
	Orientation	0°
Urban	Distance between buildings	X= 13.50 Y= 8.45
Topography	Flat terrain	0

However, if the target design solution does not fit the performance criteria, the designer can implement changes in the initial design parameters defined in the Synthesis Module based on the current results, and perform another run of the module.

4.2 Pilot Project Results and Observation

Based on the observation of the experiment, the results of the first design solution showed that the average wind velocity decreased from 10 metres per second to 9.35 metres per second associated with average wind pressure 75.52pm and average turbulence of 17786.301 m2/s2 at the pedestrian level when the buildings have the similar height of 20m, same width and length of 4m and 2m respectively and the distance between buildings is 12m in both direction X and Y. However, when buildings rotated 45° in the second design solution with the same value of the buildings and urban parameters, the average wind velocity increased to reach 14.92 metres per second with an average pressure of 114.17pm and average turbulence of 45680.875 m^2/s^2.

In the third design solution, where building parameters include the height of 38.41m, the width of 8.4m and length of 25m integrated with urban parameter include distance from buildings in the X direction of 13.50m and the Y direction of 8.45, it had the best wind performance among the results. The average of wind decreased from 10 metres per second to nine metres per second with average wind pressure on the building façade of 34.5pa and average wind turbulence of 16621.91m2/s2. However, in the fourth solution where building height of 38.41m and width of 25m and length of 8.4m, and distance from buildings in the X direction is 8.45m and in the Y direction is 13.50, the average wind velocity increased to 22.61 metres per second with average wind pressure of 4.93 pa and average wind turbulence of 1040905.11 m^2/s^2.

The results of the fifth and the sixth design solutions are very similar. Building parameters in both solutions include the height of 38.41m, the width of 8.4m and length of 8.42m. However, in the fifth solution, the distance between the building in the Y direction is18.70 and the X direction is 13.50 decreases the average wind velocity to 9.62 metres per second and reached average wind turbulence of 18991.01 m^2/s^2 and average wind pressure of 116.65 pa. Similarly, in the sixth design solution the distance between the buildings in the Y direction is 13.50 and in the X direction is 18.70 has also decreased the average wind velocity to 9.60 metres per second and reached average wind turbulence of 18912.27 m^2/s^2 and average wind pressure of 132.15 pa.

Based on the results of the seventh, eighth and ninth solution, the study proved that heights of the building play an important role in controlling the wind velocity. The three design solutions share the same building parameters include width and length of 8.42, and urban parameter includes the distance between the buildings is 8.45 in the Y direction and 13.50 in the X direction. However, the building height of the seventh design solution is 52m increased the average wind velocity to reach 10.90 metres per second, average wind pressure on building façades of 202.50pa and average wind turbulence of 33007.104 $m^2/s^{2.}$ In the eighth design solution, the building height of 27.5m increased the average wind velocity to 10.90m associated with average wind turbulence of 17493.61 m^2/s^2 and average wind pressure of 60.44 pa. However, the ninth design solution that has building height of 3m, it increased the wind velocity to 11.64 metres per second associated with the average turbulence of 2171.61 m^2/s^2 and average wind pressure of 70.50 pa.

Based on the observation and analysing the results of the pilot study, it shows that controlling wind flow throughout urban microclimates depends on the relationship between building and urban parameter. In addition, the observation demonstrated the possibility to reduce the negative effects of high winds at the pedestrian level utilising CFD as the main analysis method to measure and predict wind load and flow. Consequently, this pilot project demonstrates the ability of the framework to manage multiple design parameters include the urban parameters and building parameters in a 3-dimensional environment.

4.2.1 Exploration of Multi-Design Parameters at Multi-Dimensional Scale

The aim of this pilot study is to explore the ability of the framework to solve a higher level of complexity relative to strong wind profile problem within small a cluster of buildings block and to investigate the ability of the system to bridge the gap between building scale and urban scale. The study based on a complex problem of wind flow within a rectangular area of 75m X 92m includes 40 buildings as shown in Figure 4.6. Wind flow is approaching from the South reaching a velocity of 10 metres per second causing discomfort areas at the pedestrian level. The assumed design objectives are to achieve (i) the minimum wind velocity, (ii) wind load on buildings' facade and, (iii) lowest turbulence. In this fictitious city block, a minimum building height should not be lower than 3m and should not exceed 52 metres. In addition, a minimum building width and length should not be less than 3m and not more than nine metres.

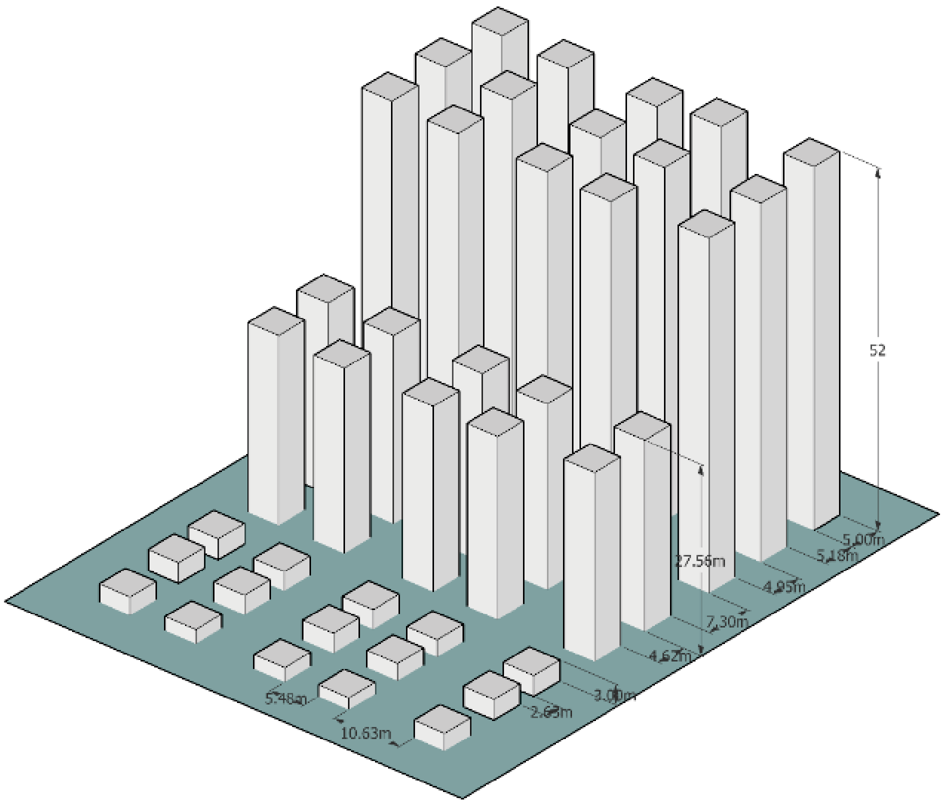


Figure 4.6 City block

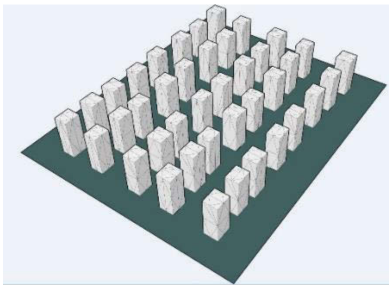
4.2.2 Synthesis module

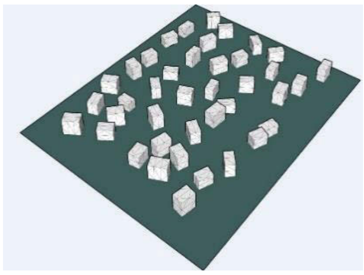
The module defines the design objective and the boundary of design parameters and constraints. The design objective as mentioned in the previous section is to achieve (i) the minimum wind velocity, (ii) wind load on building's facade and, (iii) lowest turbulence. The system boundary based on two sets of parameters namely: building parameters (height, width, and length) and urban parameters (distance between the buildings) as shown in Table 4.5. By assigning different values to the building and urban parameters, the values of the wind performance parameters are accordingly adjusted in parallel with the geometrical change of the tall building envelope.

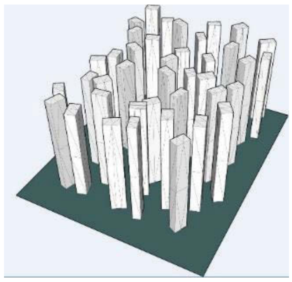
Consequently, it generates nine different alternative design solutions as shown in Figure 4.7. The flexible relations between geometries, wind load, and flow performance can then be analysed by the subsequent module. The module utilises Rhino/Grasshopper as the parametric modelling tool as it is suitable due to the flexibility of modelling rendering and design workflow as mentioned in Section 3.1. The generated model, therefore, is a surface-based parametric rig composed of geometric primitives (points, polygons, and surface).

Table 4.5 Building and urban parameters

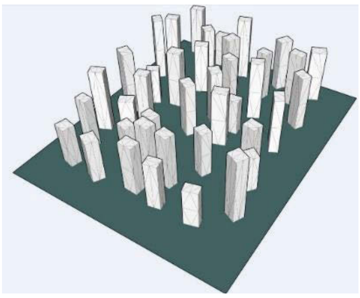
Parameter category	Parameters	Value
Building	Height	3 m to 55 m
	Width	2 m to 9 m
	Length	2 m to 7 m
	Orientation	0 to 360°
Urban	Distance between buildings	From 13 m to 37.5 m
Topography	Flat terrain	0

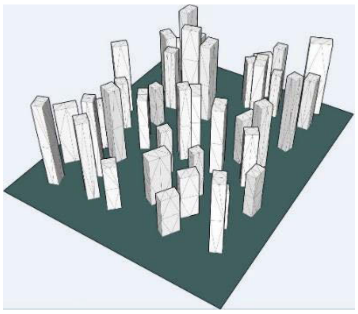


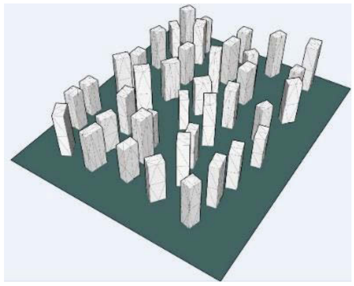




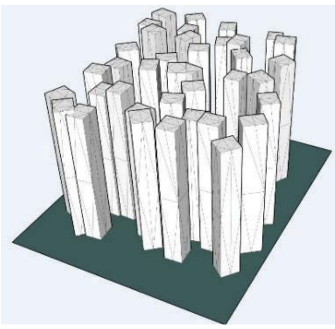
Solution One **Solution Two** **Solution Three**

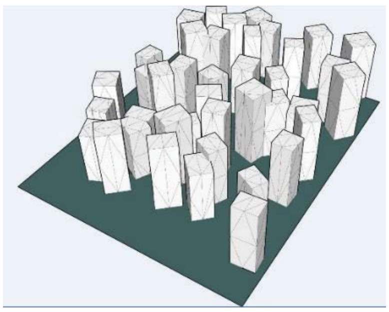


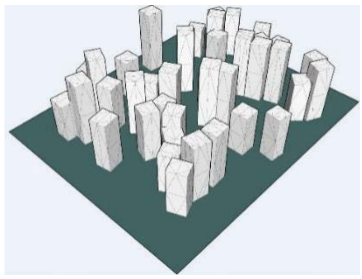




Solution Four **Solution Four** **Solution Four**







Solution Seven **Solution Seven** **Solution Seven**

Figure 4.7. Alternative Design Solutions

4.2.3 Analysis module

It simulates relationships between building geometries and wind load and wind flow performance outcomes of the synthesis module. The simulation workflow enables the analysis of the impact of the wind load on and wind flow around of the geometrical parameters with the numerically and graphically of data. The module involves Autodesk Flow Design as CFD method that utilising the Reynolds-Averaged Naiver-Stokes Equations. Table 4.6 shows the quantitative assessment of the wind performance of the alternative solution.

Table 4.6 Quantitative assessment of the wind performance of the alternative solution

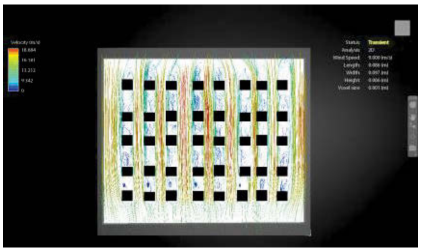
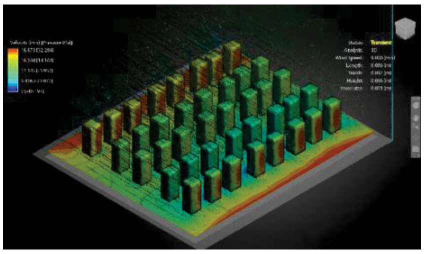
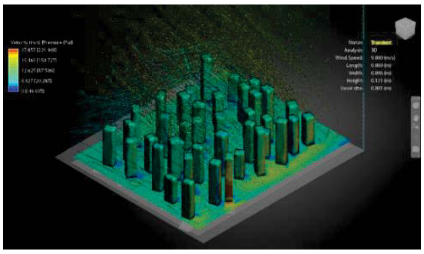
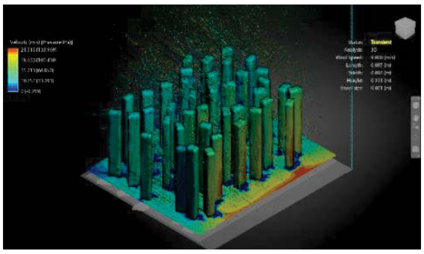
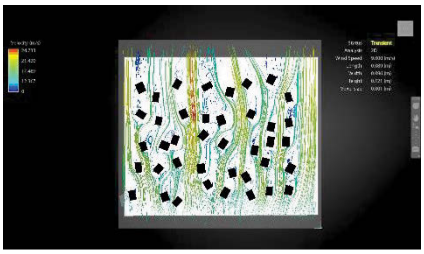
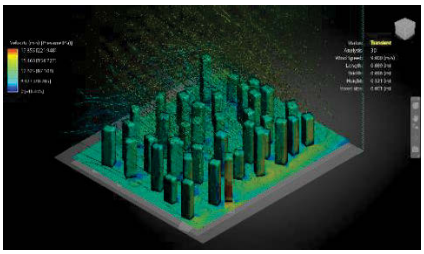
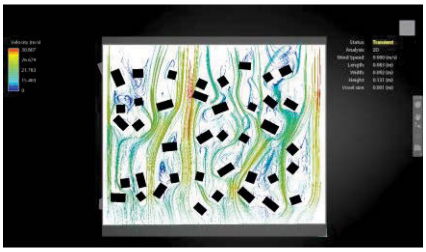
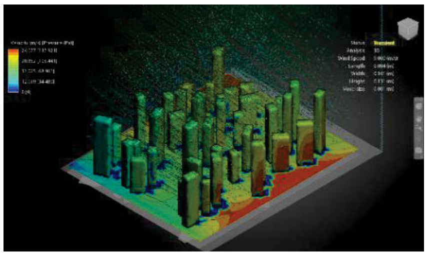
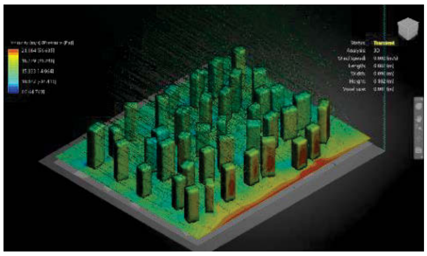
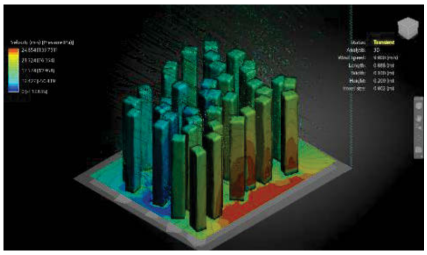
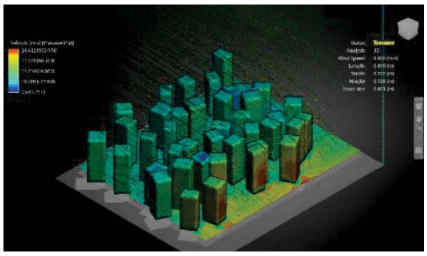
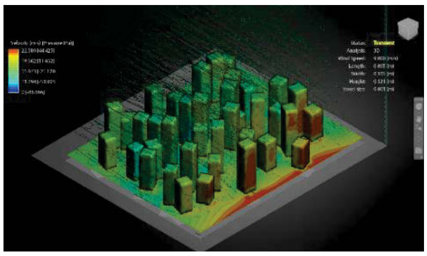
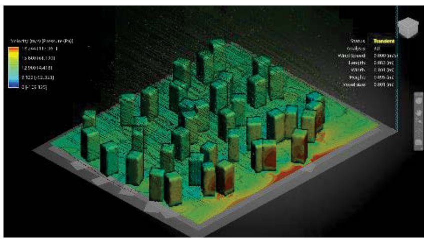
Solution number	Velocity and turbulence	Pressure
Solution: One **Average wind velocity: 9.43 m/s** **Average Wind Turbulence: 17786.301 m^2/s^2** **Average wind pressure: 16.10 pa**		
Solution: Two **Average wind velocity: 10.64 m/s** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 228.92 pa**		
Solution: Three **Average wind velocity: 10.75 m/s** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure: 66.45 pa**		
Solution: Four **Average wind velocity: 8.92 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 110.5 pa**		

Table 4.6 Quantitative Assessment of the Wind Performance of the Alternative Solution.

Solution number	Velocity and turbulence	Pressure
Solution: Five **Average wind velocity: 12.03 m/s** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 68.95 pa**		
Solution: Six **Average wind velocity: 10.84 m/s** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure: 28.31 pa**		
Solution: Seven **Average wind velocity: 12.42 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 69.50 pa**		
Solution: Eight **Average wind velocity: 10.20 m/sec** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 77.98 pa**		
Solution: Nine **Average wind velocity: 11.25 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 22.22 pa**		
Solution: Ten **Average wind velocity: 28.41 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 117.96 pa**		

4.2.4 Evaluation module

Consisting of filtering functions that can evaluate the results of the analysis module and compare results with regard to performance parameters derived from building codes and city development design guidelines. The objective of this module is to filter design solutions by discarding unmatched solutions that do not meet the appropriate wind load (building) and wind flow (urban) design criteria. As this study is fictions experiment, the module discarded the solutions that consist of overlapping or interrelated buildings include solutions number seven, eight, nine and ten. Then, the module evaluates and ranks the feasible solutions relative to the wind performance criteria as shown in Figure 4.8.

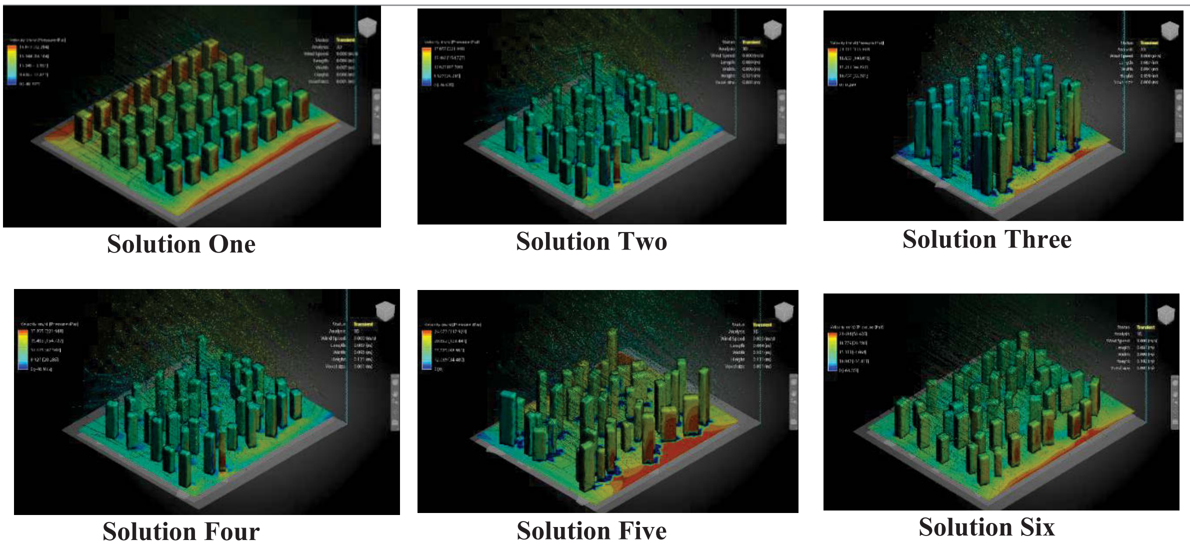


Figure 4.8. Feasible design solutions

4.2.5 Exploration 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 exploration module is to evaluate and choose the fittest of the available, feasible alternatives designs solution based on the objective function and the performance criteria. The experiment shows that the fourth design solution is the optimum design as it satisfies the objective functions and the performance criteria.

4.3 Results and Observation

The aim of the second pilot study is to explore the ability of the framework to solve a higher level of complexity relative to strong wind profile problem within small a cluster of buildings block and to investigate the ability of the system to bridge the gap between building scale and urban scale. Based on the results and observation, the experiment demonstrated the effectiveness of the proposed framework for exploring wind flow at the complex urban area. The framework succussed minimising the average wind velocity at the pedestrian level from 10 metres per second to 8.92 metres per second in the fourth design solutions. In addition, the experiment demonstrated the significant role of the evaluation module in filtering and evaluation the alternative solutions resulted from the previous module. Figure 4.9 shows the discarded design solutions, as they have not met the objective functions.

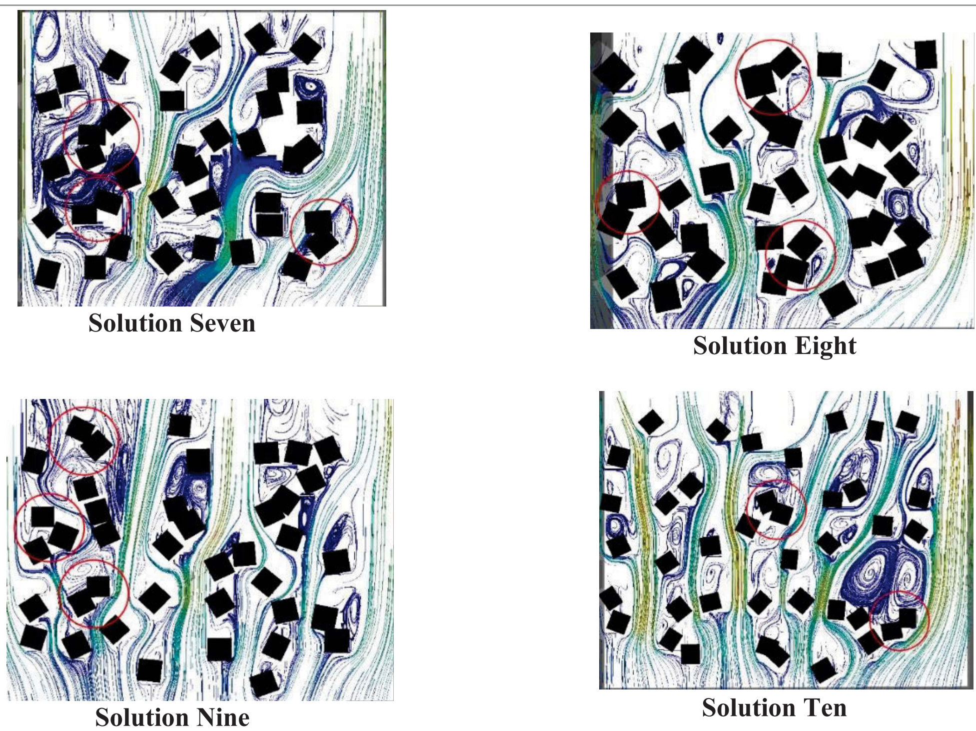


Figure 4.9. Infeasible Design Solutions

At the first design solution, the results showed that the average wind velocity decreased from 10 metres per second to 9.43 metres per second associated with average wind turbulence of 17786.301 m2/s2 and average wind pressure 16.10pa at the pedestrian level. However, at the second design solution, the average wind velocity increased from 10 metres per second to 10.64 metres per second with average wind pressure of 228.92pa and average wind turbulence of 45680.87 m2/s2. The third design solution increased the average wind velocity to 10.75 metres per second with average wind pressure of 66.45pa and average wind turbulence of 166.21.91 m2/s2. However, the fourth design solution has the optimum design performance relative to wind flow. It decreased the average wind velocity to from 10 metres per second to 8.92 metres per second associated with average wind pressure of 110.5pa and average wind turbulence of 11786.30 m2/s2.

The fifth alternative solution has the heights average wind velocity among the domain of feasible solutions. It increased the average wind velocity to 12.03 metres per second with average wind pressure of 68.95 and average wind turbulence of 45680.87 m2/s2 while the sixth design solution increased the average wind velocity to 10.84 metres per second with average wind pressure of 28.31pa and average wind turbulence of 16621.91 m2/s2.

The results and observation of this pilot study indicate the possibility of the framework to mitigate the negative effects of high wind load on building façade and wind flow at the pedestrian level. In addition, it demonstrated the ability to manage dependencies between the building and urban wind flows; thus, supporting the exploration of tall building envelope designs.

4.4 Findings

The objective of the experiment is to assess the performance of each module of the method. In addition, to explore the overall capacity of the system in managing and control different parameters at a multi-dimensional scale and produce a number of feasible solution. The assessment of the synthesis module is based on the number of the innovative solutions that the module is able to generate, and the quality of the solutions. Whereas the assessment of the analysis module is based on the accuracy of the output data that will feed the evaluation module and will play an important role in the direction making. Further, the assessment of the evaluation module is based on the ability of the module to discard the infeasible design solutions, and the produce a quantitive assessment that will contribute in the exploring for the optimum design solutions among the different feasible solutions.

In the first pilot study, the synthesis module was able to generate nine genuine solutions by manipulating the different value of the urban parameters and building parameters to create a large pool of solution space of alternatives, whereas in the second pilot study the module was able to generate ten genuine design solutions.

The analysis module proved its ability to analyse the wind performance (wind velocity, pressure, and turbulence) of each solution the wind parameters and produce a high level of accuracy of numerical and graphical data as input to the evaluation module in both experiments. Since the first pilot study is based on the simple wind flow problem in a fictitious site that have no constraints, the experiment could not assess the evaluation module relative to its ability to filter out the infeasible solution. However, the module proved its ability to provide a quantitative assessment that contributes to identifying the optimum performing design solutions relative to the objective function. Whereas the second pilot study, the evaluation module proved its capability in synchronising with the design constraint and discarding four unmatched design solutions that do not meet building code and/or city design guidelines. In addition, the module was able to produce a quantitative assessment that plays a significant role in exploring the optimum design solution in the exploration module.

From this perspective, the experiments proposed in this chapters highlights the ability of the synthesis module to produce innovative, feasible solutions that reach 60% of the total generated solutions, and the capacity of the analysis module to produce high accuracy numerical and graphical data. In addition, the capability of the evaluation module to discard the unmatched design solution while providing a quantitative assessment that feeds the exploration module. Further, the experiments proved the flexibility and the strong interdependencies between the framework's modules that will support decision-making in a complex wind flow problem

4.5 Summary

The chapter describes the initial prototype of the performance-based simulation method through pilot studies that involves multiple parameters and scales. The method aims at bridging the gap relative to dependencies between the two scales of urban and building design to mitigate the negative effects of the wind flow at the pedestrian level. The chapter then implemented the proposed method into two different levels of complexity through pilot studies aiming at testing the feasibility and the applicability of the method. Based on the results and the observation, the framework succussed at minimising the average wind velocity at the pedestrian in both pilot studies.

In addition, the experiments demonstrated the functionality of the framework for managing multiple design parameters include the urban parameters and building parameters in a three-dimensional environment as well as exploration wind flow in a complex urban area. The syntheses module proved its significant role in providing the means for automatically generating all the possible design solutions by assessing the different values of both building and urban design parameters. However, the experiments indicate the need for specifying the best values for urban and building parameters relative building standards, city development guidelines the aerodynamic modification techniques.

The workflow demonstrates the importance of integrating CFD modelling technique into the system process. It tests the performance of the alternative designs solution relative to the wind load on and wind flow. Furthermore, it provides analysis feedback including numerical and graphical data of wind flow representation at any point in building scale and urban scale. However, the experiments show the importance of specifying the grid structure of the model, discretisation method and boundary conditions of the model for accurate results. The evaluation module was used to successfully filter and evaluate alternative solutions generated by the previous module based on the design constraints provided by the designer.

The experiment showed that simulating and analysing both feasible and infeasible design solutions before the evaluating module is time-consuming. Further, the study showed the need for integrating building codes and city guidelines of development design pertaining to the design of tall building envelopes for wind loads and urban wind flow requirements for more accurate results.

The experiments verified the applicability of the exploration module by searching for the most suitable design solution in the domain of the feasible alternative solutions that meet the objective functions. However, the experiments showed the need for evolving and developing design solutions to enhance the exploration process instead of only searching for the most suitable design solution.

In conclusion, the observations and the results of the two experiments illustrated the ability of the system to meet the main research objective. However, it shows the limitation of the performance of the proposed method relative to the analysis, evaluation and exploration modules. The next chapter will present the significant improvement of the framework and will test the improved system via the case study.

Chapter Five

Multi-objective Simulation and Exploration

This chapter introduces a multi-objective simulation and exploration framework and highlights the system structure. A generative approach and a CFD technique are used to support the flexibility and the interdependencies between the framework's module. The chapter then presents the workflow of the system and the anatomy of each module of the system.

5.1 Improvement on the multi-objective simulation and exploration method

This section presents the structure and the workflow of the multi-objective simulation and exploration method in tall building envelop design. The objective of this section to present the improvement and partially automation of the tall building design process. The ultimate motivation of the method is the automatic determination and explorations of tall building envelop design that satisfies the design objective in conjunction with building and urban standards. This is the fundamental driver for combining computational fluid dynamics with evaluation and exploration techniques for aerodynamic shape exploration problems. To achieve this goal, the initial framework presented in Chapter Three will involve the method and technical requirements that discussed in Section 3.1, the relative building standards and city development guidelines, and the aerodynamic modification approaches for tall building.

The research developed and improved the multi-objective simulation and exploration method to achieve a better overall system. The system structure of the method was developed based on five modules and seven steps carried out in a sequential manner as shown in Figure 5.1. The detail of the system structure and the workflow are explained in the following Section 5.2. A summary of the improvements is as follows.

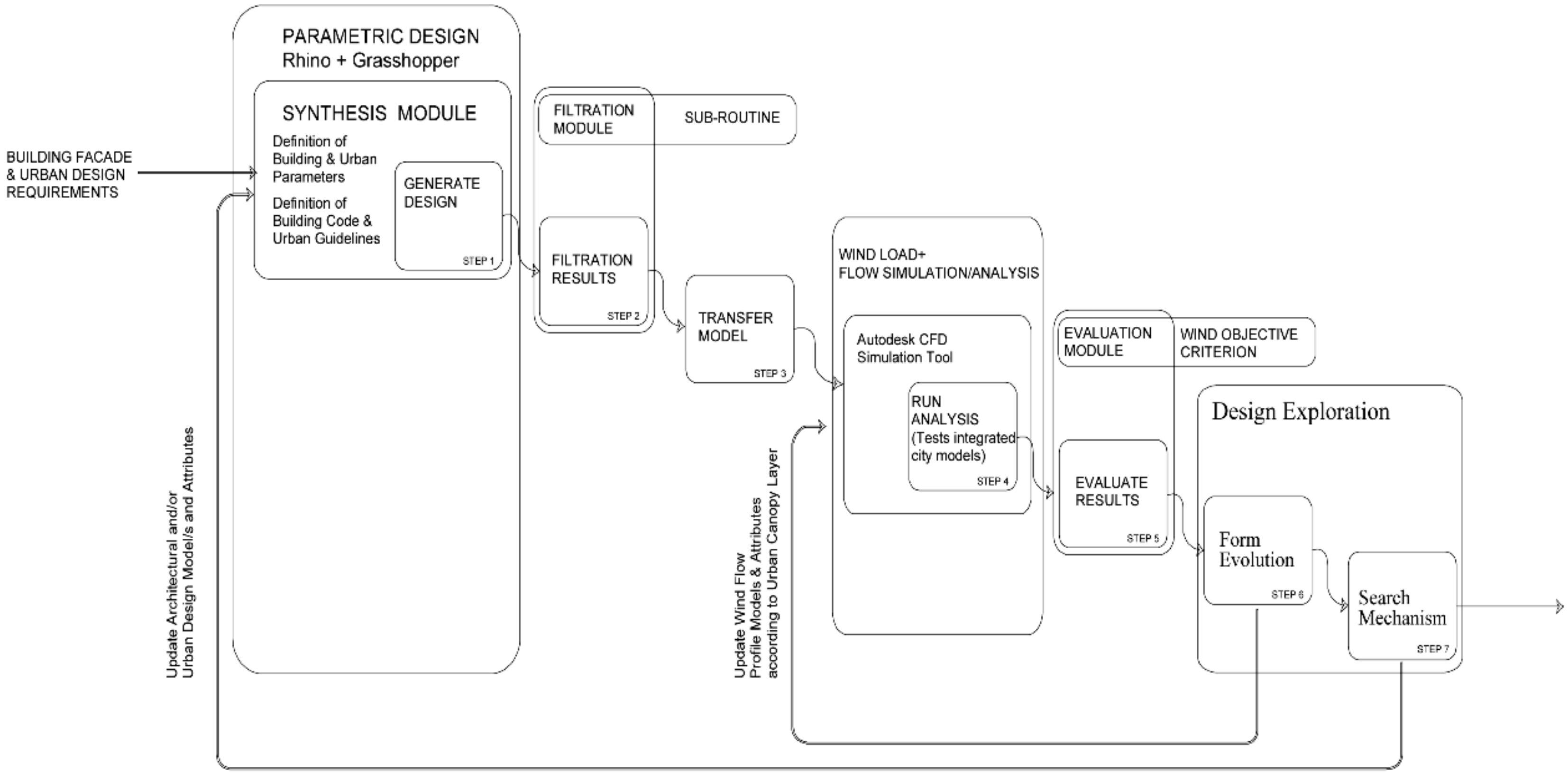


Figure 5.1. Framework of performance-exploration wind design for urban micro-climate

As presented in Chapter Three, the initial synthesis module implemented automatically generates all possible design solutions by manipulating the values of building and urban parameters. Nine buildings parameters and three urban parameters were defined according to the design domain providing categories of structural parameters. Associated functional constraints and parameters were also defined to setup the parametric rig. A range of values for each parameter was specified to generate a solution space that would seed a large pool of façade design alternatives while satisfying the constraints of an aerodynamic shape it was found that it is essential to establish a parametric rig based on the main parameters that play an effective role in the performance of the building relative to wind load and wind flow. By defining the value ranges of those parameters as well as the relationship between them, will contribute to generating all the possible solutions. The number of generated solutions is vary based on design parameters and constraints. The details of these improvements are discussed in Section 5.2

This module improvement detailed in Section 5.2 is aimed at overcoming the limitations of the initial synthesis module by increasing the number of the high-performance alternatives solution generated by the synthesis module. High-performance solutions refer to the number of solutions that objective functions in conjunction with building and urban standards.

This limitation also relates to the accuracy of the results of the analysis module in the initial framework, which relies on their unique specification using the CFD analysis methods. Therefore, the effectiveness and accuracy of the CFD solver approach therefore required further improvements to the turbulence modelling equations, domain sizes, boundary conditions of the generated alternative solutions, and grid discretisation taking into the consideration that the quality of the grid affects the accuracy of the flow solution (Blazek, 2015). Further development of these four aspects of the CFD analysis method is aimed at providing a higher level of accuracy of numerical and graphical data as outcomes, and the details of these refinements are documented below in Section 5.2.

The pilot experiment presented in Chapter Four also demonstrated the lack of contribution to the exploration module to achieve the fittest design solution. This inadequacy of the exploration module lay-in of the lack of further design development or refinement of the alternative design solutions generated and analysed as satisficing the design problem. The exploration module in the initial prototype of the framework is incapable of developing the geometries of the generated solutions to achieve higher levels of design performance in terms of wind parameters. Therefore, module improvements were made to develop the design alternatives assessed as being 'fit' relative to the wind performance by utilising a 'selection' technique (Alfaris, 2009). Selection techniques provide a method to select those building and urban parameters reflected in the highest performing design solutions from a population of alternative solutions that are then used to 'seed' or 'breed' a new generation and thereby improve wind performance, as described below in Section 5.2.

5.2 System Structure Refinements

This section describes a detail improvement on each module of the proposed system. The improving aims at overcoming the limitation of the system performance that has been reported and observed in the pilot studies to improve the overall system performance. The improvement includes synthesis module, filtration module, the analysis module, evaluation module and exploration module.

The aim of the synthesis module is to define objective functions, parameters, and constraints. This module is a combination of building and urban parameters that are connected in different rules to generate a physical architecture form. The designer in this stage is responsible for defining the objective function, the geometric and urban variables based on a tall building aerodynamic modifications technique, the design constraints and the system boundary. The system boundary is defined based on the following specifications for two categories of parameters and two groups of constraints as the main components of the performative wind-based façade design system, the two group of the parameters namely:

1. *Geometric parameters* – plays the main role at defining the tall building envelope design, including building location that define the latitudes and the longitudes of the building, orientation which directly affect the wind flow pattern (Iqbal *et al*., 2016) , Form Manipulation #1: Chamfered Corners ranges from nine to 16% of the building breath cause a noticeable reduction in in both along wind and crosswind (Kwok *et al*., 1988) , Form Manipulation #2: Corner Cut ranges from five to 10% of the building breadth reduces the crosswind fluctuating wind force of a geometry (Housneret *et al*., 1997), Form Manipulation #3: Corner Recession ranges from five to 10% of the building breadth decreases the peak amplitudes of a crosswind force (Gu *et al*., 2004), Form Manipulation #4: Rounded Corner ranges >10% of the building breadth improves the aerodynamic behaviours of the tall buildings against the wind excitation (Kareem *et al*., 1999), Form Manipulation #5: Elliptical cross-section reduces the wind pressure loads (Schueller, 1977), Form Manipulation #6: Tapering ranges from 2.5% to 15% from the ground to the highest point of the building could reduce the wind induced excitation of tall buildings (Kim, 2002), Form Manipulation #7: Openings ranges from 1.5% to 25% can reduce

aerodynamic forces (Dutton and Isyumov, 1990), Form Manipulation #8: height has a strong relation of wind velocity and it affects the wind pattern (Capeluto *et al.*, 2003)

2. *Urban parameters* – plays the key role at defining the urban environment include urban density which has a linear relationship with wind velocity by means that increase of the gross building coverage ratio decreases the wind velocity (Kubota *et al.*, 2009), street width and length which effect on wind flow condition (Reiter, 2010), urban porosity (urban open spaces) which able to increase the air ventilation in the city (Ng *et al.*, 2011), building Separation which demonstrated the effect on the characteristic flow pattern (Cheung *et al.*, 2011).

The two groups of constraints are:

1. *Topographic constraints* - defining slope categories as it has a significant effect on the wind profile. Therefore, it is necessary to define a terrain category to find hourly wind speeds and gust wind speeds (Mendis *et al.*, 2007).
2. *Wind performance constraints* - defining wind load on the building façade and wind velocity and wind turbulence around the building. The definition of the wind load on and wind flow varies from one country to another. Therefore, it important to obtain a reference wind speed based on statistical analysis of wind speed records obtained at meteorological stations throughout the country (Mendis *et al.*, 2007).

Details of the value ranges for the two categories of parameters and constraints are described in Table 5.1 and Table 5.2. By assigning different values to the geometric parameters, and urban parameters, the value of the wind performance is accordingly adjusted in parallel with the geometrical change of the tall building envelope and consequently generates all possible design solutions in terms of the tall building envelope. The flexible relations between geometries, wind load, and wind flow performance can then be analysed in the following module.

A governing model is therefore established based on the main parameters that affect the performance of the building relative to wind load and wind flow, namely: (1) building parameters that include building location, orientation, form, and building height, and (2) urban parameters that include urban density (Floor Area Ratio (FAR)), buildings separation, street width and length. An example of defining the design parameters is shown in Figure 5.2, and an example of output from this module is shown in Figure 5.3.

Table 5.1: Building and urban parameters

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	Based on the building and city standards
Urban	Urban Density	Based on the building and city standards
	Street width and length(m)	Floating Value
	Urban Porosity	Floating Value
	Building Separation	Based on the building and city standards

Table 5.2: Topography and wind constraints

Topography	**Category One**	**0m (open terrain with no obstructions)**
	Category Two	1.5m to 5m with no more than two obstructions per hectare
	Category Three	3m to 10m
Wind	Velocity	Based on the location
	Turbulence (TKE)	Floating value
	External pressure coefficients	Based on the site building code

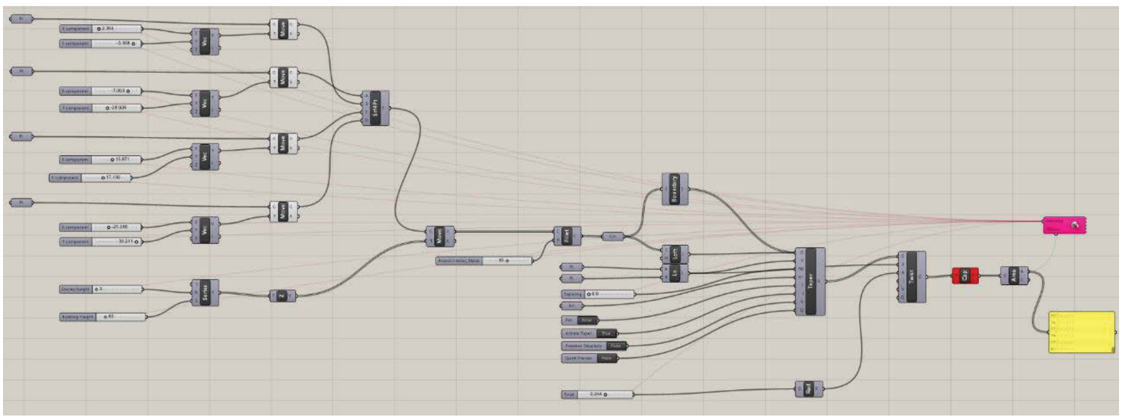


Figure 5.2. Example of defining the design parameters using grasshopper

Grasshopper, a visual scripting editor within Rhinoceros, was selected as the parametric modelling tool due to the flexibility of modelling rendering and design workflow. In addition, Galapagos, a plug-in of Grasshopper, was adopted as a bi-directional approach to multi-objective problem-solving. The module then generates all the possible alternatives facades solutions based on the design parameters and design constraints. Therefore, the number of alternatives solutions varies from site to another taking into consideration that more design constraints will limit the number of generated solutions. In addition, it is not possible to implement all the building parameters across all of the valid value ranges, as some of those parameters will conflict with each other such as rounded corner and the chamfer corner parameters. The generated facades are surface-based models composed of geometric primitives (points, polygons, and surface) as a 3DS file format. Figure 5.4 shows some example of generated models.

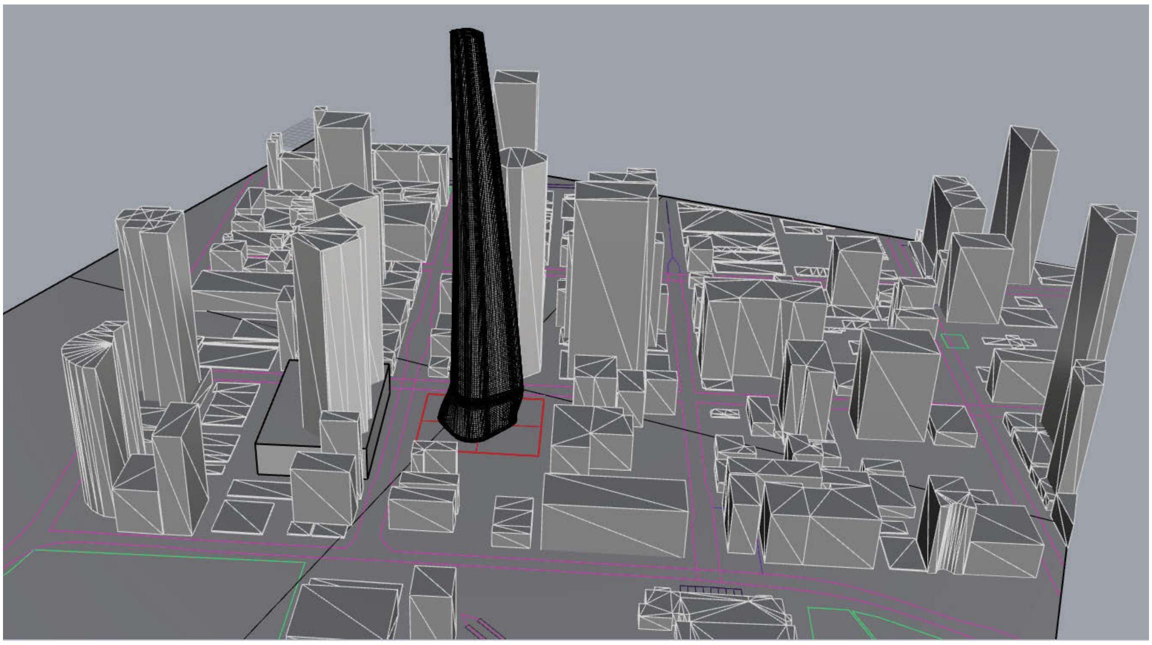


Figure 5.3 Example output of synthesis module: building facade

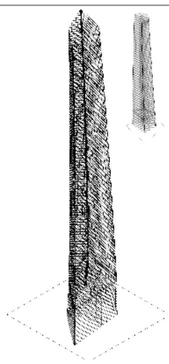
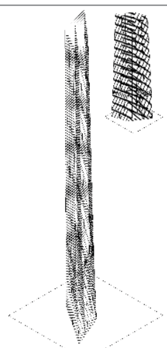
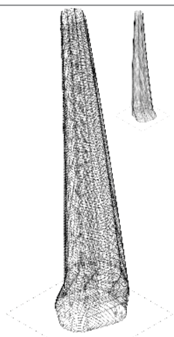
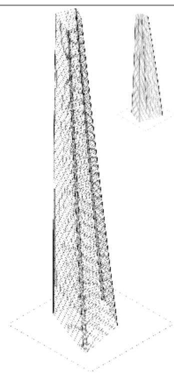
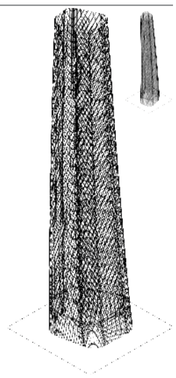
Example	1	2	3	4	5
Geometry					

Figure 5.4 Example of generated building facades

The filtering module is a process of discarding from the system designs that are an infeasible solution. Infeasible design solutions are design solutions that produce results that are incompatible with the performative design constraints—that is, the building codes and city design guidelines for optimal wind load and wind flow conditions.

Figure 5.5 Infeasible design solutions

The process refers to overall results of the synthesis module. Since building codes and design, guidelines are defined in the synthesis module, yet the system is not able to prevent generating a solution that incompatible with building code and city design guidelines due to the limitation of the parametric modelling environment to deal with complex geometric calculations as shown in Figure 5.5.

The design solutions resulting from the previous module produce a 3DS formatted file that enables visual inspection by the designer/ design team so as to manually assess them relative to the building codes and city development design guidelines. Once a feasible set of design solutions are identified, a sub-routine is instantiated, which functions as an ‘external constraints process. This process is aimed at extending the initial filtration process enabling other design constraints to be considered that may be relevant to the site context, for example, proximity to airports and height policy restrictions, construction constraints, etc. Once the process is concluded, feasible design solutions can be assessed by the analysis module using the 3DS file. The workflow is shown in Figure 5.6.

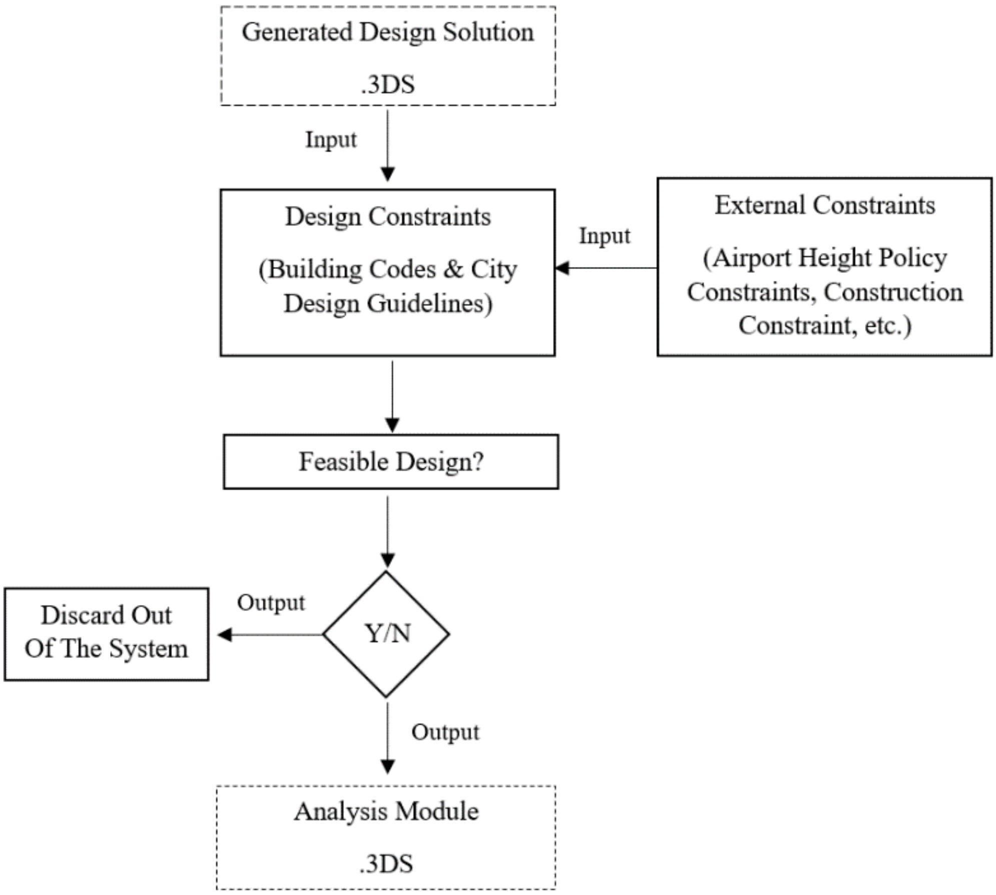


Figure 5.6 Filtration module workflow

Analysis and Simulation Module

The analysis and simulation module consists of the simulation of the flexible relationships between geometry and wind load and wind flow performance outcomes of the filtered design solutions (resulting from the previous module). The simulation workflow enables the analysis of the impact of the wind load on and wind flow around both the geometrical parameters and performance variables with the numerically and graphically of data points assisting in the confirmation of different performance locations throughout the test site on all X, Y and Z axes. The module involves CFD as a core simulation technique for the prediction of wind performance at different heights defined by the building's overall geometric form and its relationship with the surrounding building context. The input of this module is the feasible design solutions resulted from the filtration module as a 3DS file format. The process of this module is based on three stages: pre-processing, solution, and post-processing, as shown in Figure 5.7.

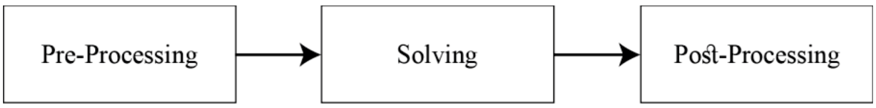


Figure 5.7 CFD Data Process

Pre-processing defines the geometry modelling that is surface-based models composed of geometric primitives (points, polygons, and surface) as a 3DS file format. During the stage, the boundary conditions of the urban area and the building physical are set. In addition, the materials of the building's geometry, surrounding buildings, and the land of the area are also defined. The final step in this pre-processing stage requires the specification of the settings of the mesh generation. The experimental studies in Chapter Four utilised Autodesk Flow Design as a CFD tool that provides an automatic mesh generation that affected the level of the result's accuracy.

Therefore, the system's development requires a manual definition of the mesh type. An unstructured mesh is utilised at this stage. The rationale for selecting the unstructured mesh instead of the structured mesh (see Figure 5.8 and Figure 5.9) is because it uses a mix of hexahedra, tetrahedral, prisms and pyramids shapes that enhance the ability of the mesh to be applied on complex and irregular 3D forms. In addition, the unstructured mesh type is compatible with the different discretisation method include FEM, FDM and FVM. The granularity of the mesh—whether it will be fine or dense mesh—effects the level of the results' accuracy and the processing time. A denser mesh provides higher accuracy and higher processing time relative to a fine mesh.

Furthermore, the designer is responsible for defining the flow type that includes steady flow or unsteady flow, incompressible flow or compressible, laminar flow or turbulent flow.

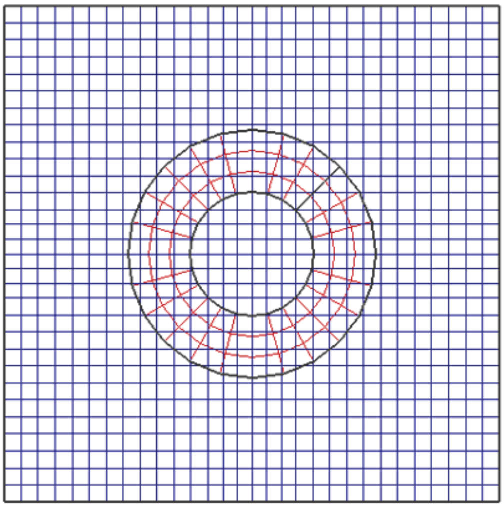


Figure 5.8 Structured mesh

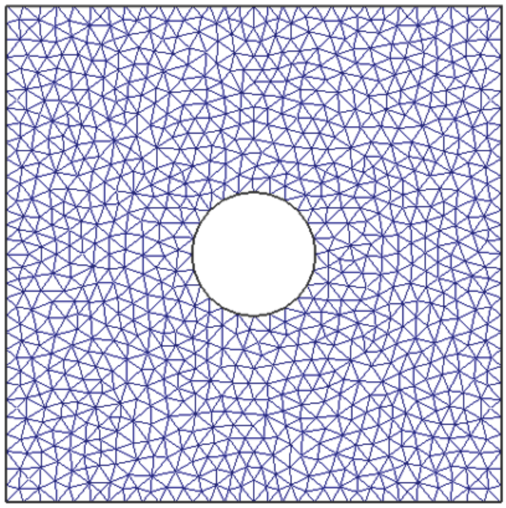


Figure 5.9 Unstructured mesh

Solving or processing is the main module of the CFD process, defining the discretisation method to solve the mathematical governing equations and assess the performance of the façade relative to wind load and wind flow conditions acting on the building. It specifies the discretisation method (FDM, FEM, or FVM) that will be utilised in the solving stage. Due to the nature of complex geometries and unstructured grids of the alternative design solutions generated from the Synthesis module, this stage will utilise the FEM method as it is able to model any level of complex shapes. This stage of the module is then responsible for solving the mathematical governing equations of the fluid flow to provide numerical values of each cell of the defined mesh. The approach solves the mathematical governing Naiver-Stokes equations as expressed by the following (Anderson, 2009).

$$\partial(\rho u)\partial t + \partial(\rho u2)\partial x + \partial(\rho uv)\partial y + \partial(\rho uw)\partial z = -\partial p\partial x + \partial\partial x(\lambda\nabla\cdot\vec{V}+2\mu\partial u\partial x) + \partial\partial y\,[\mu(\partial v\partial x + \partial u\partial y)] + \partial\partial z[\mu(\partial u\partial z+\partial w\partial x)] + \rho fx$$

Equation 1

$$\partial(\rho v)\partial t + \partial(\rho uv)\partial x + \partial(\rho v2)\partial y + \partial(\rho vw)\partial z = -\partial p\partial y + \partial\partial x[\mu(\partial v\partial x+\partial u\partial y)] + \partial\partial y(\lambda\nabla\cdot\vec{V} + 2\mu\partial v\partial y) + \partial\partial z[\mu(\partial w\partial y + \partial v\partial z)] + \rho fy$$

Equation 2

$$\partial(\rho w)\partial t + \partial(\rho uw)\partial x + \partial(\rho vw)\partial y + \partial(\rho w2)\partial z = -\partial p\partial z+\partial\partial x[\mu(\partial u\partial z+\partial w\partial x)] + \partial\partial y[\mu(\partial w\partial y + \partial v\partial\ )]+\ \partial\partial z(\lambda\nabla\cdot\vec{V} + 2\mu\partial w\partial z) + \rho fz \quad \text{Equation 3}$$

where:

x,y, and z components of velocity are given respectably by:

$u=u(x,y,z,t)$ Equation 4

$v=v(x,y,z,t)$ Equation 5

$w=w(x,y,z,t)$ Equation 6

ρ is the density of the fluid (kg/m³) field is given by:

$\rho=\rho(x,y,z,t)$ Equation 7

$\partial\partial t$ is the local derivative, which is physically the time rate of change at a fixed point, $\lambda\nabla\cdot\vec{V}$ is the convective derivative, which is physically the time rate of change of the volume due to the movement of the fluid element from one location to another in the flow field, per unit volume, μ is the viscosity of the dynamic fluid (Pa·s or N·s/m² or kg/m·s), p is the pressure force (v= μρ⁄) (m²/s), fx, fy, and fz are x-, y-, and z-components of the body force f per unit mass acting on the fluid element.

Post-processing evaluates the data generated by the processing stage. It provides a quantitative analysis data of the results of the solving stage as a numerical representation of a CFZ and CSV file formats and graphically represented as a JPEG file format. In addition, it shows the defined mesh together with vector plots of the velocity of the fluid flow or contour plots of scalar variables such as wind velocity and wind pressure within the defined boundary condition**.** Consequently, the change of performance parameters can be visualised within the system in this module.

The module, therefore, assists designers to understand the nature of wind load and wind flow behaviours at both building and urban scales. Autodesk CFD Design Study Environment is used in the analysis module as a CFD tool, including the finite element method for analysing wind loads and flows. The analysis module, therefore, enables the testing of model geometry relative to the building envelope in the context of the urban environment. Simulations are run for two general scenarios: (i) high winds in extreme weather conditions, and (ii) low winds in the case of stagnant air conditions. The quantitative outcome of the module will feed the evaluation module.

Evaluation Module is a manual process of assessing each design solution in terms of the level of effectiveness of wind performance. The input to an evaluation module is the data resulted from the analysis module as shown in Figure 5.10. The evaluation process is usually performed by means of an objective function that consists of a figure of merit describing the quality of a design solution (Alfaris, 2009). It aims at processing the data from the previous module to transfer it into quantitative information by comparing the results from the analysis module with the wind performance objective criteria defined by the designer. This implies that there is no optimal solution but rather a whole set of possible solutions of equivalent quality (Abraham *et al*., 2005). It, therefore, ranks design solutions relative to wind performance objective criteria at the pedestrian level using a 'secularisation' approach. This approach consists of combining several objectives into one scalar function. Approaches based on scalarisation are often used in multi-criteria decision-making (Eckart Zitzle *et al*., 2003). The output of the Evaluation module is quantitative data as a TXT file format and a geometric representation as a 3DS file format.

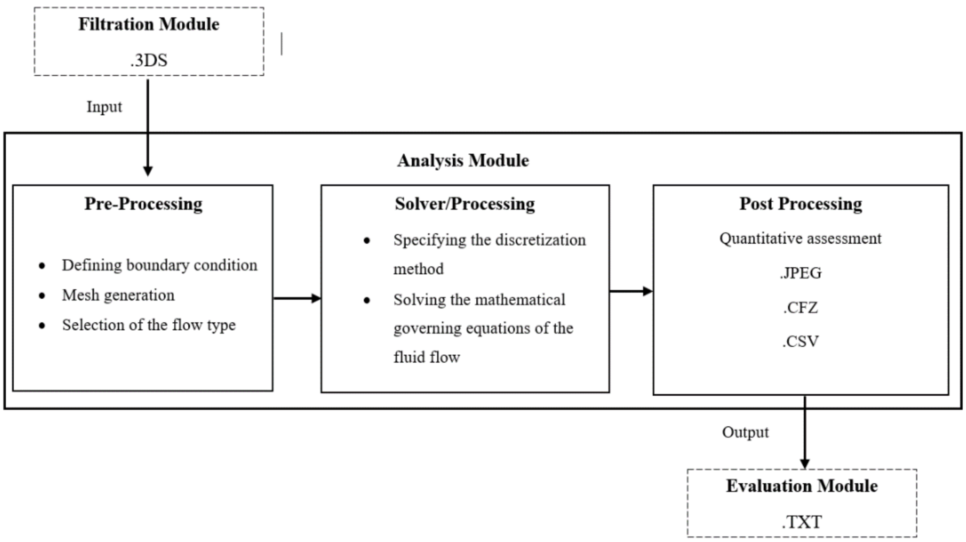


Figure 5.10 Analysis module workflow

The Exploration module provides a process that identifies the suitable design solutions that satisfy the objective function defined by the designer/design team based on pedestrian comfort and safety in terms of wind flow, building codes, and urban design guidelines compliance criteria among the feasible alternatives. The input of this module is the result of the evaluation module is a geometric representation of a 3DS format and a quantitative representation as a TXT file format. In this module, the design decision-maker is responsible for choosing the best alternative solutions in terms of the wind performance among of different design performance that resulted from the evaluation module. The number of the chosen alternative solutions is based on designer preferences. However, the number should not be less than two solutions to able the exploration process to proceed. The module includes two stages of development and exploration process, namely Form Evolution, and Exploration, which they based on the 3DS file format.

Form evolution is a process of developing the selected alternative design solutions (minimum of two solutions). The mechanism of this process includes an elitism selection method (Alfaris, 2009). This method allows the selection of the fittest design solutions' and their parameters (building and urban parameters) in terms of wind performance of each alternative design and combines them together to generate a new parametric rig that will enable the generation of alternative design solutions. Employing the elitism selection method implies passing the fittest solutions' parameters from one generation to the next aiming improving the design solutions.

The designer, based on the result of the evaluation module, is responsible for doing this manual process. The manual process includes selecting the fittest design solutions and their parameters based on the quantitative results from the evaluation module and combining the parameters to generate the new solution. Grasshopper is selected as the parametric tool for the combing process as it has been utilised in the Synthesis module. The purpose of this stage is to produce new properties of geometry that will allow the system to improve the design solutions' performance and limiting the number of feasible alternative design solutions.

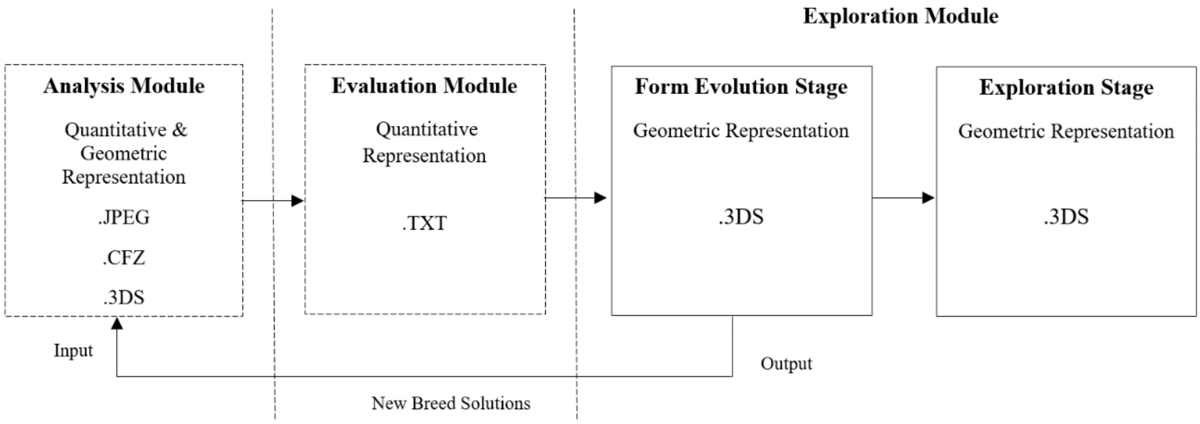


Figure 5.11 Analysis, evaluation and form evolution workflow

The result of this stage is the input of the analysis module as a geometric representation in a 3DS file format in order to test and analyse the design performance of the newly generated design solutions in term of wind parameters. The result of the analysis, evaluation and form evaluation loop is the input of the exploration stage as a geometric representation in a 3DS file format as shown in Figure5.11. In addition, there is no required transfer from form evolution stage to the exploration stage.

Exploration module is implemented here as a manual process of searching for the near-optimal design solution. Because of the current limitation of computer software that is able to combine all the framework's modules in one platform and run an automated exploration, and due to the complexity of developing such a program, this research utilises a manual search of near-optimal solutions. The near-optimal design solution refers to the solutions that provide the best design performance in terms of the wind performance that satisfies the objective function, building standards and city design guidelines, and designer preferences. The objective of this space search mechanism is variable and not constant. It depends on city development guidelines constraints, building codes constraints, objective function and the designer preferences relative to wind velocity, directions, and turbulence. The result of this stage is a geometric representation in the form of 3DS file format that will help to inform the decision maker of the best form of tall building envelop design that satisfies the different requirements in the early stage of the design process. However, if the selected design solution does not fit the performance criteria or the designer preferences, the designer can implement changes in the initial design parameters in Synthesis module based on the acquired simulated results to run another cycle.

5.3 Summary of system development

The chapter described the developing of the performance-based simulation and exploration method. The method development aimed at overcoming the limitation of the system performance by improving each module of the method. The improvement of the synthesis module includes defining the design parameters and design constraints as the main components of the performative wind-based design system. The design parameters categorised into geometric parameters and urban parameters. Geometric parameters have been defined by nine parameters that have a direct effect on wind flow patterns include building location, orientation, form manipulation (chamfered corner, corner cut, corner recession, rounded corner, an elliptical cross-section, tapering, and opening) and building height. In addition, the improvement includes specifying the value of each parameter that has a significant effect on the wind profile as discussed in Section 5.2.

The urban parameters have been defined by three parameters that play a vital role in controlling wind flow around the tall building include building coverage ratio, street width and length, urban porosity (urban open spaces), and building separation. The definition of the value of the urban parameters is based on the city design guidelines; thus; it varies from city to city. The improvement of the synthesis module also includes defining two groups of the constraints topographic constraints that define the topographic slope categories as it has a significant effect on the wind profile, and wind performance constraints that define wind load and wind flow.

Furthermore, the improvement includes adding a filtration module before the analysis module. The purpose of adding this module is to filter and identify the feasible solutions generated from the synthesis module to be analysed in the analysis module. By doing so, the analysis module simulates and analyses feasible solutions only, rather than analysing the solutions generated from the synthesis (including feasible and infeasible solutions), saving time. The system identifies the feasible solution by comparing the generated design solutions with building code and design guidelines, which vary from country to another. Further, the benefit of integrating the Sub-Routine into the filtration module is to extend the filtration process to enable other design constraints to be considered that may be relevant to the site context.

The analysis module is developed by including three stages of the CFD process are pre-processing phase that defines the boundary conditions of the urban area, the materials of the building's geometry, surrounding buildings, and the land of the area, the unstructured mesh type, and the flow type, solution phase that defines the discretisation method as a FEM to solve the mathematical governing Navier-Stokes governing equations as mentioned in Section 5.2, and post-processing phase provides a quantitative analysis data of the results of the solving stage as a numerically and graphically representation. Consequently, the objective of improving the Analysis module is to increase the level of the result's accuracy and to visualise the change of performance parameters within the system in this module.

The improvement of the evaluation module includes assessing each design solution in terms of the level of effectiveness of wind performance. The assessment includes comparing the results from the analysis module with the wind performance objective criteria defined by the designer. The purpose of this improvement is to rank the design solutions relative to wind performance. The author used a 'scalarisation' approach duo to its capacity to perform once or repeatedly as a part of an iterative process (Miettinen *et al*., 2012). In addition, scalarisation method is able to provide multiple solutions for multi-objective problem (Marler *et al*., 2010). The improvement of the exploration module involves two stages of the exploration process: form evolution and exploration. Form evolution develops alternative design solutions using an elitism selection method. The benefit of this employing this method involves passing the fittest solutions' parameters from one generation to the next aiming improving the design solutions. Exploration searches for near-optimal design solutions. The interaction of human expertise and computer-based exploration is essential for the process to be successful (Flager, 2009). Further, the benefit of this module is informing the decision maker of the best forms of tall building envelope design that satisfies the different requirements in the early stage of the design process. The next chapter will validate the proposed method via a real case study to determine the benefits and the limitations of the method.

Chapter Six

Exploration of the validity of the method

This chapter aims at demonstrating the applicability of the framework through a case study based in Melbourne, Australia. The chapter will test and verify the multi-objective simulation and exploration method through a comparison of an existing building generated by conventional tall building design methods and an alternative solution generated by multi-objective simulation and exploration method. The chapter then will compare their design performance in term of wind parameters at three levels: the pedestrian level and the podium level at the height of 29 metres, the second zone (119 metres), and the third zone (224 metres). This is followed by an assessment of the quality of both buildings against a wind load and wind flow performance criteria that highlight the limitations and strengths of both buildings envelope design.

6.1 Experimental setup

The objective of this experimental case study is to calibrate the proposed computational method across multiple performance objectives in multi-scale in the early stage of the tall building design process. The experimental case study includes the implementation of the proposed computational method for the simulation and exploration of design alternatives of building envelope. For the current investigation, a central area of Melbourne city in Australia has been chosen and modelled as the case study. The models were initially generated in Rhinoceros 3D V5 using the Grasshopper version 090076 plug-in. The context of the surrounding buildings was modelled in simplified rectilinear forms, which would be more suitable for CFD analysis. The case study is based on a comparison between an existing tall building design in Melbourne as shown in Figure 6.1a, 6.1b and 6.1c, and a proposed tall building design that will be generated by utilising the proposed computational method. The existing site of the case study is 130m length and 100m width.

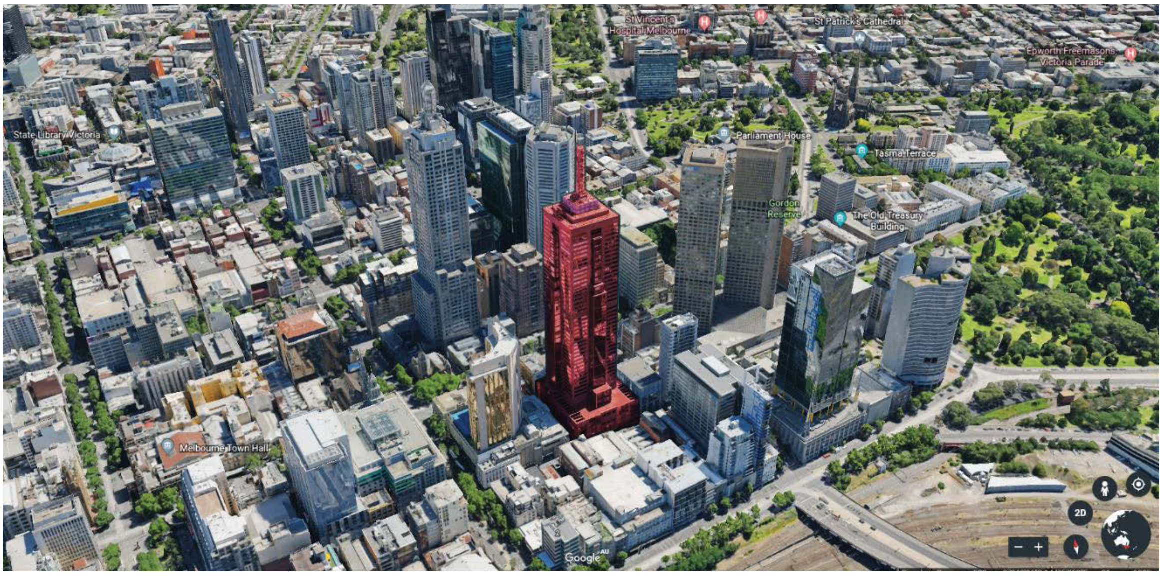


Figure 6.1a The Existing Tall Building and The Surrounding

Figure 6.1b Existing Tall Building Design by CTBUH

Figure 6.1c The Existing Tall Building Street View by CTBUH

According to Australian Bureau of Meteorology, the wind velocity around the proposed site reaches 15 metres per second from the North and seven metres per second from East as shown in Figure 6.2a and 6.2b. The consequence of the wind flow condition of the area, designing a tall building in a proposed site that satisfies Australian building code and planning scheme of Melbourne city is could have a negative impact on wind flows at the pedestrian level and the surrounding area. The framework, therefore, is utilised in the early stage of the design process to assist and to inform the decision-maker about the building envelope design shape that is aiming to increase the level of comfort at the pedestrian level. The details of the implementation of the system and workflow are explained in Section 6.2.

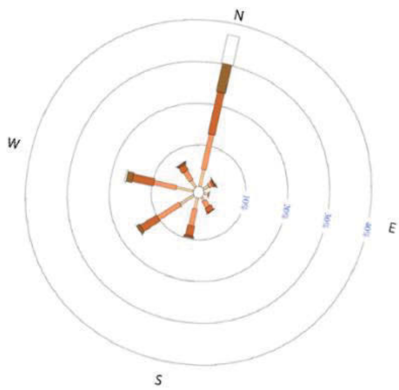


Figure 6.2a Proposed area

Figure 6.2b Melbourne wind rows

6.2 System Implementation

Based on the experimental setup, this section applies the proposed computational design, and it describes the workflow of the system components as the following:

In the synthesis module, the designer defines the objective functions, parameters, and constraints relative to the specific site. The design objective in this study includes designing a building's envelope that achieves:

(i) wind velocity ranges from 2.5 metres per second to five metres per second in both directions (north and east) at the pedestrian level (zero metres to 25 metres) and
(ii) The wind pressure, *r*
(iii) ranging from -480n/m² to +480n/m² at the building facade.

The system boundary is defined based on three groups of parameters are:

(i) Wind performance parameters: wind pressure on building façade, wind velocity and turbulence around the building,

(ii) Geometric parameters: building location, building orientation, building form and building height, and

(iii) Urban parameters: urban density, street width, and length, building site length and width, and building separation as shown in Table 6.1.

In addition, the design constraints are defined as:

(i) Topographical constraints that include terrain category two range from 1.5 metres to five metres.

(ii) Wind constraints as defined by the Australian Government Bureau of Meteorology, shown in Table 6.2.

Table 6.1 Defined design parameters

Parameter category	Parameters	Value
Building	Building location	Coastal, 37.8136° S, 144.9631° E
	Building orientation	0 to 360°
	Chamfered corner	9% to 16% of the building breadth
	Building taper	2.5% to 15% from the ground to the highest point of the building
	Building twist	0° to 360°
	Building height	⩽265m
Urban	Urban density	⩽12:1
	Street width	Exhibition St 13m Collins St 16.80m George Parade 7.40m Flinders Ln 6.20
	Building block width and length	Width 130m, length 100m

Table 6.2 Defined design constraints

Constraints category	Constraint	Value
Wind	Velocity	North 15m/s
		East 7m/s
	Turbulence (TKE)	Floating value
	External pressure	⩽ ± 480n/m²
Topography	Terrain category two	1.5m to 5m

As mentioned in Chapter Five, the designer is responsible for encoding the design parameters in the synthesis module and for defining the relationships between the design parameters, as shown in Figure 6.3 using Rhinoceros 3D V5 using the Grasshopper Version 090076 plug-in.

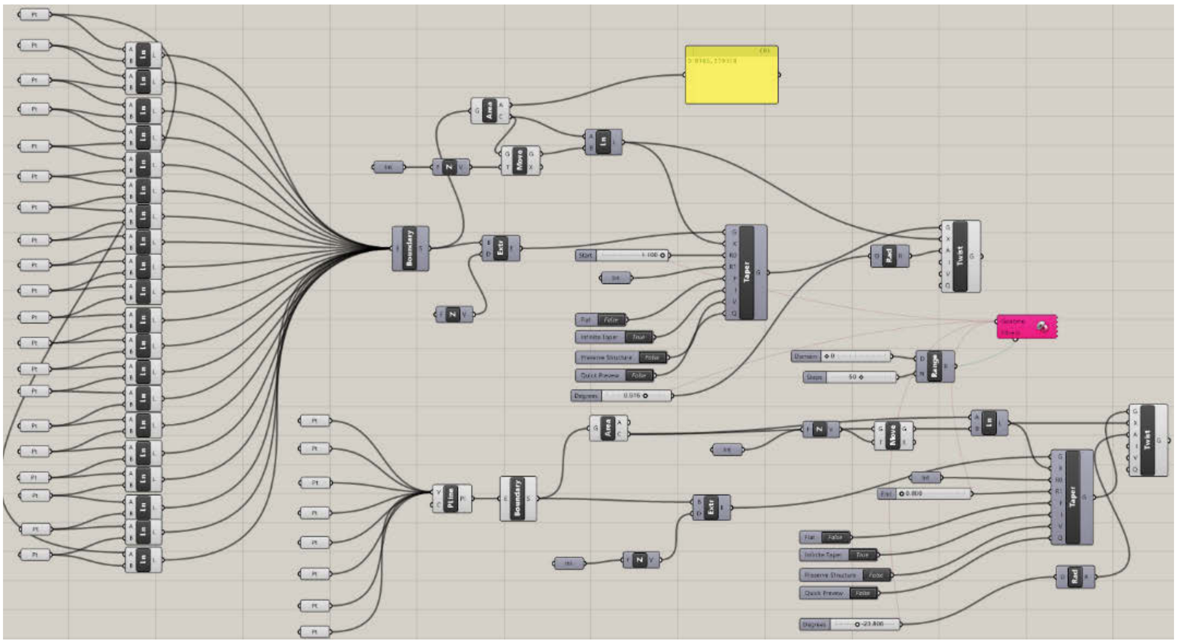
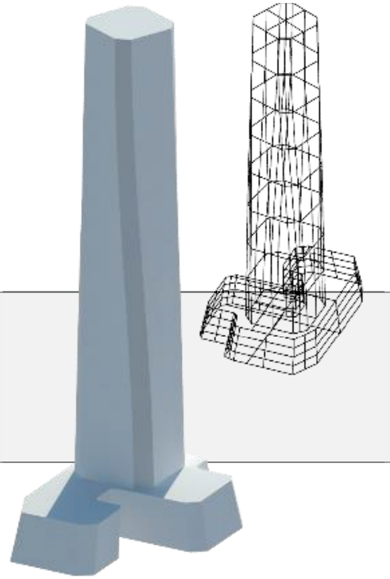
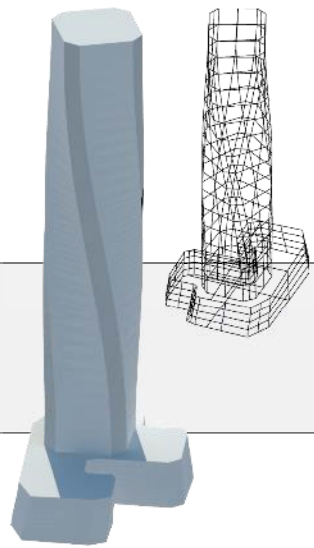
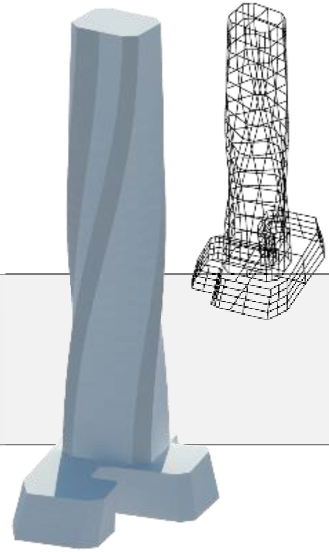
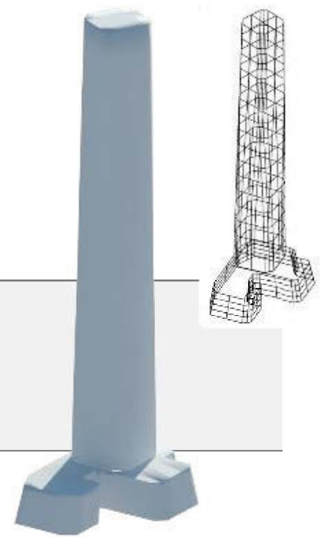


Figure 6.3 Defining the parameters OF relationship encoding and the relationships between design parameters

By assigning different values to the geometric and urban parameters, the values of the wind performance parameters are adjusted in parallel with the geometrical change of the tall building envelope and consequently generated fifty alternative design solutions. However, due to the time and the limitations of the tools, the author has chosen the first four design solutions to be tested for proof of concept as shown in Table 6.2. In this experimental case study, Galapagos, a plug-in of Rhino Grasshopper, is adopted as a bi-directional approach to multi-objective problem-solving. The design solutions resulted from this module are a geometric representation as surface-based models composed of geometric primitives (points, polygons, and surface) in the form of 3DS file format. The output of this module is the input of the Filtration module transferred manually by the designer.

Table 6.2 Generated design solutions

Solutions	Zones	1	2	3	4
Geometry	**Third Zone** **(224)**				
	Second Zone **(119)**				
	Pedestrian and Podium Zone **(25)**				

Filtration Module aims of this module is to filter and discard the infeasible design solutions resulted from Synthesis module. The process starts by comparing the four generated design solutions with the Australian building codes and Melbourne planning scheme. The result of this process in this case study showed that all the design solutions had met the Australian building codes and Melbourne planning scheme. The system, then, extends the Filtration module by applying the **Sub-*Routine - External Constraints*** module to consider Melbourne Airport Building Height Restrictions Policy in term of the design of the tall building. As Melbourne airport states that building height should not exceed 317m in the proposed site, the fourth solutions failed to comply with the restriction and the designer as the fourth solution height is 365m. Therefore, the designer discards this design solution from the system. The results of this module transfer to Analysis module as a 3DS file format as shown in Table 6.3. Figure 6.4 illustrates the filtration module process.

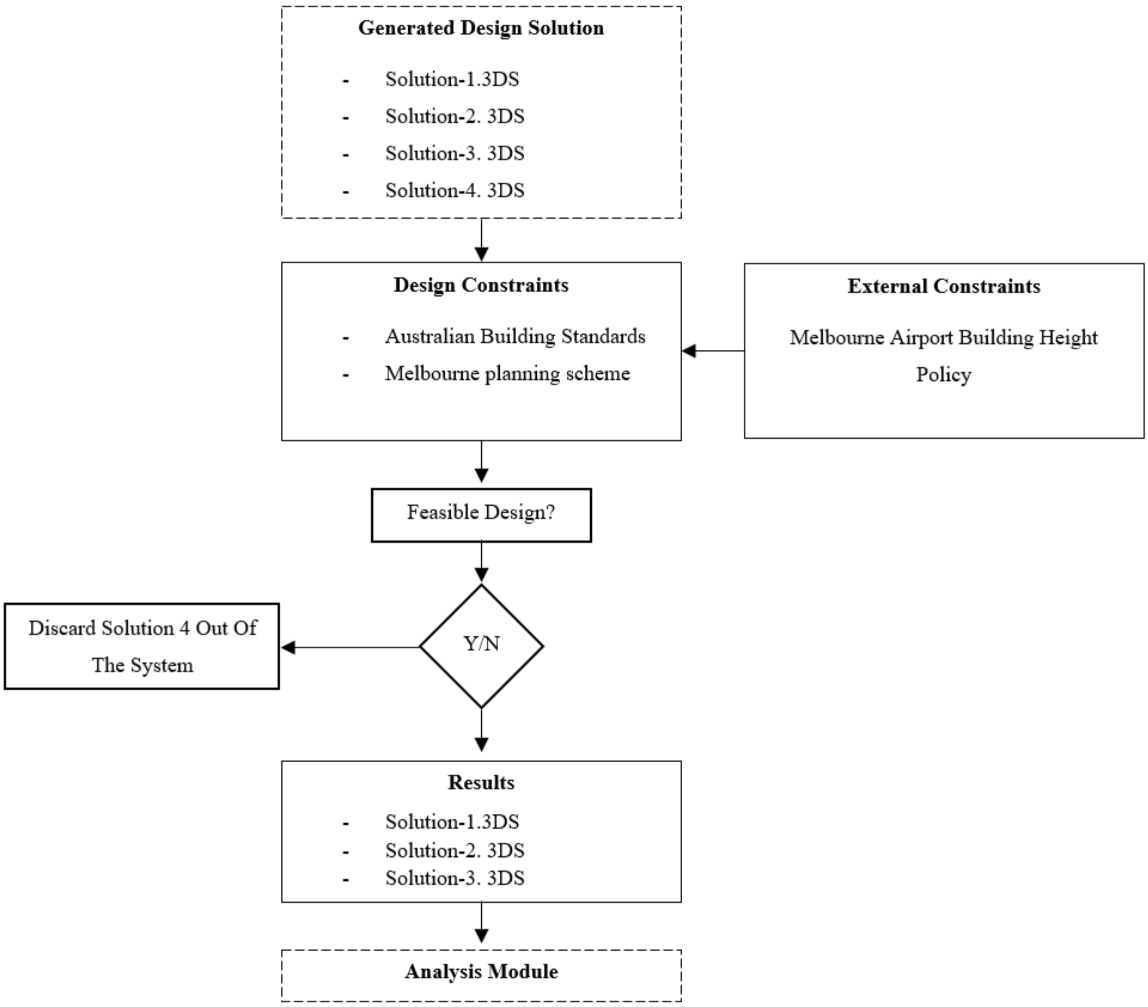
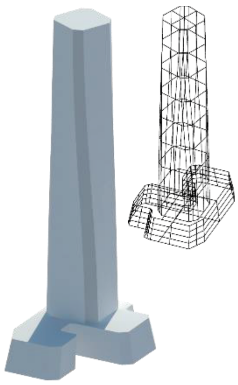
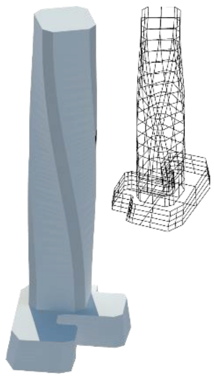
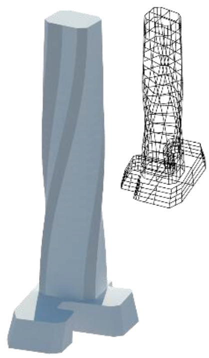


Figure 6.4 Filtration workflow

Table 6.3 Feasible design solutions

Solutions geometry	1	2	3
			

Analysis and Simulation Module aims at testing and analysing the geometry of the building envelope of the feasible design solutions resulted from Filtration module integrated into the context of the urban environment in terms of wind performance at North and East. The stage includes multidisciplinary simulation and analysis. Simulations are run for strong wind profile approaching from the North direction with a velocity of 15 metres per second, and the prevailing wind flow approach from East direction with a velocity of seven metres per second. At the building scale, the simulations run in three different zones of building height: the pedestrian and podium zone (25 metres), the second zone (119 metres), and third zone (224 metres) in term of designer preferences.

In addition, at the urban scale, the simulations run at different points around the building. The points specified due to the context of the streets around the building. The objective of the simulations is to measure the impact of design alternatives on wind profile include (i) wind velocity (V), (ii) wind pressure (P) and (iii) wind turbulence (T) at the surrounding area. The average results in the North and the East directions are taken for assisting the designer in evaluating the performance of the alternative solutions at the Evaluation module. Autodesk Computational Fluid Dynamics is adopted as the performance simulation and data processing tool due to the sufficiency of its use for the current investigation. As aforementioned in Chapter Five, the CFD approach includes three stages are: Pre-processing, Solving/Processing and Post-Processing.

Pre-Processing: defines the geometry of the three feasible design solutions as the following:

- Defining the boundary condition of the proposed area of 125.97m * 90.16m * 62.13m. In addition, defining the materials of the boundary condition that include soil (sandy) for the area land and concrete for the buildings at the boundary condition as shown in Figure 6.5 a and 6.5b
- Defining mesh type as unstructured mesh based on tetrahedrons shapes due to the complexity of the CAD geometries generated from the Synthesis module. The mesh size and the boundary condition are kept constant for all simulation to maintain the accuracy of the comparison.
- Defining the Airflow features as a steady flow, compressible flow, laminar flow and viscosity flow of 1.817e-05 Pa-s

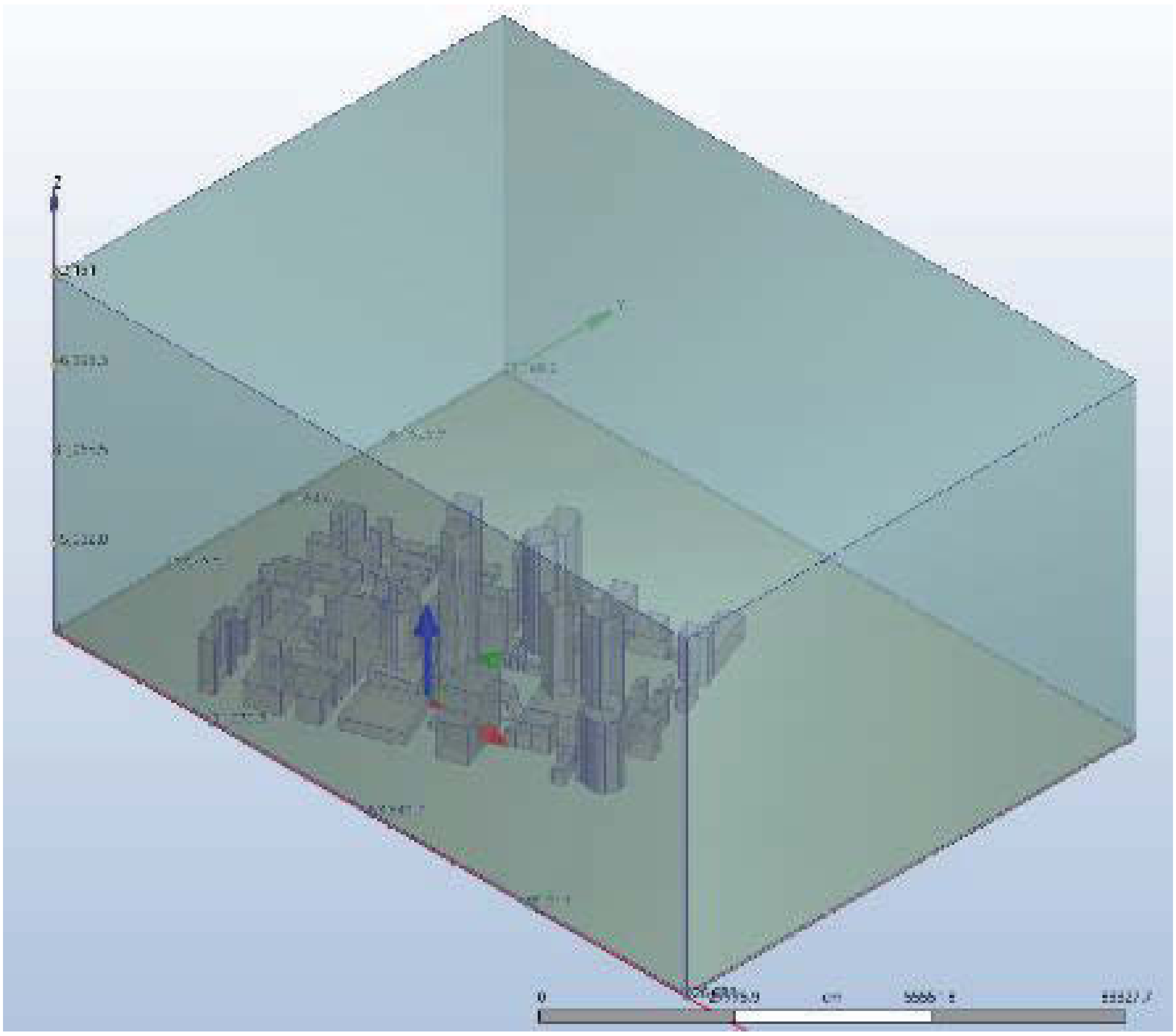


Figure 6.5a Boundary Condition Definition

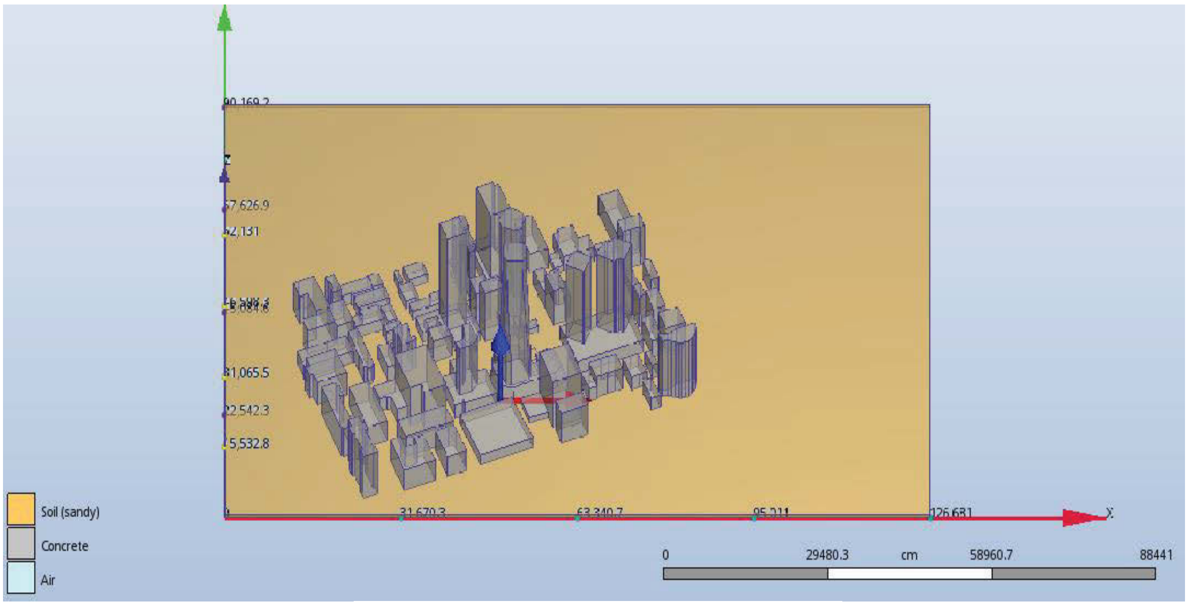


Figure 6.5b Proposed Area Martial Definition

Solving/Processing: specifies the discretisation method and solve the mathematical equations (see Chapter Five) as the following

- Utilising the Finite Element Method (FEM) as a discretisation approach. The proposed area discretised into 2195406 unit as shown in Figure 6.6a and 6.6b.

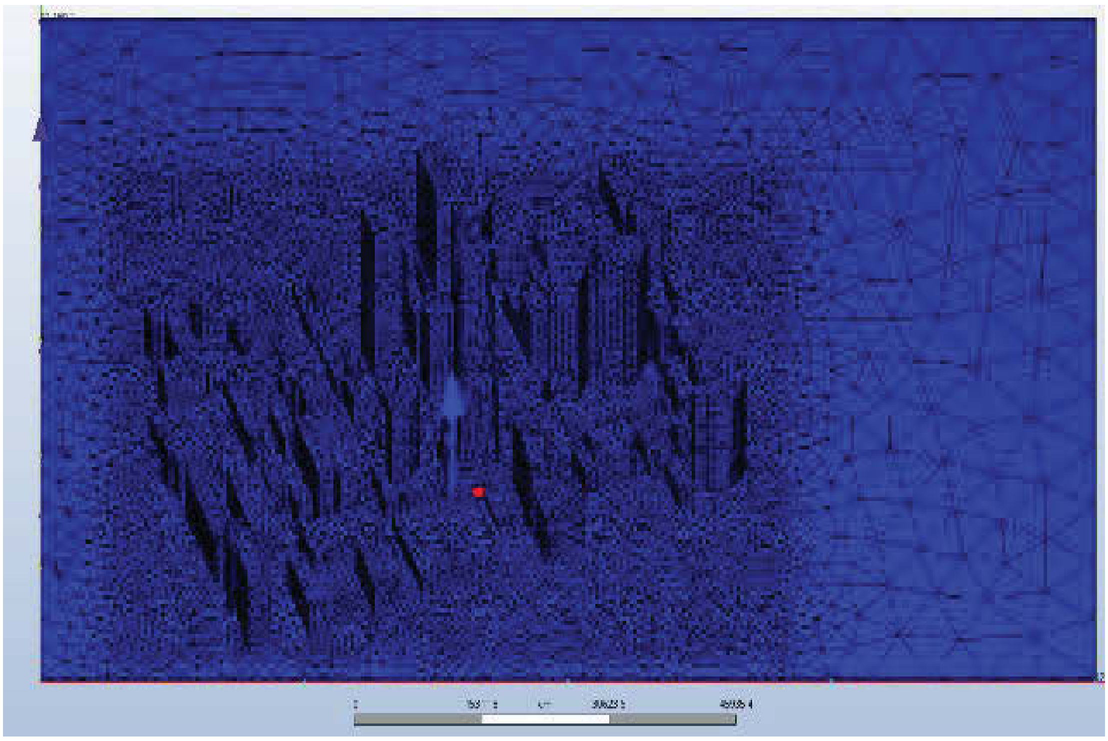


Figure 6.6a Finite Element Discretization Method of the Experimental Area

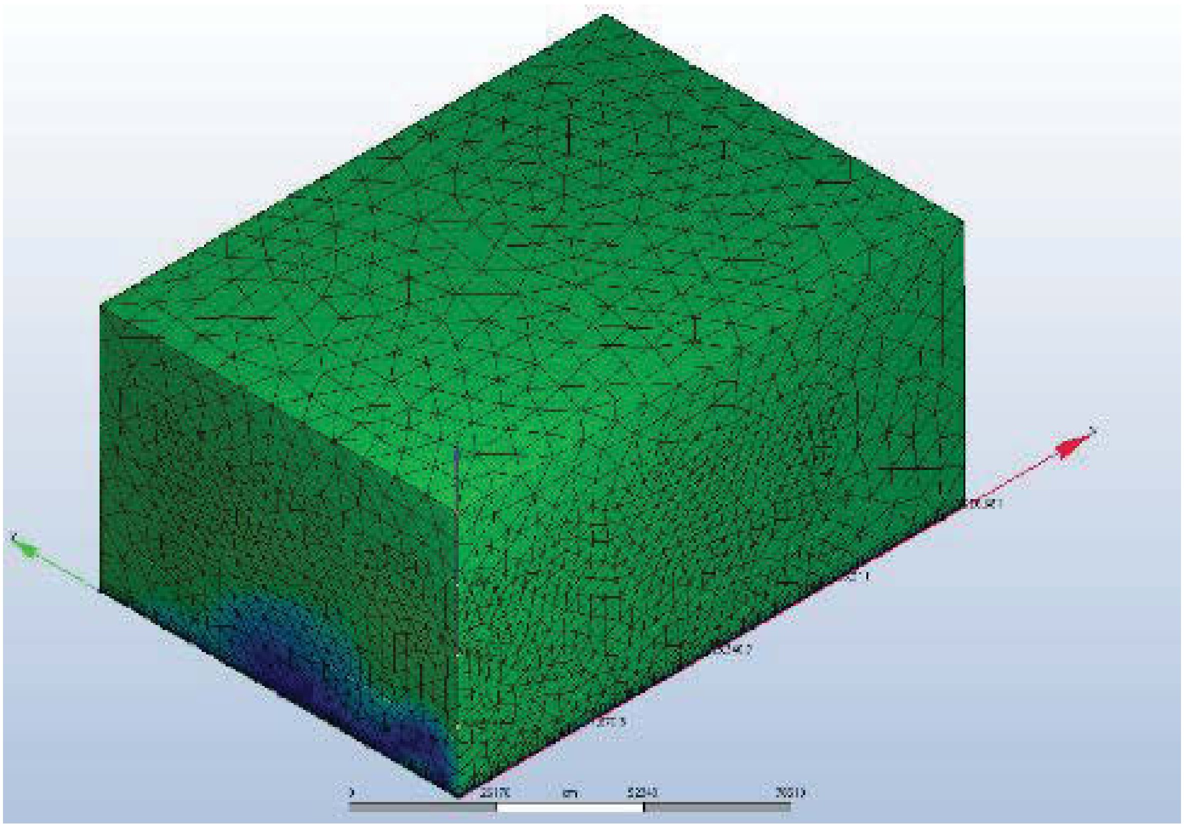


Figure 6.6b Finite element discretisation method of the model

- Solving the mathematical governing equations and K-epsilon (k-ε) turbulence model of the fluid flow to provide numerical values of each cell of the defined mesh as mentioned in Chapter Five.

Post-processing evaluates the data generated by the processing stage. It provides a quantitative analysis of the results of the solving stage numerically and graphically (2D and 3D). Table 6.4 shows the graphical simulation results of the three alternatives design solutions where Table 6.5 illustrates the numerical results of the alternatives design solutions.

Table 6.4 Graphical assessment of the effectiveness of wind performance of the alternative design solutions

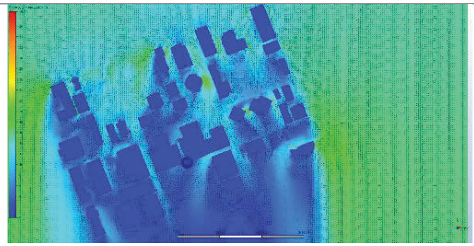
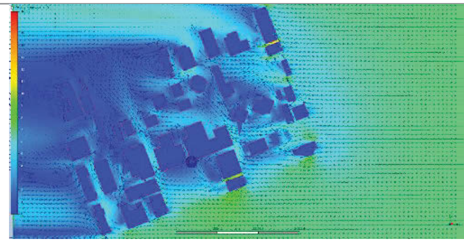
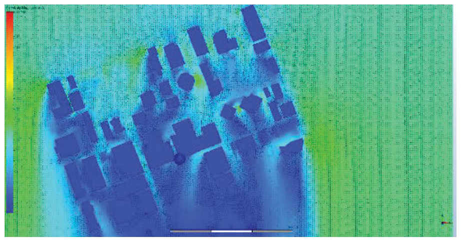
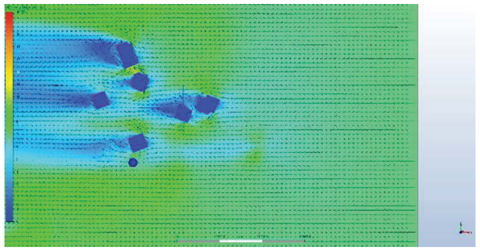
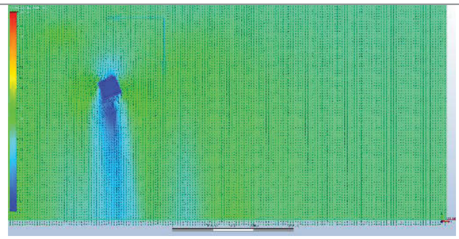
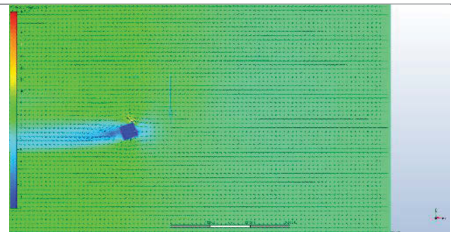
Solution	Height (m)	Wind parameters	
		North	East
Existing	25		
	119		
	224		

Table 6.4 Graphical assessment of effectiveness of wind performance of the alternative design solutions

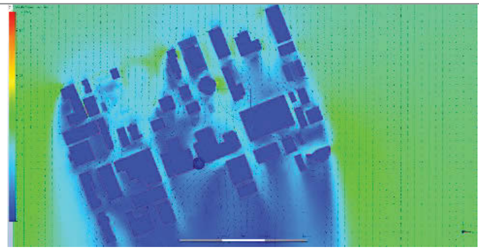
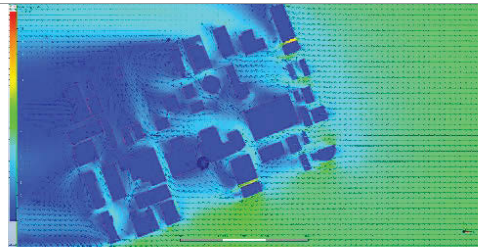
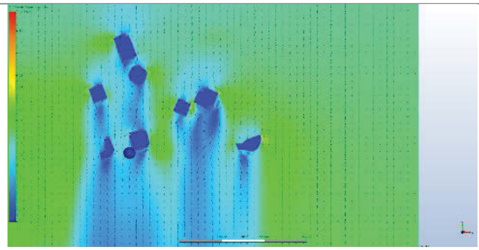
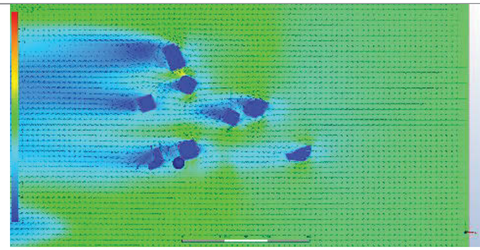
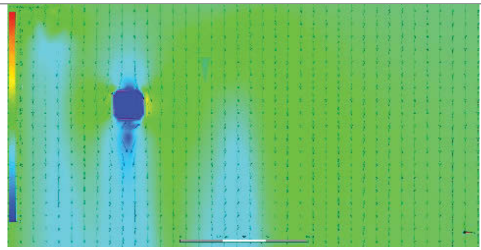
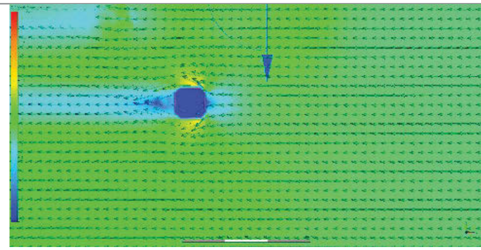
	25		
Solution 1	**119**		
	224		

Table 6.4 Graphical assessment of effectiveness of wind performance of the alternative design solutions

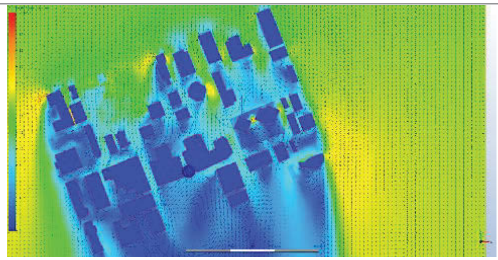
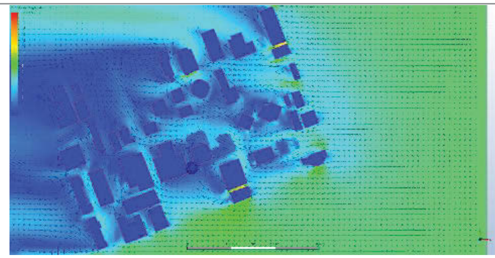
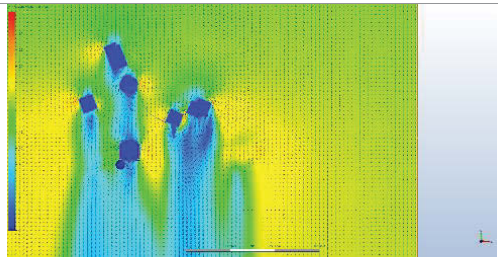
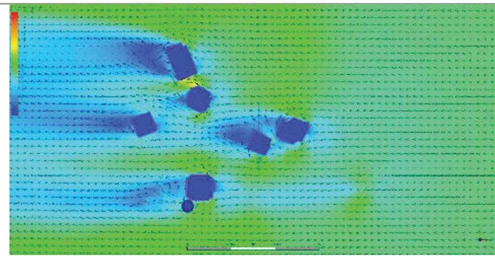
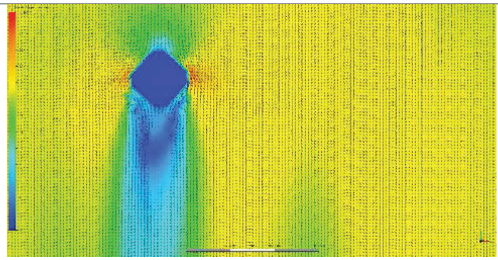
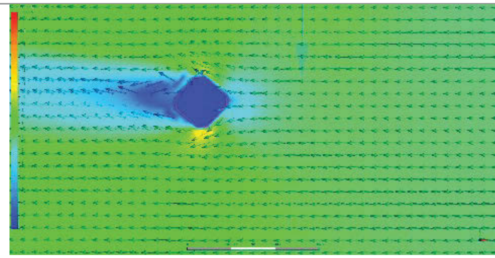
	25		
Solution 2	**119**		
	224		

Table 6.4 Graphical assessment of effectiveness of wind performance of the alternative design solutions

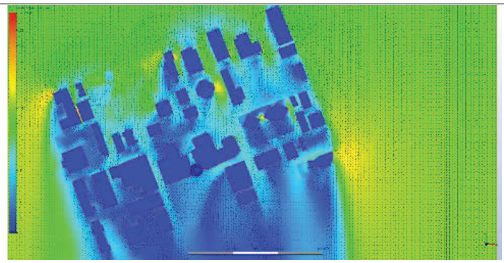
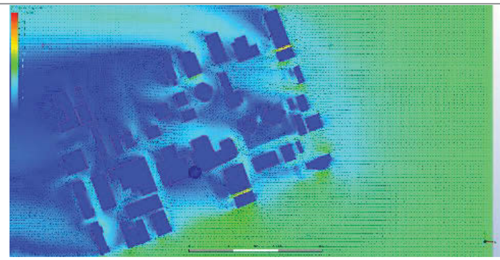
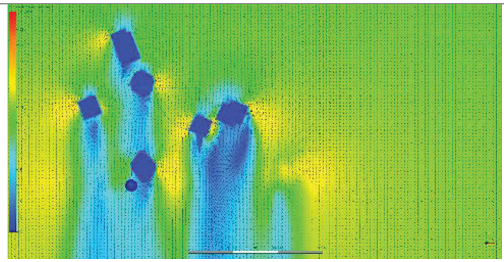
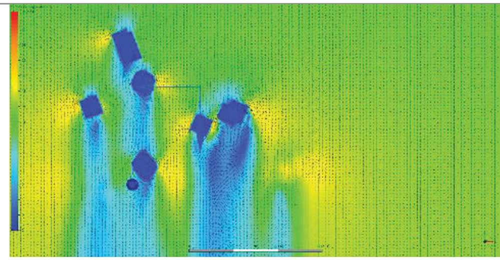
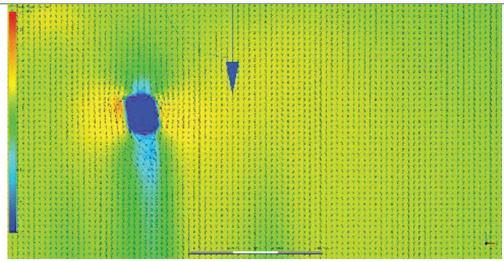
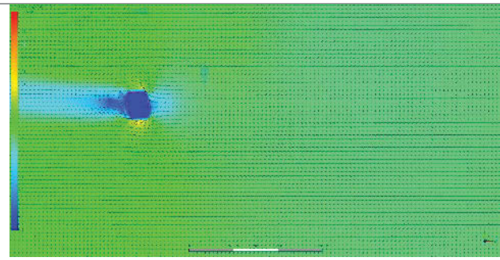
	25		
Solution 3	119		
	224		

Table 6.5 Numerical assessment of effectiveness of wind performance of the alternative design solutions

Solution	Height (m)	North V (m/s)	North P (n/m²)	North T (m²/s²)	East V (m/s)	East P (n/m²)	East T (m²/s²)	Average V (m/s)	Average P (n/m²)	Average T (m²/s²)
Existing	25	7.91	10.14	5.10	3.07	3.11	9.37	5.49	6.62	7.23
	119	12.19	-15.03	7.60	5.79	-5.72	9.70	8.99	-10.38	8.65
	224	13.61	-7.66	7.08	7.15	-.15	1.14	10.38	-3.91	4.11
Solution 1	25	7.86	0.43	7.66	2.84	2.03	1.09	5.35	1.23	4.37
	119	10.85	-8.75	1.05	5.83	-0.06	1.60	8.34	-4.41	1.32
	224	15.01	-15.5	6.79	7.34	-1.14	1.37	11.16	-8.32	4.08
Solution 2	25	7.66	4.97	6.33	2.83	3.02	1.0	5.25	4.00	3.67
	119	11.72	-17.08	9.86	5.94	0.34	1.46	8.83	-8.37	5.66
	224	13.30	-20.05	8.59	7.29	-3.20	1.54	10.30	-11.63	5.07
Solution 3	25	7.50	15.40	6.89	2.86	2.53	1.18	5.18	8.97	4.04
	119	12.19	-13.52	8.67	5.50	-1.83	1.70	8.85	-7.68	5.19
	224	15.20	15.54	6.29	7.11	-1.94	1.51	11.15	6.80	3.90

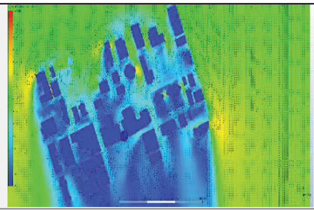
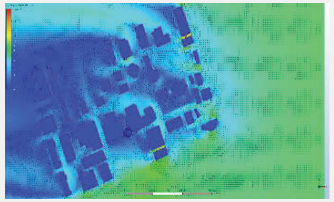
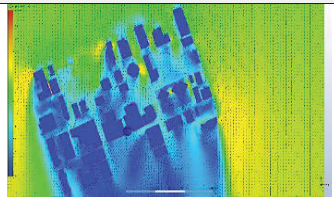
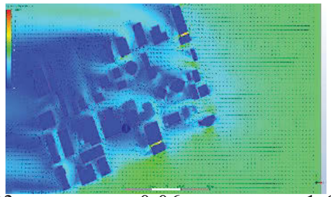
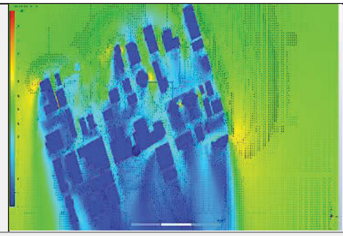
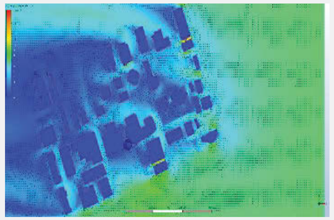
The evaluation module compares the results from the previous module with the wind performance objective criteria to provide a quantitative assessment of the effectiveness of the wind performance of alternatives design solutions as a TXT format. In this experimental, the wind performance criteria to achieve: (i) average wind velocity of 2.5 metres per second to five metres per second in north and east directions, and (iii) wind pressure ranging from -480n/m² to +480n/m², as shown in Table 6.6.

Table 6.6 Wind performance objective criteria

	Performance parameters		
Performance objectives	Wind velocity	Wind pressure on the building facade	Wind turbulence
	2.5m/s to 5m/s at the podium level	⩽ ± 480n/m²	Floating value

The module, therefore, ranks the alternative design solutions based on Utility Function method using the wind performance objective criteria. Table 6.7 illustrates the best solution in term of wind performance at the different building height zones. At the podium and pedestrian level height zone of 25m, the third design solution has the best effect on the wind flow at both wind directions; it achieved average wind velocity of 5.18/s, wind pressure of 8.97 n/m² and the wind turbulence of 4.04 m²/s². At second zone height of 119, the first design solution has the finest impact on the wind movement at both North and East directions as it reaches average wind velocity of 8.34 metres per second, wind pressure of -4.41 n/m² and wind turbulence of 1.32m²/s². At the third height zone of 224m, the second design solution has the most favourable effect on the wind flow in the North and East directions as it reaches the average wind velocity of 10.30 metres per second, wind pressure -11.63n/m and wind turbulence of 5.07m²/s²

Table 6.7 Numerical and graphical results of the alternative design solutions

Solution	Height (m)	Wind simulation: North V (m/s)	North P (n/m²)	North T (m²/s)	East V (m/s)	East P (n/m²)	East T (m²/s²)	Average V (m/s)	Average P (n/m²)	Average T (m²/s)
Solution 3								5.18	8.97	4.04
	25	7.50	15.40	6.89	2.86	2.53	1.18			
Solution 1								8.34	- 4.41	1.32
	119	10.85	-8.75	1.05	5.83	-0.06	1.60			
Solution 2								10.30	-11.63	5.07
	224	13.30	-20.05	8.59	7.29	-3.20	1.54			

The output of the Evaluation module is quantitative data as a TXT file format and a geometric representation as a 3DS file format. The designer manually transfers the results to the design exploration module to utilise the resulted date to develop the design solutions.

Design exploration module aims at manually finding and developing the most suitable design solution in term of wind performance objective function and compliance criteria. This module based on two stages, namely form evolution followed by exploration.

Form evolution is a process aimed at evolving the most suitable design solutions that satisfy the objective function together with the Australian Building Code and Melbourne Planning Scheme. This process is based on the selection method. The strategy of this method depends on selecting the best design parameters of the generated solution that achieved the best performance in term of wind performance. The system, therefore, selects podium zone (25m) of the third design solution, the second zone (119m) of the first design solution, and the third zone (224m) of the second design solutions based on the quantitative data received from the Evaluation module. The system, therefore, combines the three different zones to generate a new breed of the design solution using Grasshopper as a combining tool as shown in Figure 6.7. The result of this stage is a geographical representation in the 3DS file format.

The system, then, manually send the hybrid solution to the Analysis module to test and simulate the building envelops integrated into the urban environment in terms of wind performance and to start another loop. Consequently, in this experimental study, the hybrid design solution shows the best performance effect on the wind flow at the north and the west direction as shown in Table 6.8 illustrates the graphical result of the analysis module where Table 6.9 shows the numerical results of the analysis module.

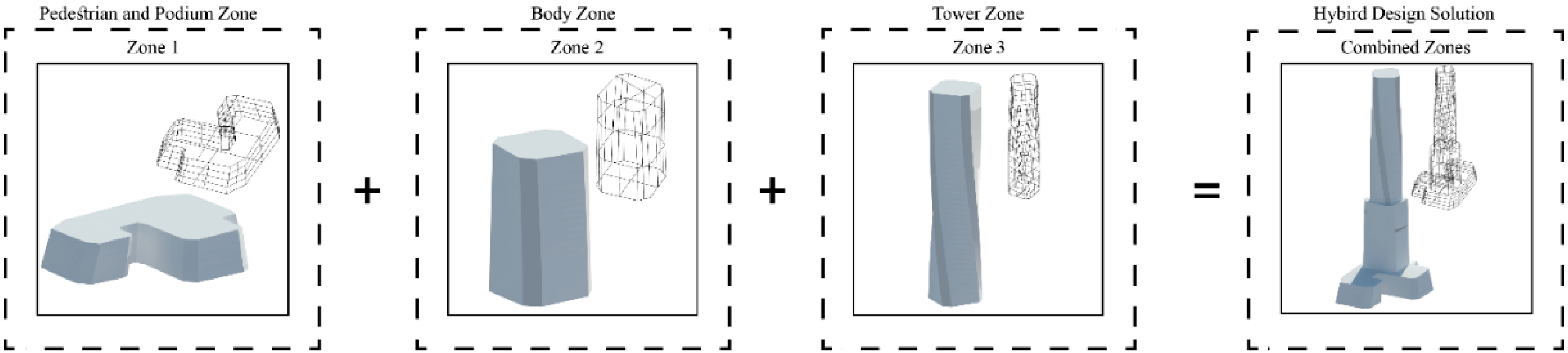


Figure 6.7 Alternative solution design evolution

Table 6.8 Graphical assessment of the effectiveness of wind performance of the hybrid design solution

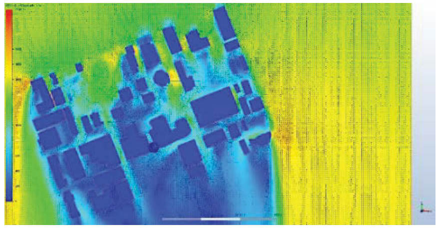
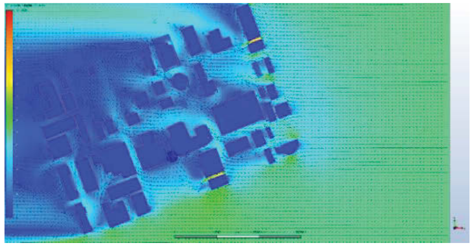
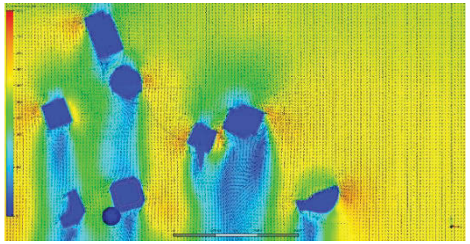
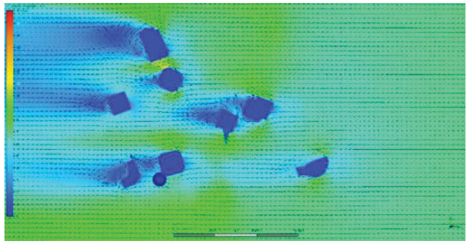
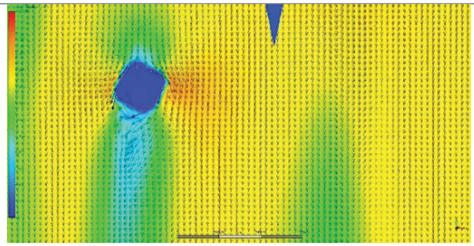
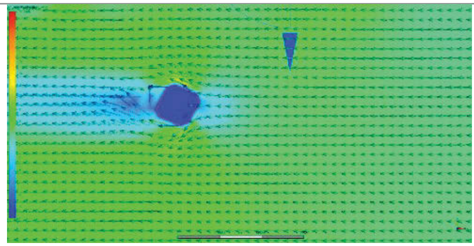
Solution	Height (m)	Wind parameters	
		North	East
Hybrid	25		
	119		
	224		

Table 6.9 Quantitative assessment of the effectiveness of wind performance of the hybrid design solution

Solution	Height (m)	Wind parameters								
		North			East			Average		
		V (m/s)	P (n/m²)	T (m²/s²)	V (m/s)	P (n/m²)	T (m²/s²)	V (m/s)	P (n/m²)	T (m²/s²)
Hybrid	**25**	7.50	5.21	6.79	2.80	4.18	1.16	5.15	4.70	3.98
	119	11.33	11.13	9.43	5.36	2.03	1.36	8.35	6.58	5.40
	224	13.35	-8.38	3.92	7.12	1.16	0.89	10.24	-3.61	2.41

At the podium and pedestrian level height zone (25 metres), the hybrid design solution achieves average wind velocity of 5.15 metres per second, wind pressure of 4.70 n/m^2 and the wind turbulence of 3.98m^2/s^2 where the second zone (119 metres) it reaches an average wind velocity of 8.35 metres per second, wind pressure of 6.58 n/m^2 and wind turbulence of 5.40m^2/s^2. At the third zone (224 metres) it reaches the average wind velocity of 10.24 metres per second, wind pressure -3.61n/m and wind turbulence of 2.41m^2/s^2. The result of this stage is a geographical representation in the form of 3DS file format. The designer then, starts the exploration stage, and no transfer data is required between the form evolution stage and exploration stage.

Exploration works as a space search mechanism. The designer in this stage searches for the fittest design solutions within the domain of feasible crossbred design solutions using the results of the wind performance objective criteria. The aim of this module is to identify the fittest design from among the available designs solutions based on both the design performance and the wind performance criteria. The objectives of design exploration may be variable and not constant depending on design and context requirements relative to wind velocity, directions, and turbulence. The chosen design solution, therefore, will support the decision-making in the early stages of the design process. However, if the target design solution does not fit the performance criteria, objective function, or the designer preferences, the designer then can implement changes in the initial design parameters defined in the Synthesis module based on the current results, and to run another cycle.

6.3 Findings

The objective of the experiment is to assess the performance of each module of the method and to explore the overall capacity of the system in managing and control different parameters at multi-dimensional scale and produce a number of feasible solution. Based on the observation and the results of the experiment, the advanced computational method proved its ability to assist designers in exploring, developing and evaluating different design scenarios of tall building envelope shapes at a multi-dimensional scale. The parametric modelling used to encode architecture and urban design systems. The assessment of the Synthesis module is based on the number of design solutions that the module is able to generate, and the quality of the generated solutions. In this experiment, the module has generated four design solutions that are able to assist in decision making in the early stage of the design process. The assets of the quality of the generated design solutions based on the number of feasible design solutions that pass through Filtration module.

The assessment of the filtration module is based on the capacity of the module to integrate all the design constraints that could affect the final design solution. In addition, the ability of the module to discard any design that unmatches with the design constraints. In this experiment, the module proved its ability to involve the Australian building code and the City of Melbourne Design Scheme as design constraints. Further, the Subroutine module extended the Filtration module and involved the building height restriction policy provided by Melbourne airport. The module, therefore, discarded only one design solution that dissatisfied the design constraints. From this result, it can be concluded that the Synthesis module succeeded in producing a high quality of the feasible design solutions that reached 75% of the total generated solutions.

Analysis module proved its ability to analyse the wind performance (wind velocity, pressure, and turbulence) of each design solution and produce a high level of accuracy of numerical and graphical data. The computational method emphasised the importance of integrating CFD modelling approach into the method workflow to provides analysis feedback including numerical and graphical statistics of wind flow in two different directions at three different height levels include pedestrian and podium level (25m), second zone (119m), and the third zone (224m).

Learning from the pilot studies, this experimental study showed the importance of specifying the grid structure of the model, discretisation method and boundary conditions of the proposed area for the accurate results. Table 6.10 summarises the stages of CFD processing.

Table 6.10 Summarised CFD processing stage

Stage		Type	Value	Assigned to
Pre-processing	Geometry of feasible design solutions	Geometric primitives points, polygons, and surface	-	Urban area and buildings
	Material	Solid (sandy)	-	Urban area ground
		Concrete	-	Buildings
		Air	-	Boundary box
	Boundary condition dimension	Length	1259.7m²	Boundary box
		Width	935.297m²	Boundary box
		Height	520m	Boundary box
	Mesh	Unstructured	-	- Boundary box - Proposed area ildings
	Air Flow	Viscosity	817e-05 Pa-s	Boundary box
		Specific Heat	1004.0 J/kg-K	
		Compressibility	1.4	
Solving/processing	Mesh generation	Finite element method	2195406	- Boundary box Jrban area ildings
	Equation Solving	- Time-Averaged governing equations - K-epsilon (k-ε) turbulence model	-	- Boundary box Jrban area ildings
Post- processing	Data evaluation	Numerically and graphically 2D & 3D	-	- Urban area Buildings

Evaluation module assessment was based on the capability of the module to compare the result of the previous module with the wind performance criteria. The evaluation module demonstrated the vital role of comparing and evaluating the results from the Analysis module with wind performance criteria and providing a quantitative assessment of the effectiveness of the wind performance of three different scenarios. The module utilised the scalarisation method to rank the feasible design solutions at the different building height zones of each alternative design solutions based on the wind performance objective criteria. Based on the quantitative assessment of the previous module, Exploration module was able to explore the wind performance for each design solution at a different height level. Each scenario performs differently at a different level. The main findings from the experiment with regard to design outcomes can be summarised by the following.

- The third design solution has achieved the best wind performance at the pedestrian and podium level (25m) as it decreased the wind velocity approaching from the North from 15 metres per second to 7.50 metres per second associated with a wind load of 15.40 n/m^2 and wind turbulence of 6.89m^2/s^2. The third design solution also decreased the wind velocity in the East direction from seven metres per second to 2.86 metres per second associated with wind pressure of 2.53 n/m^2 and wind turbulence of 1.18m^2/s^2.
- The first design solution showed the best wind performance at the second zone (119m) where wind velocity has decreased at the North direction from 15 metres per second to 10.85 metres per second associated with wind pressure of -.875 and wind turbulence of 1.05. In addition, at the West direction, the wind velocity has been decreased from of seven metres per second to 5.83 metres per second associated with wind pressure of -0.06 n/m^2 and wind turbulence of 1.60 m^2/s^2.
- The second design solution achieved the best wind performance at the third level (224m) where wind velocity decreased to reach 13.30 metres per second associated with wind pressure of -20.05n/m^2 and wind turbulence of 8.59 m^2/s^2 at the North direction. Additionally, in the East direction, the wind velocity has decreased to reach 7.29 metres per second associated with wind pressure of -3.20 n/m^2 and wind turbulence of 1.54 m^2/s^2.

Furthermore, the Exploration module demonstrated the capacity of evolving the design solutions by the Selection method. The process of the method involved selection of the podium zone (25m) of the third design solution, the second zone (119m) of the first design solution and the third zone (224m) of the second design solutions to generate a hybrid design solution. Table 6.11 compares and illustrates the difference of the wind performance between the existing tall building design and hybrid proposed solution. As it can be noticed from the comparison, the hybrid design solution has a higher-performance relates to a definition of pedestrian comfort/discomfort at street level.

Table 6.11 Comparison of wind performance of existing tall building design and the hybrid tall building design

Solution	Height m	Wind Parameters								
		North			East			Average		
		V m/s	P n/m²	T m²/s²	V m/s	P n/m²	T m²/s²	V m/s	P n/m²	T m²/s²
Existing	**25**	7.91	10.14	5.10	3.07	3.11	9.37	5.49	6.62	7.23
	119	12.19	-15.03	7.60	5.79	-5.72	9.70	8.99	-10.38	8.65
	224	13.61	-7.66	7.08	7.15	-.15	1.14	10.38	-3.91	4.11
Hybrid	**25**	7.50	5.21	6.79	2.80	4.18	1.16	5.15	4.70	3.98
	119	11.33	11.13	9.43	5.36	2.03	1.36	8.35	6.58	5.40
	224	13.35	-8.38	3.92	7.12	1.16	0.89	10.24	-3.61	2.41

Drawn from the results of the comparison, this section concludes that the proposed design solution has a higher-wind performance than the existing building. Table 6.12 shows the percentage of wind mitigation between the existing building and the hybrid recommended solutions.

Table 6.12 Wind mitigation percentage comparison between the existing solution and a proposed solution

Solution	**Height (m)**	**Wind parameters**			
		North		**East**	
		Velocity (m/s)	**Wind mitigation (%)**	**Velocity (m/s)**	**Wind mitigation %**
Existing	**25**	7.91	-47.26	3.07	-56.14
	119	12.19	-18.73	5.79	-17.28
	224	13.61	-9.26	7.15	+2.14
Hybrid	**25**	7.50	-50	2.80	-60
	119	11.33	-24.46	5.36	-23.42
	224	13.35	-11	7.12	+1.71

6.4 Summary

The chapter validated the proposed computational method through a case study. The validation process involved a comparison between an existing design of tall building located in Melbourne, Australia generated by conventional tall building design method, and proposed design of tall building generated by multi-objective simulation and exploration method. The aim of the case study is to prove the feasibility of the proposed method. The experiment focused on the design performance in term of wind parameters at three zones include the pedestrian zone and the podium level at the height of 29 metres, the second zone at the height of 119 metres and the third zone at the height of 224 metres.

The experiment involved encoding the building parameters and the urban parameters utilising Rhinoceros 3D Version 5 using the Grasshopper Version 090076 plug-in. The synthesis module generates fifty alternative design solutions. However, because of the time and the equipment limitations, the research has used the first four generated design solution to validate the computational method. The filtration module compared the four design solutions with the Building Code of Australia and the Melbourne Planning Scheme. As a result, the filtration module discarded one design solution that did not satisfy the regulatory standards. The analysis and simulation module tested the three design solutions resulted from the filtration module involving CFD. The simulations ran for strong wind flow approaching from the north and the prevailing wind flow approaching from the east at the three different height zones of the building. Evaluation Module provided a quantitative assessment of the effectiveness of the wind performance of alternatives design solutions by comparing then wind objective performance criteria. Form Evolution evolved the design solutions utilising Selection method based on the quantitative assessment of the effectiveness of wind performance of each solution.

Based on the observation and the results of the case study, the method demonstrated the capacity to integrate the building parameters and urban parameters and to define the relationship between them across the building scale and urban scale. Consequently, the computational method leads to design an integrated tall building with the surrounding urban context which effects on urban environment performance as discussed in Section 2.2.2. Further, the computational method demonstrated the capacity of enabling the designers to explore parametric variations of design scenarios based on the support of analytical feedback and evaluation. The limitation of the method will be discussed in Chapter Seven.

Chapter Seven

Discussion

This chapter reviews the summary of the thesis and includes the motivation of the research project and a summary of the proposed multi-objective simulation and exploration method. In addition, this chapter discusses the significance of the research and provides suggestions and questions for the future use of the system as a strategy for the performance-based computational method in different fields. The chapter then expands the discussion on the system contribution in urban and architectural fields. This chapter also highlights both limitations in the development of multi-objective simulation and exploration design system. The chapter then, provides suggestions and opportunities for future work, specifically in the development of system modules.

7.1 Summary

This research project aims to address the research question what an effective tall building design approach would be that able to mitigate the impacts of strong wind condition while encouraging the wind flow in case of stagnant wind condition at two inter-related scales: the building scale and urban city scale in dense cities. The research has aimed to answer the question by developing a computational design method that able to mitigate the negative impact of wind-related hazards caused by tall buildings in a dense urban environment. Further, this method is able to bridge the gap between building codes and city design guidelines relative to the wind flow. The following objectives were met to achieve this aim.

1. **Investigate formal regulatory requirements at the urban scale and building scale related to the control and mitigation of wind flow in urban city environments.**

As discussed in Chapter Three, the research has investigated ten different building codes and design guidelines for ten countries and cities including Australia, Hong Kong and the USA. The result of the investigation illustrates that design principles that are typically described in city development design guidelines relate to four aspects of tall building design include (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 a positive wind condition. However, the result of the investigation also shows that building codes and design guidelines 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 the pedestrian level.

2. **Identify existing computational approaches of controlling and mitigating wind load and wind flow for urban design and tall building design.**

This thesis showed different approaches to tall building design and urban design in Section 2.4.2 and 2.4.3. A variety of research studies have adopted different generative systems approaches such as parametric design to work within a design process that includes a performance analysis feedback loop that supports early design decision-making (Alfaris, 2009; Corry, 2014; Turrin *et al.*, 2014; Oxman, 2008). Furthermore, the research has highlighted the benefits of utilising parametric modelling at the early stage of the design process aiming at converting an abstract definition into measurable criteria.

3. **Develop and test the generative performance-based simulation and exploration method via series of pilot studies.**

This research presented the development and testing of advanced computational design method supporting exploration of tall building envelope design according to wind flow constraints at the early stage of the design process of multi-objective simulation and exploration technique in Chapter Three. Furthermore, Chapter Four has tested the framework through two pilot studies with different complexity aimed at exploring the effectiveness and efficiency of each module of the system through a simple wind flow problem within a fictitious site and to investigate the ability of the system to bridge the gap between building scale and urban scale.

4. **Verify the computational method by implementing the approach on a case study based on the existing conditions in an urban city environment.**

Chapter Six has verified the system's ability to generate different design solutions and to manage the design complexity in multiscale by conducting a case study on an existing site in Melbourne city. The objective of the experiment is to assess the performance of each module of the method and to explore the overall capacity of the system to manage and control different parameters at multi-scale and multicriteria and produce a number of alternative solution. Based on the observation and the results of the experiment, the advanced computational method proved its ability to assist designers in exploring, developing and evaluating different design scenarios of tall building envelope shapes at a multi-dimensional scale.

5. **Explore the approach's relevance to the concept of urban resilience regarding urban planning and architectural design guidelines and policies.**

In this chapter, the research presents the value and the importance of the method in contributing to the implication of urban resilience focusing in "Reduce Losses" and the potential benefits that both designers and local government planning authorities can achieve.

7.2 Contribution to Design Computing

Currently, there are limited design methods that can assist designers in the generation of tall building design that explores wind flow in the built-up urban environment (Capeluto *et al*., 2003. Khallaf & Jupp, 2016). Thus, the primary objective of this research project is to develop a decision-support design method utilising performance-based simulation and exploration design that accounts for wind load and wind flow compliance criteria in a city environment.

Recently, academic research has attempted to fill the gaps between design strategy and good planning principles, and the requirements of urban wind flow design. For example, the urban scale velocity ratio (VRw) – the ratio between the wind speed at pedestrian level and boundary layer level- has been proposed as an indicator for air ventilation assessment in high-density urban environments (Ng *et al*., 2009). Hong Kong planning policies also require urban scale VRw values to be provided as an objective quantitative input to the evaluation and comparison of proposed building design options. Ng (2016) indicates that planners utilise different engineering approaches to explore wind flow at the pedestrian level based on planning parameters that include (i) site coverage, and (ii) building plot ratio. Further, Yoshie *et al*. (2008) have also deduced that there is a linear relationship between site coverage and VRw. This means that, the more ground surface area occupied by buildings, the less availability of wind ventilation. A variety of 'good design' principles have also been proposed to control wind flow in city environments impacted by strong wind flows as discussed in Section 2.3.3.

However, existing computational design methods that have been proposed in the last decades for testing performance of tall building designs and pedestrian impact is often based on prescriptive methods that are unable to explore the desired performance at both the building scale and city scale integrated. The evaluation of the tall building design relative to wind loads and wind flows is separate from each other. In addition, the previous computational methods neglect the importance of addressing design criteria surrounding wind flow in the early conceptual stages of design.

Consequently, this research project filled the gap between design strategy and good planning principles by developing a computational method that is able to integrate the design strategy and planning principles and to explore the wind performance of a tall building at both the building scale and city scale integrated. The development of the multi-objective simulation and exploration method presented in this thesis demonstrates a research-based exploration into performance-driven solutions of the complex urban design problems. It surrounds the exploration and design of comfortable wind flow in high-density urban environments with tall buildings.

The new presented decision support method provides a new interactive method for tall building envelop design exploration that utilises a generative approach integrating with CFD analysis to have the ability to generate and analyse a range of different design scenarios. The system prototype developed the computational performance-based design exploration method by utilising parametric techniques and CFD techniques. Furthermore, the developed system has developed two new modules that have never been done before including the *Filtration* module and *Form Evolution* module to support decision-making system. The computational method is based on five modules and seven steps carried out sequentially as mentioned in Chapter five including (i) ***Synthesis module*** defines the objective functions and the design parameters-urban parameters and building parameters- and design constraints. The module is responsible for generating all possible design solutions can be generated. (ii) ***Filtration module*** that can evaluate the results of the synthesis module and compare results with building codes and city development design guidelines as well as other constraints relevant to the tall building, (iii) ***Analysis module*** that enables the analysis of the impact of the wind load on and wind flow around both the geometrical parameters and performance variables with the numerically and graphically of data points assisting in the confirmation of different performance locations throughout the test site on all X, Y and Z axes. The module utilises CFD as an analysis method based on three stages are

Pre-Processing that defines the geometry modelling, the materials of the building's geometry, surrounding buildings, and the land of the area. In addition, it defines the mesh type-unstructured mesh- and mesh size. In this stage, the designer also responsible for defining the flow type that includes steady flow or unsteady flow, incompressible flow or compressible, laminar flow or turbulent flow.

Solving/Processing solves mathematical governing Navier-Stokes equations using FEM discretisation method. This sage includes assessing the performance of the façade relative to wind load and wind flow conditions acting on the building.

Post Processing that evaluates the data generated by the processing stage and provides a quantitative analysis data of the results of the solving stage.

(iv) ***Evaluation module*** that is assessing each design solution in terms of the level of effectiveness of wind performance by comparing the results from the analysis module with the wind performance objective criteria defined by the designer. In addition, it uses scalarization approach to rank design solutions in terms of wind performance objective criteria, (v) ***Exploration module*** that identifies the suitable design solutions that satisfy the objective function defined by the designer/design team based on pedestrian comfort and safety in terms of wind flow, building codes, and urban design guidelines compliance criteria among the feasible alternatives. The module includes two stages are:

Form Evolution that develops the alternative design solutions by Elitism Selection method to generate a new parametric rig that enables the generation of alternative design solutions.

Exploration searches for the near fittest design solution that provides the best design performance in terms of the wind performance satisfies the objective function, building standards and city design guidelines.

The proposed method was developed and validated through two pilot studies and one case study. The pilot studies aimed at (i) exploring the ability of the system at managing and controlling different parameters include urban parameters and building parameters at multi-dimensional scale, (ii) to determining the efficiency and effectiveness of each module of the system and, (iii) to investigate the limitation that surrounds each module. The case study, then, aimed at demonstrating the applicability and the efficiency of the system through a comparison between an existing tall building generated by conventional design method, and an alternative solution generated by multi-objective simulation and exploration method. The results of the case study proved that the computational method is able to assist designers in exploring, developing and evaluating different design scenarios of tall building envelope shapes at a multi-dimensional scale. In addition, the results demonstrated the ability of the proposed system to support of analytical feedback, evaluating the alternatives and the exploration method for achieving designs that able to rationally meet the requirements of a sustainable and a safe built environment.

Based on the results of the case study, the research contributes to the design computing by expanding the understanding of the performance-based design simulation process focusing on tall building design to provide a designer with a better decision-support method that capable of generating, simulate and develop alternative solutions.

7.3 Contribution to Building Codes and City Design Guidelines Authorities

The rapidly growing population and rapid urbanisation played an important role in increasing tall building types especially in dense cities (Ali, 2010, Ayoub, 2012). As mentioned in Section 2.2.2 tall building has a strong relationship with the city fabric. Therefore, the design of tall buildings should be based on an appropriate layout to contribute positively to the neighbourhood, community and city where they are located (Ilgin, 2006). Tall buildings are drawing the attention of planning authorities like no other type of development due to their potential to contribute negative effects to the urban environments. A tall building can cause strong winds conditions through accelerating wind flow around building corners and tunnelling effect between neighbours (Cammelli *et al.,* 2017; Khallaf & Jupp, 2016). In addition, the tall building can increase health hazards due to airborne diseases by blocking air permeability ventilation.

Focusing on comfort and safety of pedestrians in the urban fabric, separate policies include building codes and design guidelines aimed at the building, and urban scale stipulate how a variety of safety, health and comfort requirements must be supported. However, building codes and design guidelines in most cities around the world neglects the importance of addressing design criteria surrounding wind flow in the early conceptual stages of design. As mention earlier in Chapter three, building codes for tall buildings aim at specifying the requirements for structural wind loads acting on tall buildings such as Part 2 of the Australia Standard AS 1170.1-1989 and Australian and New Zealand AS/NZS 1170-2, are to specify the minimum design loads on structures such as tall buildings whereas city design guidelines aim at specifying the wind flow impacts arising from tall buildings at the pedestrian level to maintain the comfort level such as Air Ventilation Assessment (AVA) system in Hong Kong. As separate compliance processes, building codes and design guidelines define different criteria, calculation methods, scales and testing procedures for assessing wind loads and wind flows for design compliance. Consequently, the interdependencies between architectural and urban scales are disregarded. Further, the increased complexity of looking beyond a single building is a strong argument for the need for adequate design decision-support methods, given that decisions based on intuition or simple guidelines are no longer sufficient (Nault, 2018).

In response, the research presents a novel approach to predict and provide instantaneous wind pressure data on tall buildings facade, and wind flow data at the surrounding area in early stage of the design process. The method is essential since early-stage decisions for instance on building massing can lead to significant differences in the performance of a project. The results of the research proved the ability to define both problem and solution in the same model via a series of experiments. This advantage, therefore, can assist planning authorities in exploring, developing and evaluating different design scenarios of tall building envelope shapes at a multi-dimensional scale that reduces the uncertainties towards multi-problems related to wind flow in an urban environment.

Consequently, the research contributes to understanding the gap between the building codes and city design guidelines, and it provides a method that is able to contribute to filling this gap. The proposed computational method is beneficial for designers, local councils and planning policies authorities. Designers can utilise the proposed method to conform to the requirements of the building code and design guidelines relative to different wind conditions in the early stage of the design process. While local councils and planning authorities can consider applying the method in developing guidelines to assess the proposed tall buildings prior to the development approval.

7.4 Contribution to The Implication of Urban Resilience

As cities continue to develop and grapple with the uncertainties and challenges of climate change and unprecedented urbanisation, the need of mapping and drawing the scenarios of uncertainties that may affect the cities are growing as well as enhancing the resilience of cities. (Jabareen *et al*., 2013; Meerow, 2016). In addition, increased climate hazards coupled with rapid urbanisation are likely to put increased strain on the capacities of local governments (Tanner *et al.,* 2009). Securing a commitment to ecological urban design requires that governing authorities first pledge to a new way of thinking about design control and review (White, 2015). Focusing on the wind-related hazards, Munich Re Group (2002) claimed that most of the properties' losses occurred at locations where vulnerable urban settlements were developed near known wind-hazard areas, such as hurricane-prone. Prater *et al*. (2000) suggested changing land use and building construction practices to reduce the losses caused by a strong wind. Focusing on building construction, Prater *et al*. (2000) suggested that the structures must be properly designed and constructed to withstand the extreme forces of wind. In responding, Klein (2003) presented strategies aim at reducing the risks caused by wind-related hazards that can be applied from the level of the individual up to the level of an entire city. Klein (2003) classified those strategies into three categories are:

(i) ***Choosing Change*** strategy identified as accepting the hazard and changing land use or relocation of exposed populations,

(ii) ***Accepting losses*** strategy includes bearing the loss by exploiting reserves or sharing the loss through mechanisms such as insurance,

(iii) ***Reducing Losses*** strategy includes attempts to reduce the impacts of a hazardous event when it occurs.

From this perspective, this research contributes to expanding the current understanding of "Reducing Losses" strategy. Through the review of the relevant literature in Chapter Two, the gap was revealed between existing knowledge of tall building design, urban resilience, the complex system of the city, and the wind effect on the urban environment. The significance of the interpretation of this understanding contributes to reducing the impacts of a hazardous event that relative to the wind before it happens

Chapter Six shows that the proposed method contributes to the implementation of the concept of Urban Resilience due to its multidisciplinary approach. The benefit of the method surrounds the feedback of tall building envelops design relative to the context of its wind performance within the dense urban fabric at their levels. The proposed system enabling three significant benefits to urban resilience include:

1. Model-based simulation and analysis that helps to define and measure accurately the targeted levels specified by the policy.
2. A multidisciplinary and multi-criteria system that helps to manage design complexity and generate solutions effectively.

3. The objective-based process that can be applied to different urban design problem rather than a subjective tool

7.5 Limitations

7.5.1 Research Method and System Validation.

The work presented in this thesis has drawn attention to the principles by which determinants of the architectural and urban form may contribute and impact on wind flow to the detriment or benefit of the surrounding context. Its scope is delimited by the following aspects.

Firstly, the research involves the investigation and development of an advanced performance-based system focused on wind-related hazards. The research method adopted the information systems (IS) methodology because it can address the issues involved in developing computational systems. The approach involves a series of stages through which a system develops from a conceptual method into a prototype to be evaluated. The five stages of the research process included:

1. Construction of a conceptual method
2. Development of a system architecture
3. Analysis and design of the system
4. Building on the prototype system
5. Observation and evaluation of the system

This is a necessary limitation in order to keep simulation times feasible and observation of effects tractable. This method is suggested when the proposed solution of the research problem cannot be proven mathematically and tested empirically. Researchers, therefore, may elect to develop a system to demonstrate the validity of the solution, based on the suggested new methods, techniques or design. Whilst other approaches such as L-system, genetic system, shape grammar, etc., facilitate the description and implementation of other design parameters, results become hard to analyse. The execution and analysis of large amounts of parameters of interacting variables become computationally expensive as the geometry and the behaviour of wind flows around the building form become more complex.

Secondly, the results are not directly comparable to empirical evidence as discussed in Chapter Six. The research experiments reported here can be seen as a 'case study' as a way to generalise and build theory about the city and its individual buildings as a complex system based on the generation of all possible architectural and urban forms and how environmental factors, such as wind impact on the behaviour of wind flow around them. The case study of Melbourne that discussed in Chapter Six was proposed to calibrate the system across multi-criteria and multi-scale in the early stage of the tall building design process. The case study included an existing tall building of 130m length and 100m width and 265m height in central Melbourne. The objective of the experiment is to assess the performance of each module of the method and to explore the overall capacity of the system in managing and control different parameters at multi-dimensional scale and produce a number of feasible solutions.

A third limitation is related to the modelling of wind flow behaviours. The existing building and the surrounding areas were modelled in Rhinoceros 3D V5. The Grasshopper version 090076 plug-in were utilised in order to encode the architecture and urban parameters of the area. Due to the time constraint and advanced tool limitation, the building purposely modelled in the simplified rectilinear form in order to be suitable for CFD analysis. Therefore, the result of verifying the system via case study can be more accurate if the research has the luxury of time and tools. However, the approach of conducting this research is equivalent to a proof-by-demonstration presented by (Nunamaker & Chen, 1990).

7.5.2 Multi-objective Simulation and Exploration Method

Although the design method demonstrates a potential contribution to urban design, tall building envelope design and computing design, there are still several challenges and areas that need further research. The following issues are acknowledged in this thesis.

7.5.2.1 Synthesis Module Research Issues and Extensions

The objective of the synthesis module is to connect the building and urban parameters to each other in different rules based on defined value to generate all the possible design solutions. However, the difficulty in this module surrounds the technical skills of the encoding process that the designer is responsible do in order to define the geometric and urban parameters, the relationship between the design parameters, and the design constraints. The complexity of the encoding process is based on the number of design parameters and constraints. By means, more design parameters and constraints that need to be encoded in the system will increase the complexity of the encoding process.

7.5.2.2 Analysis and Simulation Module Research Issues and Extensions

The aim of the analysis and simulation is to predict and simulate the flexible relationships between geometry and wind load and wind flow performance outcomes of feasible alternative design solutions utilising computational Fluid Dynamic technique. The determination of air flow patterns around buildings is important for the prediction of wind flow conditions in urban areas. Yet, the behaviour of wind flow is a complex phenomenon that presents certain limitations when conducting wind simulation and analysis. The limitation surrounds the complexities of providing comprehensive data for a wind flow in specific urban areas which play an important role as input data for the simulation and analysis process. The difficulties also, surround this module is the high-technical skills and a good knowledge of fluid dynamics fields that is required from the designer to have to maintain the accurate results. In addition, utilising Computational Fluid Dynamic technique requires a high-performance computer to define and calculate the boundary conditions, grid size, turbulence model, etc. for accurate results and feedback. Another limitation that surrounds this module is modelling curvilinear shapes and small details. The simulation equations have limitations to calculate small rims and holes that affect the accuracy of the results.

Furthermore, this module contains CAD geometries represents the alternative solutions cannot be mapped directly from the synthesis module. The designer should manually transfer the CAD geometries from CAD application to CFD application. By doing so, the manual transfer process may affect the model and therefore, the result accuracy and can cause difficulties for the designer. Thus, more investigating is required include this module to establish a direct link between the synthesis module and analysis module to avoid the manual transfer.

7.5.2.3 Exploration Module Research Issues and Extensions

The goal of the exploration module is to develop and to find the most suitable design solution in term of wind performance, objective function and compliance criteria through two stages of the process include ***Form Evolution*** followed by **Exploration**.

Form Evolution process aims to evolve the suitable design solutions that satisfy the objective function together with building and city design standard via the Selection method. The limitation that surrounds this stage the manual process of the Selection method that is required from the designer to do instead of utilising an automated computation process. Due to the complexity of the manual Selection process, it can cause a challenge for the designer when the number of suitable design solutions increase. Therefore, more investigating is required at this stage to achieve an automated Selection method that can integrate with the system and thus, module the system performance.

The objective of the ***Exploration*** stage is to search manually for the suitable design solutions among feasible alternative solutions. The challenge of this stage includes the manual search process that the designer is responsible for doing to identify the fittest design solution from among the available designs solutions based on both the building and city design standards and the wind performance criteria. The complexity of this process is based on the number of alternatives solutions that the designer should search among them to identify the most suitable. By means, when the number of alternatives solutions increase, it will increase the complexity of the searching process. Thus, more investigating is required to integrate an automated search method at this stage to support the exploration module and enhance the result accuracy.

7.6 Future Work

Although the proposed multi-objective simulation and exploration system framework provides a novel approach for exploring different design solutions for tall buildings based on the wind performance, some aspects of the complex relationship between the design of the architectural form and the impact on the surrounding urban form can be further explored in future work. The former refers to experiments that can be conducted with minimal modifications or additions to the current design method as described in this thesis. In addition, the directions of research identified during this work which would require significant changes and extensions to the methods and tools of inquiry.

The thesis represents a remarkable step towards the development of a comprehensive method to achieve a positive wind flow in dense urban areas and to bridge the gap between building codes and city design guidelines. However, due to the complexity of encoding building regulations and city development design guidelines, and the need of higher level of computer coding skills and advanced tools, the method requires more extensive research and development that focuses on:

1. Develop a platform that has the ability to enable full automation of the design method
2. Impact of planning policies on evaluation outcomes
3. Encode different building codes and design guidelines

4. Different Wind Conditions
5. More complex envelop geometry
6. More complex urban geometry
7. Considering other important design criteria such as views, overshadowing, pedestrian permeability and solar orientation.

This thesis presents insights into the development of tall building design method based on performance-based design systems. The generation and exploration of tall building envelop design simply one area to which such a system can be applied. Future work will see the continual development and improvement of the tall building design method, coding and application as it is tested and applied to different case studies.

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8 Appendices

8.1 Appendix A

8.1.1 Definitions

Due to rapid population expansion, cities are now home to more than half the world's population. It predicted that populations in towns and cities would reach 2.5 billion by 2050 (World Urbanization Prospects Revision 2014). It is therefore crucial that urban cities be designed to ensure the comfort, health and safety of their inhabitants and users. Of the many design criteria that must be addressed, wind conditions and dynamics are one that is often overlooked. Wind velocity, direction, and flow patterns interact in complex ways with the urban morphology of cities, the structure and safety of buildings and the pedestrian comfort of city inhabitants. All these issues are important and interacting criteria that must be considered by urban planners, design engineers and architects. The modelling of airflow patterns around buildings is of great importance for the prediction of environmental wind conditions in urban areas.

This chapter provides an overview of the factors at play in the generation of the wind, and the interactive relationship between airflow and buildings. It first presents some general definitions from the field of aerodynamics and describes the phenomena and characteristics of a variety of wind conditions. In providing these definitions, the chapter will build an understanding of airflow patterns around buildings, before then describing the computational methods used to simulate wind forces and dynamics to obtain aerodynamic pressure and force distributions that can affect both city and building morphology design.

8.1.2 Wind: Understanding Global Circulation

Globally, wind generated by differences in the temperature between the equator, and north and south poles. While the regions lying near the equator is closer and vertical to sunlight they receive a much larger amount of solar radiation than those closer to the pole regions. Consequently, the equatorial regions become hotter with a lower air density than in the Polar Regions. This leads to the creation of a temperature, density and pressure gradient. The pressure gradient together with the effects of the Earth's rotation set up a large, global scale wind circulation system in the atmosphere (NOAA 2010).

8.1.2.1 Aerodynamics

Aerodynamics is a branch of dynamics that deals with the motion of air and other gaseous fluids and the resulting forces acting on bodies immersed in these fluids (Merriam Webster dictionary, Aerodynamics, 2014). Aerodynamics often used to express an understanding of gas dynamics. However, Air Flow Patterns used to understand the motion of air around an object that helps to calculate pressures, forces, and moments acting on that object. Typical properties calculated for a flow field include velocity, pressure, force, density, and temperature as a function of position (space) and time (Anderson, 2001). The use of aerodynamics through mathematical analysis can involve wind tunnel experimentation and computer simulations. With regard to air flow, aerodynamic problems can be classified into external aerodynamics, which is considered as the flow around objects of various shapes, and internal aerodynamics, which is the study of flow through passages inside objects.

8.1.2.2 External Aerodynamics

Typically, for external aerodynamic studies of structures, there are three basic levels of wind studies that are needed to be considered (Mendis *et al*, 2007)

- **Environmental Wind Studies** investigate the wind effects on the surrounding environment caused by the erection of a building structure. This type of study is important to assess the impact of wind on the pedestrian level and architectural features, which utilize the public domain in the context of a proposed building that is the scope of this research; it also aimed at helping to reduce the Urban Heat Island effect and pollution levels.
- **Wind Loads for Façade Studies** to assess design wind pressures throughout the surface area of the building for designing the cladding system. Due to the significant cost of typical façade systems in proportion to the overall cost of very tall buildings, engineers cannot afford the luxury of conservatism in assessing design wind loads.
- **Wind Loads for Structure Studies**: to determine the wind load for designing the lateral load resisting structural system of a building to satisfy various design criteria. However, both of wind load for façade studies and wind loads for structure studies are not the domain scope in this research.

8.1.2.3 Types of Aerodynamic Bodies

In aerodynamics studies, it is beneficial to understand the types of aerodynamic bodies. There are two types of aerodynamic bodies, with respect to the Air Flow Pattern around them, which can be classified into aerofoils or streamlined bodies, such as aircraft wings and yacht sails, and bluff bodies, such as structures or buildings. This research is concerned with buildings, which are bluff bodies. Much of what is discussed in the literature concerns the AFP around single buildings in an open space. In practice, this rarely occurs. There are nearly always other buildings around, and these buildings will affect the AFP around any newly constructed structure. Consequently, one of the first questions in the assessment of the wind flow in a complex of buildings is to try to resolve the Air Flow Pattern in which the new building is to be situated, and then the mutual effect of the new on the old, and vice versa.

8.1.2.4 Aerofoil Bodies

Aerofoils, or streamlined bodies, are bodies that do not have a thickness (or have a neglected one). The flow streamlines around the aerofoil closely follow the contours of it. The flow is separated from the surface of the aerofoil by only a thin boundary layer, in which the tangential flow is brought to rest at the surface (Holmes 2007).

The essential characteristic of an aerofoil is that it has a sharp trailing edge in the rear end. The requirement of this sharp trailing edge is that the flows over the top and bottom surfaces of the aerofoil meet at the trailing edge and flow off tangentially. The implication of this is that when the aerofoil is placed in the air, the flow over the lower surface would want to turn around the trailing edge to flow up the tail end to a separation point on the upper surface, equating the length of the path on upper and lower surfaces. Because the trailing edge is sharp, a shear stress, which caused by the viscosity of the airflow, prevents this sharp turning, so the flow at the lower surface separates from it

at the trailing edge and continues in the windward direction. This creates suction at the tail of the upper surface that draws the would-be separation point down to the trailing edge (Lawson, 2001)

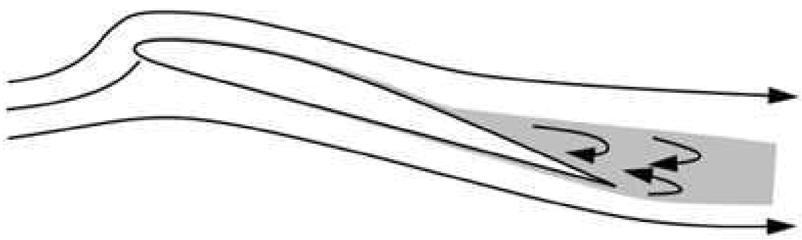


Figure 8.1 Aerofoil Body. (Holmes, 2007)

A bluff body is one in which the length in the flow direction is close to or equal to the length perpendicular to the flow direction (Newcamp, 2002). Bluff bodies are characterized by having significant lateral dimensions and normally unsteady velocity fields. The airflow around a bluff body is characterized by a separation of the flow at the leading face (or edge in case of a rectangular section). The separated flow region is divided from the outer flow by a thin region of high vorticity, which is known as a free shear layer that is similar to the boundary layer on the aerofoil, but not attached to a surface (Lawson 2001). This layer is unstable, and it will roll in the wake to form concentrated vortices (Holmes 2007). As mentioned above, all buildings are considered as bluff bodies (Cermak *et al.*1995) However,

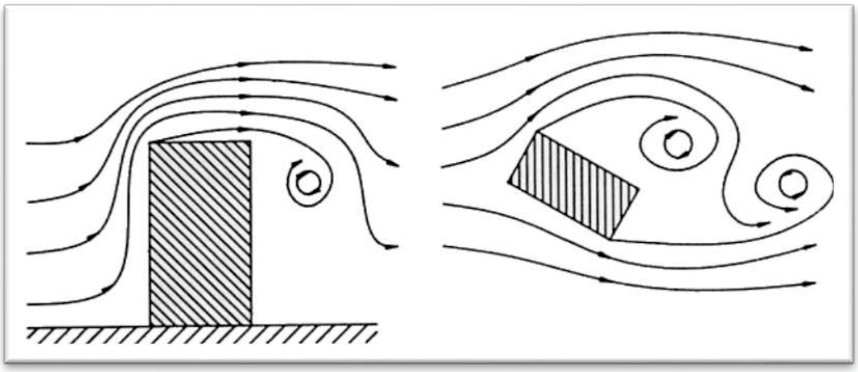


Figure 8.2 Bluff Body. (Mendis *et al*, 2007)

in cities, buildings are surrounded by other structures, which may influence the local wind loads on building drastically. Air flowing around buildings results in distortion, deceleration, acceleration, separation and sometimes reattachment of flow (Cermak *et al.* 1995).

8.1.3 Classifications of Air Flow Phenomena

8.1.3.1 Steady and Unsteady Flows

It is important to differentiate the airflow conditions and understand the movement of the air in order to optimize the wind condition in both macro and micro level. All flow properties are time (t) dependent. The functional dependence of pressure (P) at any point (x, y, and z) might be denoted by P (x, y, z, and t) (Anderson 2009). In other words, steady flow is one in which all conditions at any point in a stream remain constant with respect to time. Otherwise, flow is called unsteady. Therefore, airflow stream is usually characterized by having unsteady flow fields.

8.1.3.2 Laminar and Turbulent Flows

Laminar Flow, or streamline flow, occurs when a fluid flows at a relatively slow velocity, parallel layers, and with no disruption between the layers (Lawson, 2001). At relatively low velocities, the fluid tends to flow without lateral mixing, and adjacent layers slide past one

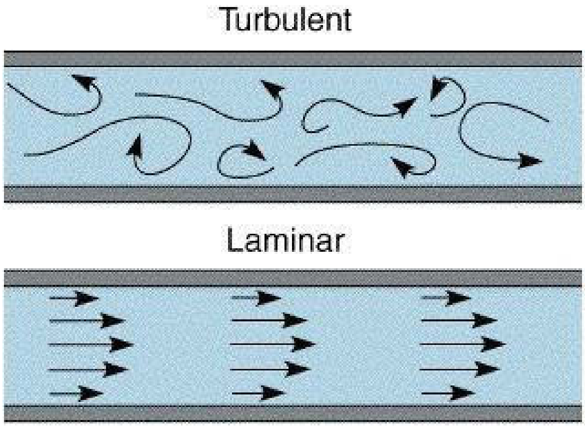


Figure 8.3 Turbulent and Laminar Flow. (Ayoub, 2012)

another. There are no crosscurrents perpendicular to the direction of flow, nor eddies or swirls of fluids. In laminar flow, the motion of the particles of fluid is very orderly, as all of them move in straight lines (Batchelor 2000). On the other hand, when the fluid's velocity increases, the flow pattern tends to change, and turbulences are formulated (Lawson 2001). The phenomenon of turbulent flow field was first investigated in the 1880s by Osbourne Reynolds in an experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels, the results of this investigation has a practical and philosophical aspects, which has become a fundamental law in fluid mechanics. The major effect of the Reynolds Number (Re) is the change from laminar to turbulent flow. In physical terms, the Re is the ratio of Inertia Forces to Viscous Forces (Holmes 2007).

8.1.3.3 Compressible and Incompressible Flows

A flow will be considered as incompressible if its density is constant (ρ = constant) (Anderson, D, 2009). In other words, the compressibility of a fluid is the reduction of the volume of the fluid due to external pressures on it. A compressible fluid will reduce its volume in the presence of an external pressure. In this case, most of the gases consider to be compressible flows because of most of them has a constant density such as air. On the other hand, a flow that has non-constant density will consider incompressible fluids such as water. In this research, this characteristic is not taking into account because it is not in the research scope. In conclusion, airflow is unsteady flow and considers being turbulent flow as well. In addition, because of airflow, the condition could change from place to another and it changes over time. Thus, it is important to study and simulate airflow to understand its effect on urban and city elements before building a new structure

8.1.4 Wind Speed.

At the height above the surface of the earth, where frictional effects are negligible, air movements are driven by pressure gradients in the atmosphere, which in turn are thermodynamic consequences of 6variable solar heating of the earth. This upper-level wind speed is known as the gradient wind velocity (Mendis *et al*., 2007). Closer to the earth surfaces the wind speed is affected by the frictional drag of the air stream over the terrain. There is a boundary layer that the wind speed varies from almost zero. The thickness of the boundary layer varies from 500 metres to 3000 metres, depending on the type of terrain.

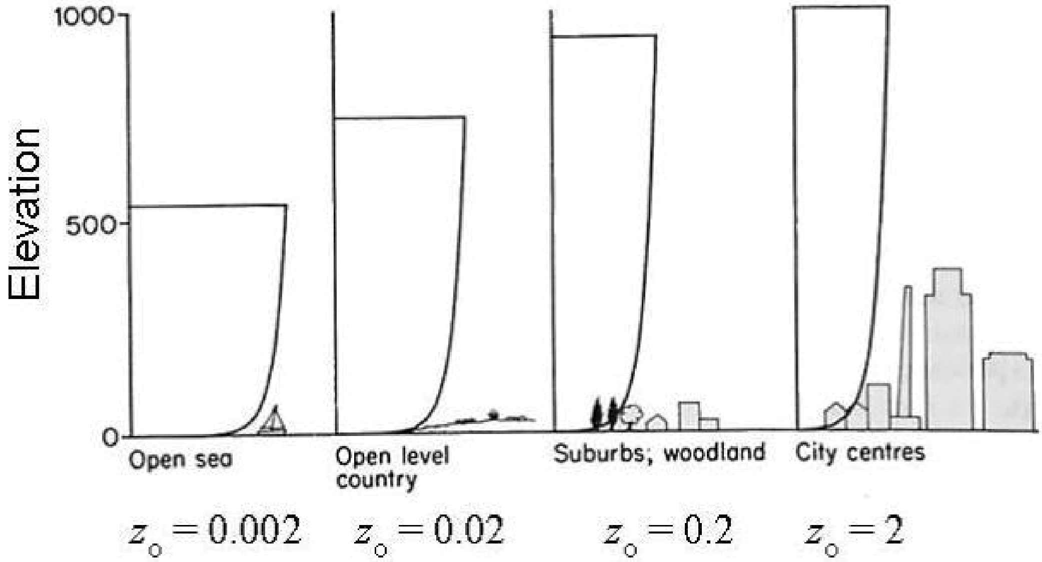


Figure 8.4 Mean wind profile for different terrain (Mendis *et al*., 2007)

Table 8.1 Terrain category (Mendis *et al*., 2007)

Terrain category	Roughness length, Z0 (m)
Exposed open terrain with few or no obstructions and water surface at serviceability wind speed	0.002
Water surfaces, open terrain , grassland with few, well scattered obstructions having heights generally from 1.0 to 10 m	0.02
Terrain with numerous closely spaced obstruction 3 to 5 m high such as area of suburban house	0.20
Terrain with numerous large, high from 10 to 30 m and closely spaced obstructions such as large city centres and well developed industrial complexes	2.00

8.1.5 Wind Loads.

Wind load means both of wind speed and wind pressure on the building. In addition, wind load increases according to the building height and the response if the structure depends on some factors (Ilgin *et al.*2014)

- Characteristics of the wind,
- Building size and Geometry,
- Stiffness of the building and the distribution of the building mass,
- The inherent damping characteristics of the structural system and of the construction material, which dissipates wind-induced building sway.
- Surrounding topography,
- The orientation of the building with respect to the prevailing wind direction

8.1.6 Wind-induced Building Motion

Under wind load subjected to structure, the structure, therefore, response to the wind load and It can divide into three types (Mendis *et al*, 2007) (Ilgin *et al*, 2014):

1. Along-Wind Motion: Building sways parallel to the direction of the wind. This motion is induced by fluctuations of wind speed, and the variation in wind pressure between windward and leeward faces of the building.

2. Across-Wind Motion: Building sways perpendicular to the direction of the wind. When the movement of the air mass is blocked by the building, because of its fluid behaviour it splits into two, passing both sides and the rear face of the building, depending on the velocity of the wind, size and aspect ratio of the building.
3. Torsional Motion: produced by two mechanisms. The first mechanism is the mean torsional excitation resulting from non-uniform pressure distributions over non-symmetrical cross-sectional geometries. Second is the torsional response resulting from eccentricity between the elastic centre of the structure geometry and resultant force centre of the aerodynamic loads subjected to the structure. In other words, if the distance between the elastic centre of the structure and aerodynamic centre is large, the structure can be subjected to torsional moments that may significantly affect the structural design.

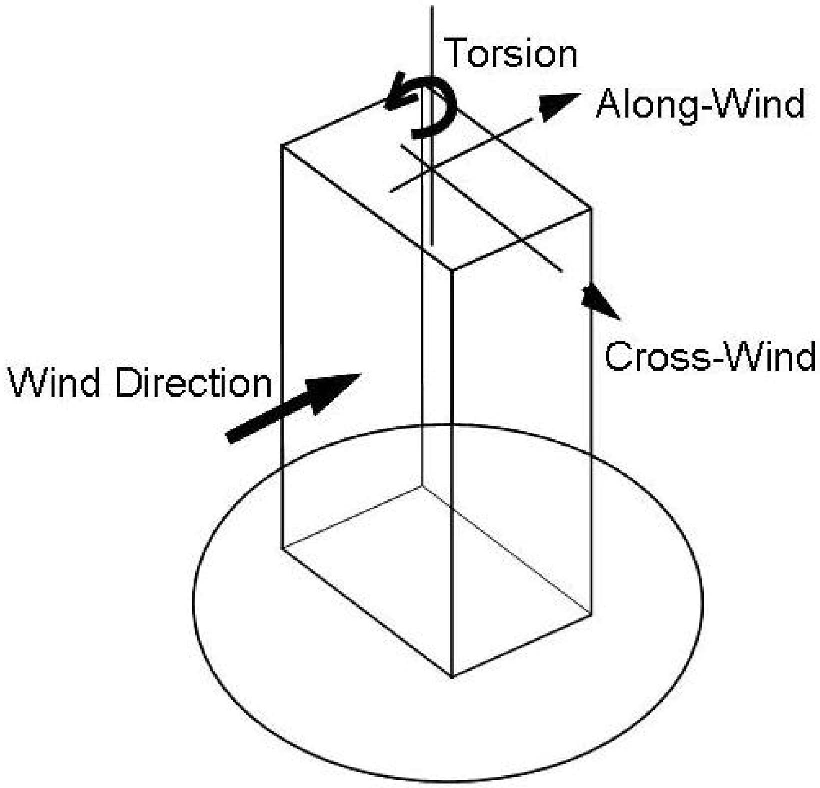


Figure 8.5 Wind response direction (Ayoub, 2012)

8.1.7 Air flow pattern around bluff bodies

Building permitted airflow around their ends and above of them. The disturbance that building creates can induce high wind speed at ground level, due to separate two type pressures (Erell et al., 2012). The first type is the flow caused by pressure distribution on windward face of a bluff body (buildings) which increase with height and related to local dynamic wind pressure (Erell *et al*., 2012). However, the second type caused by the pressure difference between the low-pressure wake regions on leeward and side faces, and the pressure regions at the base on the windward face (Erell *et al*., 2012).

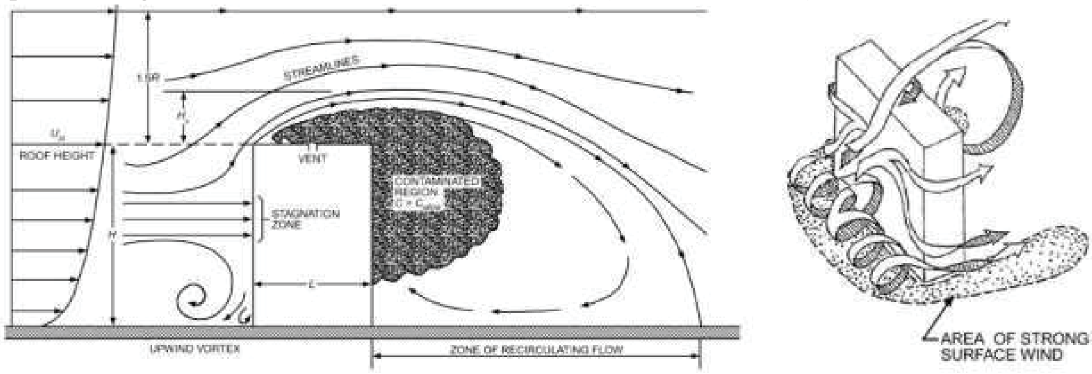


Figure 8.6 Air flow pattern around bluff body (Ayoub, 2012)

In addition, in case of groups buildings (two or more) are constructed close to each other such as cities, the wind flows through the group may be significantly deformed and cause a much more complex effect than is usually, resulting in higher dynamic pressures and motions, especially on neighbouring downstream buildings and it also generates vortices (AIJ, 2006).

8.1.8 Vortices Generation

Vortices are spiral flow formation generated by turbulence that creates negative pressure in the crosswind direction while breaking away from the surface of the building (Ilgin *et al.*2014) as shown in Figure 8.7.

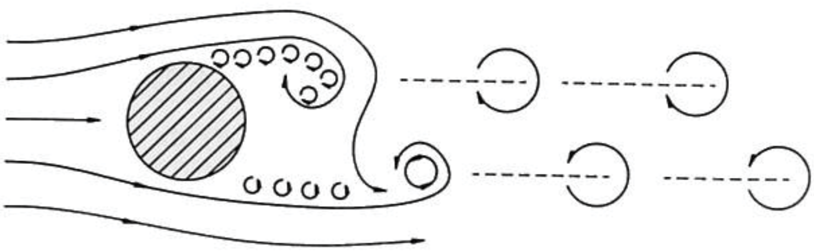


Figure 8.7 Vortices formation around bluff body (Mendies *et al*., 2007)

8.1.9 Pedestrian wind studies

Wind environment around buildings especially tall building has become a significant technological and social problem. The shape of the building or structure may create inhospitable or even dangerous wind environmental conditions for pedestrians at street level (Ilgin, 2007). Pedestrians who walk past tall building may subject to lift force that could lift their feet from the floor. In addition, they may subject to the turbulence of the wind around and near the buildings.

The wind conditions around a building affected by many factors such as, the ambient wind statistics, local topography, building mass, nearby foliage, and the closeness of similarly tall structures. All these can influence the resulting winds around the base of a new building and at elevated levels on balconies and terraces (Ilgin, 2007). Moreover, even though the acceptable wind speed is five metres per second for most outdoor activities, this speed is too high for recreational areas, parks, or similar places, for these areas, additional windbreaks can be a necessity (Ilgin, 2007).

The quality of the wind environment at the base is considerably affected by design of a building (Ilgin, 2007). For example, downwash that is strong winds flowing down on the face of the structure and accelerated around the ground-level corners after the wind reaches the ground (Figure 8.8). This occurs for buildings that taller than the surrounding buildings. In such cases, in order to prevent this kind of flow and protect sidewalk area around the entrance, large canopies are commonly used (Figure 8.9) (Ilgin, 2007), Furthermore, large podiums are also utilized for the same purpose (Figure 8.10). Moreover, an arcade or an open, columned plaza under a building frequently creates strong wind conditions (Figure 8.11). A recessed entry provides low winds at door locations (Figure 8.12) while a corner entry may increase wind concentration at building corner (Figure 8.13) (Ilgin, 2007)

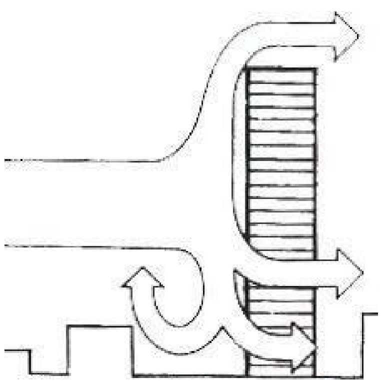


Figure 8.8 Downwash (Ilgin , 2007)

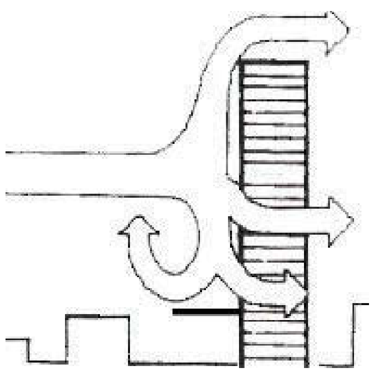


Figure 8.9 Large Canopy (Ilgin , 2007)

Figure 8.10 Large Canopy (Ilgin , 2007)

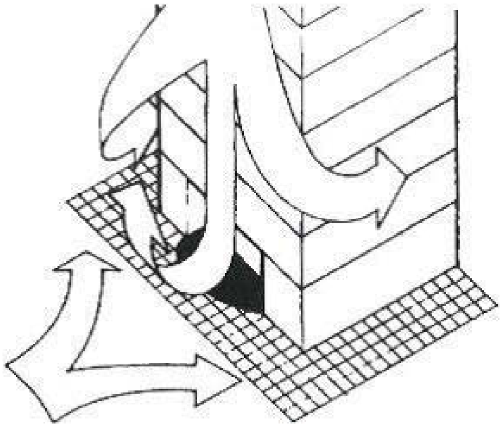


Figure 8.11 Open Plaza entrance (Ilgin , 2007)

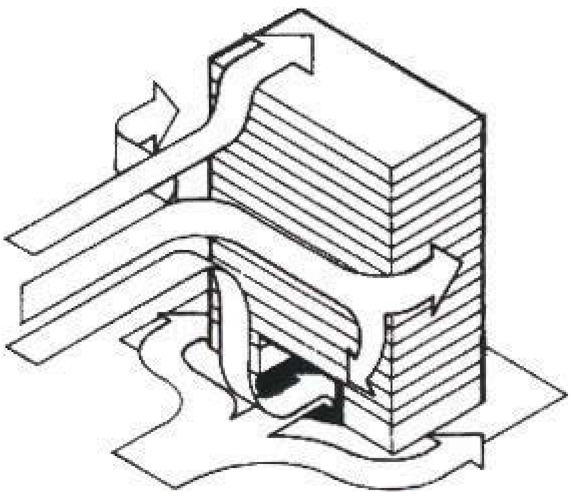


Figure 8.12 Recessed entry (Ilgin , 2007)

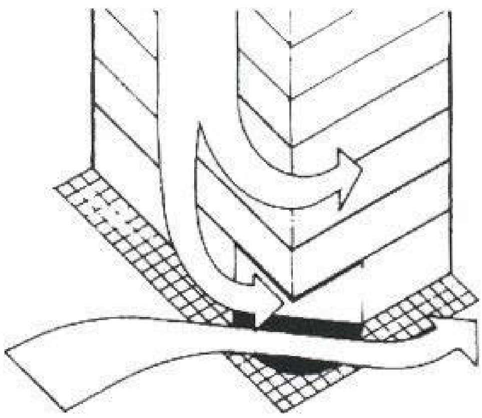


Figure 8.13 Corner Entry (Ilgin , 2007)

8.2 Appendix B – Additional Material.

Table 4.2 Quantitative Assessment of the Wind Performance of the Alternative Solution.

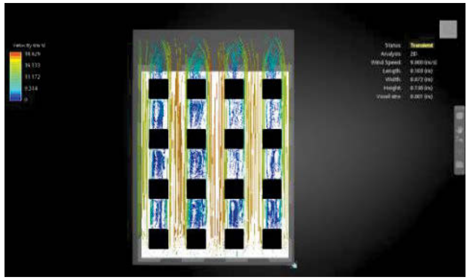
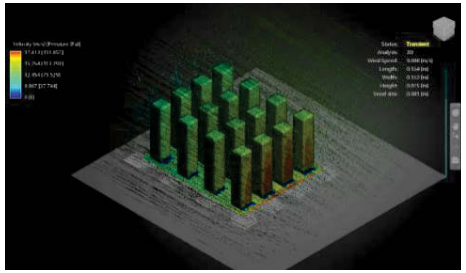
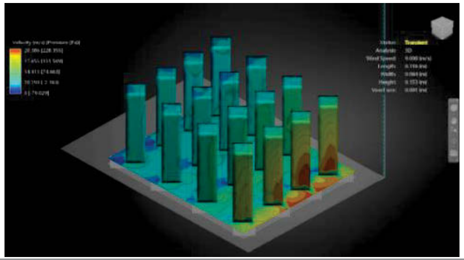
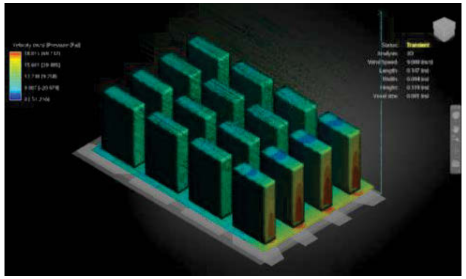
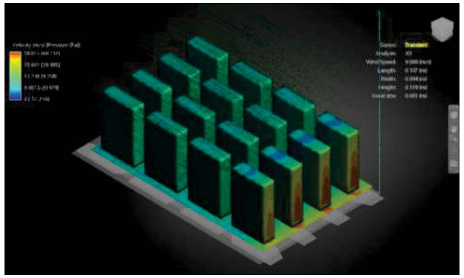
Solution number	Velocity and turbulence	Pressure
Solution: One **Average wind velocity: 9.31m/sec** **Average Wind Turbulence: 17786.301 m^2/s^2** **Average wind Pressure: 151.05pa**		
Solution: Two **Average wind velocity: 14.92m/sec** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 114.17pa**		
Solution: Three **Average wind velocity: 9m/sec** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure:34.5pa**		

Table 4.2 Quantitative Assessment of the Wind Performance of the Alternative Solution.

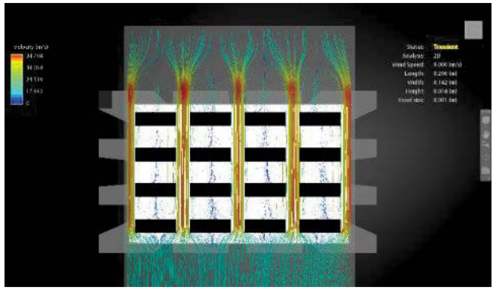
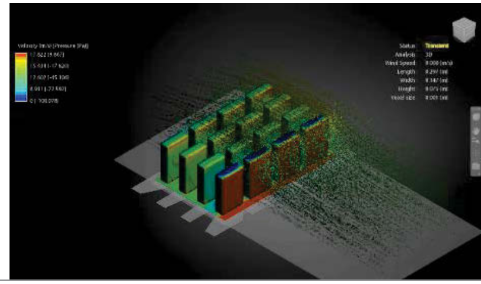
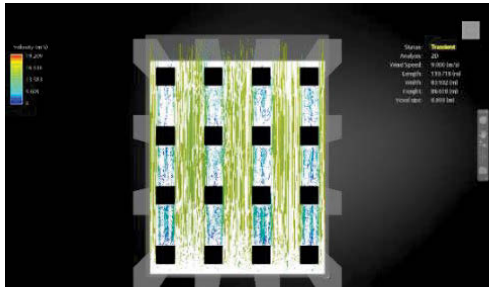
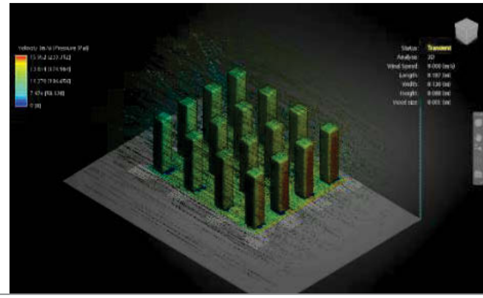
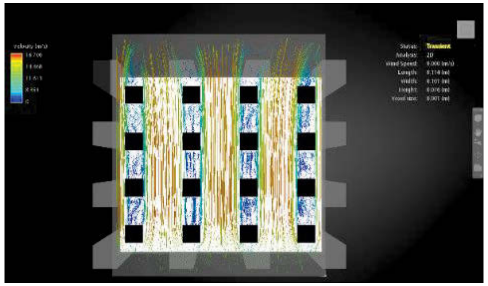
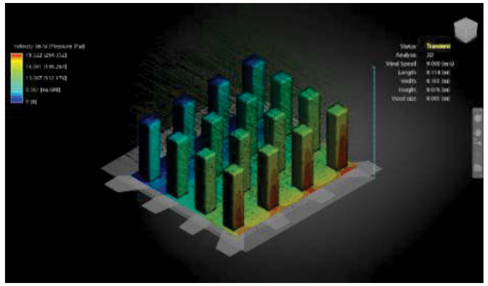
Solution: Four **Average wind velocity: 22.61m/sec** **Average wind turbulence 104905.117m²/s²** **Average wind pressure: 4.93pa**		
Solution: Five **Avg. wind velocity: 9.62m/sec** **Avg. wind turbulence** **18991.017 m²/s²** **Avg. pressure:116.65pa**		
Solution: Six **Avg. wind velocity: 9.6m/sec** **Avg. wind turbulence: 18912.272m²/s²** **Avg. wind pressure: 132.15pa**		

Table 4.2 Quantitative Assessment of the Wind Performance of the Alternative Solution

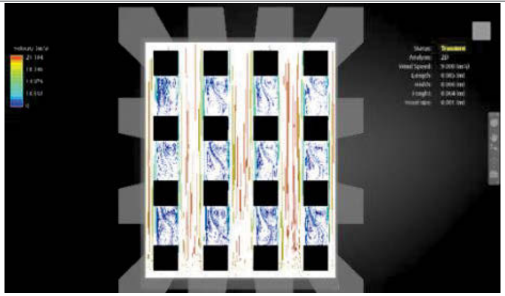
Solution: Seven

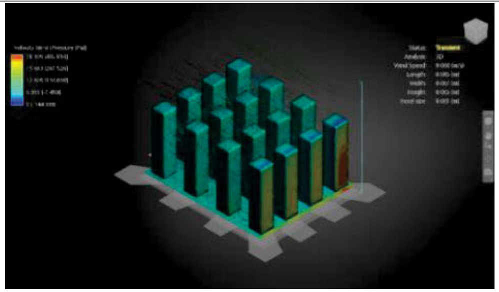
Avg. wind velocity:

10.90m/sec

Avg. wind turbulence 33007.10 m2/s2

Avg. wind Pressure:202.50pa





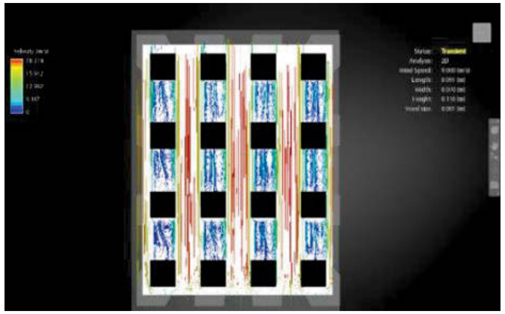
Solution: Eight

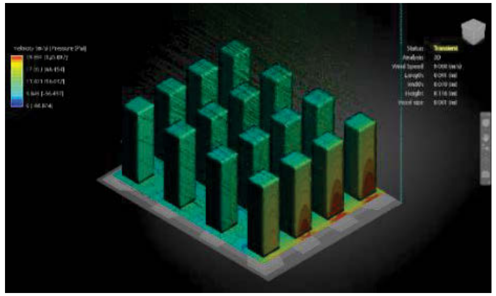
Avg. wind velocity: 10.90m/sec

Avg. wind turbulence

17493.61m2/s2

Avg. wind pressure: 60.44pa



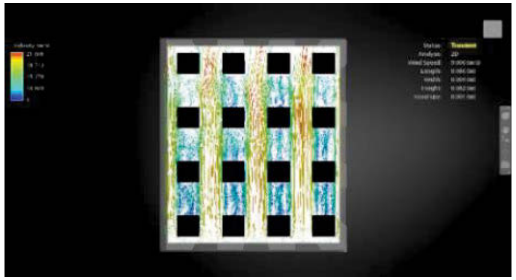


Solution: Nine

Avg. wind velocity: 11.64m/sec

Avg. wind turbulence 2171.613m2/s2

Avg. wind pressure: 70.5pa



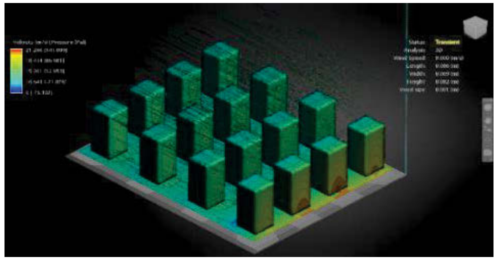


Table 4.6 Quantitative assessment of the wind performance of the alternative solution

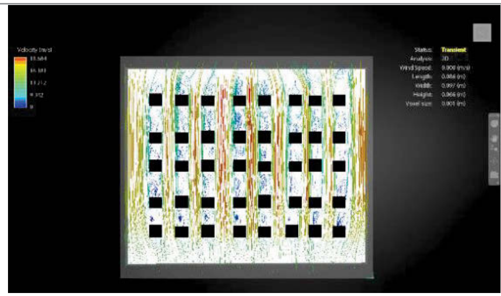
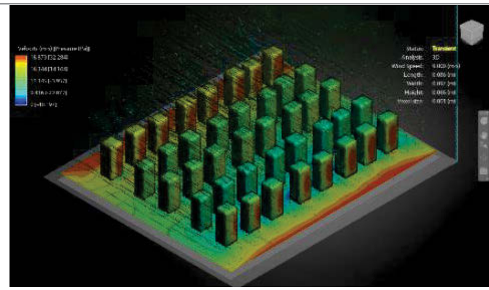
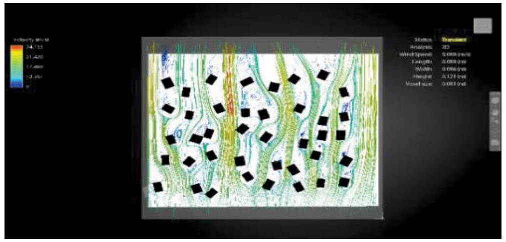
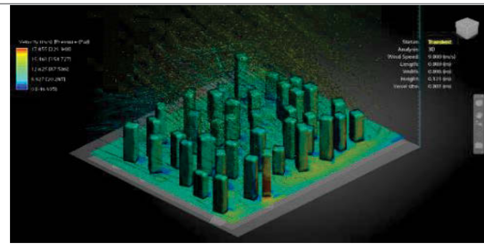
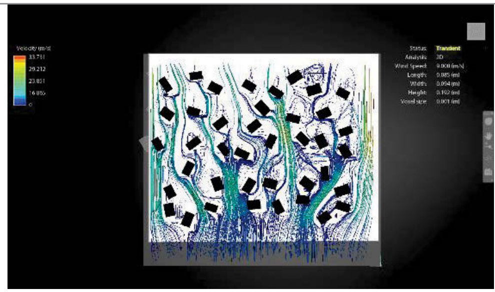
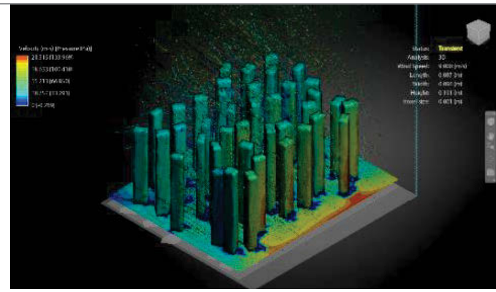
Solution number	Velocity and turbulence	Pressure
Solution: One **Average wind velocity: 9.43 m/s** **Average Wind Turbulence: 17786.301 m^2/s^2** **Average wind pressure: 16.10 pa**		
Solution: Two **Average wind velocity: 10.64 m/s** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 228.92 pa**		
Solution: Three **Average wind velocity: 10.75 m/s** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure: 66.45 pa**		

Table 4.6 Quantitative assessment of the wind performance of the alternative solution

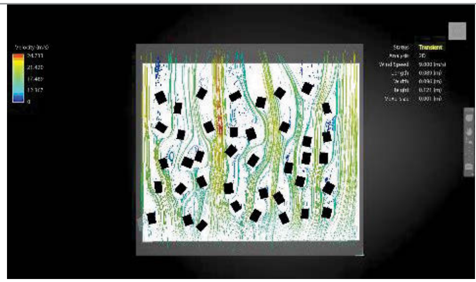
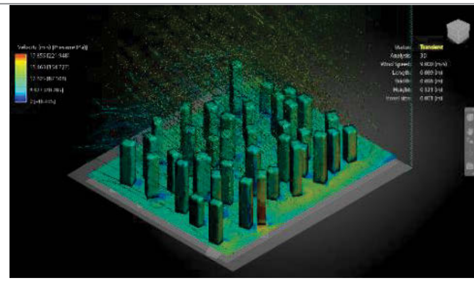
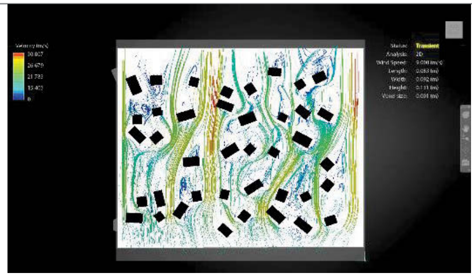
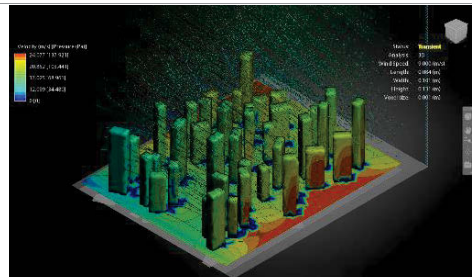
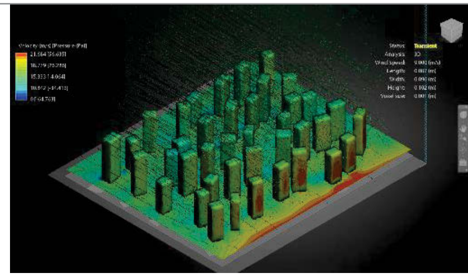
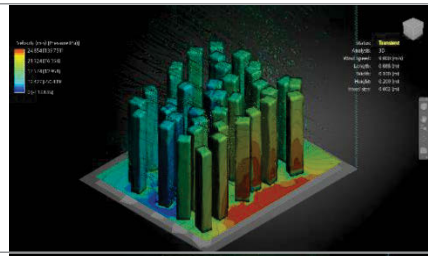
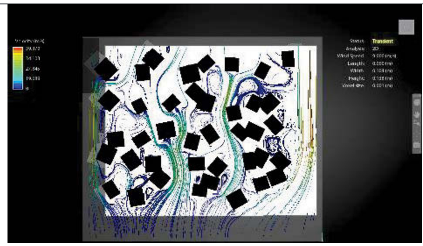
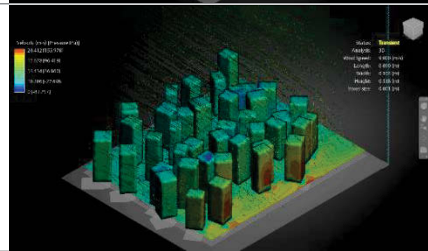
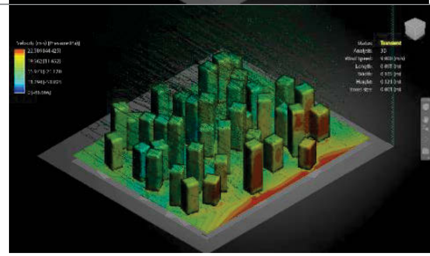
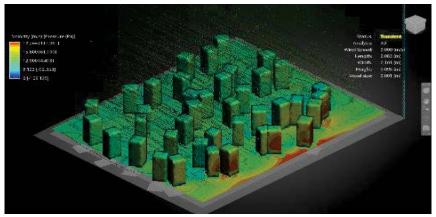
Solution: Four **Average wind velocity: 8.92 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 110.5 pa**		
Solution: Five **Average wind velocity: 12.03 m/s** **Average wind turbulence: 45680.875 m^2/s^2** **Average wind pressure: 68.95 pa**		
Solution: Six **Average wind velocity: 10.84 m/s** **Average wind turbulence: 16621.91 m2/s2** **Average wind pressure: 28.31 pa**		

Table 4.6 Quantitative assessment of the wind performance of the alternative solution

Solution: Seven **Average wind velocity: 12.42 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 69.50 pa**		
Solution: Eight **Average wind velocity: 10.20 m/sec** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 77.98 pa**		
Solution: Nine **Average wind velocity: 11.25 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 22.22 pa**		
Solution: Ten **Average wind velocity: 28.41 m/s** **Average wind turbulence: 17786.301 m^2/s^2** **Average wind pressure: 117.96 pa**		

8.3 Appendix C – Publications

Tall Building Design Exploration: Designing For Wind Resilience

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Abstract

The paper presents a performance-based design method that combines building and urban objectives for the control of winds impacting on tall buildings at the pedestrian, podium and upper levels. The performance-based method accounts for wind flow and wind load in a design exploration technique that considers a variety of criteria defining urban microclimates, defined by high-density, multi-level building forms subject to acute variations in seasonal wind conditions. The approach is based on the theoretical foundations of 'designing for urban resilience; and highlights the different objectives of this approach relative to existing (tall) building design standards and urban city planning guidelines.

1 Introduction

In the development and promotion of sustainable urban planning strategy and building design practices, the concept of resilience has become a central aspect of modern cities. By 2050, the United Nations expects 80 percent of the world's population to live in urban areas (United Nations 2009). In addition, over 310 million people live in cities with a high probability of natural disasters including the effects of hurricanes and tropical cyclones, and by 2050 these numbers are predicted to more than double (Lall & Deichmann 2012). As cities continue to expand and grapple with the uncertainties and challenges of climate change and unprecedented urbanization there is a growing emphasis on enhancing the resilience of cities (Meerow 2016)

In the implementation of tall building design standards and urban city development design guidelines, separate policies aimed at the building and urban scale stipulate how a variety of safety, health and comfort requirements must be supported. Recent initiatives surrounding 'designing for urban resilience' have adopted a more integrated 'systems' approach to building design aimed at supporting the survival, adaptation, and growth of cities against chronic environmental stresses and acute shocks. Mitigating the impacts of strong or extreme winds at the building and urban city scale is key to urban resilience.

This paper reviews literature surrounding 'designing for urban resilience' and highlights the different objectives of approaches. It furthermore reviews related literature surrounding building standards and urban city planning guidelines, focusing on the Australian Buildings Codes and Development Design Guidelines. The paper then presents a performance-based tall building design method that combines individual building and urban objectives for the control of winds impacting on tall buildings at the pedestrian, podium and upper levels. The performance-based framework therefore accounts for wind flow and load form design exploration in urban microclimates, which are defined by high density, multi-level building forms subject to acute variations in seasonal wind conditions.

2 Defining Urban Resilience.

Drawn from the literature of environmental and social sciences research, Leichenko (2011) investigates the notion of urban resilience from the perspective of the impacts of climate change. The study frames urban resilience in terms of the ability of a city or urban system to withstand a wide array of shocks and stresses. Leichenko's study highlights broad agreement among different fields of research regarding the need for cities to prepare for the effects of climate change and implement strategies for urban resilience so as to address a wider range of environmentally driven stresses and shocks. From this perspective, it is argued that efforts to promote urban development, sustainability, and resilience to climate change should be synthesized.

Similarly, Godschalk (2003) investigates resilient cities focusing on urban hazard mitigation focusing on natural disaster and terrorism. This view considers cities as a complex and interdependent systems that are vulnerable to threats from natural and terrorist hazards. Godschalk's approach proposes a strategy aimed at enabling cities to withstand both types of hazards, defining a 'resilient city' as a "sustainable network of physical systems", including buildings, infrastructure, and communities (encompassing both the formal and informal human associations that operate schools, agencies and organizations, etc.). From this standpoint hazard mitigation is defined as an action aimed at decreasing or eliminating long-term risk to people and property from the effects of environmental hazards. The scope of actions range from the development of structural engineering standards and building codes to land use, planning and property acquisition.

Based on a survey of related literature, a taxonomy of urban resilience is identified across the different environmental and social science domains. This taxonomy divides urban resilience into four categories, including:

(i) Urban ecological resilience - the ability of a city or urban system to absorb disturbance while retaining identity, structure and key processes (Alliance 2007),

(ii) Urban hazards and disaster risk reduction - the capacity of cities, infrastructure systems, and urban populations and communities to quickly and effectively recover from both natural and human-made hazards such as hurricane and international terrorism (Coaffee 2008),

(iii) Resilience of urban and regional economies - focusing on the evolution of urban and regional economic and industrial systems (Pendall 2009), and

(iv) Promotion of resilience through urban governance and institutions - focusing on questions of how different types of institutional arrangements affect the resilience of local environments (Ostrom 2010).

Based on this brief review of the literature, the authors define urban resilience as a system that able to: (i) respond to uncertainty and change in climate conditions, (ii) respond to associated social–ecological related risks, and (iii) reorganize and recover quickly from such changes, risks and disturbances. Consequently, this research investigates urban hazard mitigation from the perspective of tall building design, focusing on mitigating the impacts of strong and extreme winds at two inter-related scales: the building scale and urban city scale. The authors claim that in designing for these two scales simultaneously, urban resilience objectives can be better addressed.

3 Tall Building Design And Controls For Wind

High-density cities can be considered as a matrix of wind obstacles, comprising buildings of different sizes and forms, arranged at varying angles with different distances between them. 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. 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 Scale Structural Wind Load Requirements

One of the main objectives of the wind loading provisions defined in all building codes (e.g., Part 2 of Australia Standard AS 1170.1-1989), 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 velocity approaching the site, the building height and geometry, and the influence of surrounding buildings on the local wind flow patterns. Building codes therefore usually specify loads along the wind direction for common shapes in open and suburban terrain. An exception is the building code AS/NZ 2002, 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).

Further, 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 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 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 simple geometries, code formulae are of sufficient accuracy for design purposes and conservative results may not have a major cost impact. However codes such as the 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.

3.2 Urban Scale: City Development Design Guidelines

In response to the mitigation of wind-related hazards, similar requirements are also typically requested by city-based (council) development design guidelines for assessing wind impacts of the design on pedestrians at street level. Concerns surround the effects of wind on pedestrians is primarily related to the reduction of wind velocity and its change rate. A wind impact statement is most often required by Australian city council authorities, which demonstrates 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 is typically required as part of the development application. Generally, submissions must identify and analyses 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 sought.

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. 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 to provide a wind effects assessment that demonstrates that wind impacts will not adversely affect the amenity of the public realm and the scheme requires wind tunnel test as an assessment method. In addition, Melbourne's Planning Scheme provides proposed environmental wind criteria, including unacceptable and acceptable wind conditions based on wind velocity and the hourly average wind speed. This criteria assists designers to achieve good pedestrian activation along streets and in open space areas..

4 Performance-Based Design Approach To Design Exploration

The Building Codes and City Development Design Guidelines reviewed in the previous section vary relative to the scale that they are designed to address (structural building scale versus urban scale) and therefore their corresponding level of analysis. What they have in common concerns their typical testing requirements, which rely on wind tunnel testing or computational fluid dynamics (CFD) modelling. However compliance testing of tall building designs against these requirements are not performed until the later schematic and detailed design stages, when important design decisions about the building form and the relationship of the building envelop to its surrounding environment have already been made. Changes to the design of the tall building envelope are therefore costly as significant investment has been made to develop and detail the design across all disciplines involved (architecture, structure and all building services). Further, current building codes and design guidelines do not adequately address the interface between designing for the wind loads that act on a tall building's envelope and designing for wind flows that impact on pedestrians at street level

During the earlier stages of the design process, decision-making is aimed at searching through a range of potential design alternatives that 'satisfice' (Simon 1956) design requirements and constraints. Relative to climate-related hazards includes strong wind events, this requires finding alternative design solutions that satisfy the requirements of building codes and those of city development design guidelines. Most wind load requirements specified in building codes share common standards due to the nature of structural and physical properties. However, design guidelines vary from one region to another according to environmental conditions, including an area's vulnerability to wind-related 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 evaluating design alternatives against specific wind load and wind flow performance criteria in order to meet competing design requirements in the early stages of the design process is a challenging task. It requires an understanding of the nature of aerodynamic behavior at both the building and urban scales that can only be synthesized using advance modelling and simulation methods (Khallaf & Jupp 2016a).

The application of performance-based simulation and design exploration provides the necessary design decision support. The ultimate goal of computational simulation methods should not just be the analysis of prescribed shapes, but the automatic determination of the optimum shape for the intended application (Burkard 2000). The overall design exploration strategy developed here is based on the belief that problem formulation evolves during the process of searching and converging for the fittest (tall building envelop) solution; thus ultimately leading to a more informed and 'optimal' solution. In this way, design exploration is seen as being both a divergent and convergent process used to evolve and investigate a multidisciplinary design space that utilizes wind performance criteria with the intent of design discovery and to inform decision making trade-offs between the building and urban scales

Performance-based CFD simulation in wind engineering has seen increasing use in the assessment of risk associated with buildings subject to natural wind-related hazards (Huang et al. 2015, Khallaf & Jupp 2016b). Accordingly, the remainder of this paper presents a framework for mitigating strong wind-related hazards based according to different wind load and wind flow criteria. The framework accounts for both building and urban parameters as well as topographical parameters derived from the urban geospatial environment.

The method employs computational fluid dynamics as its core simulation technique for the prediction of wind performance at different heights defined by the building's overall geometric form and its relationship with the surrounding building context. This technique includes the definition of grid discretization, domain sizes, and boundary conditions of the generated alternative solutions. The quality of the grid affects the accuracy of the flow solution (Blazek 2001). Two equations are based on the simulation techniques Euler equations for inviscid and the Navier-Stokes equations for viscous flow. Since a wide range of evolutionary algorithms have been proposed to address various design problems (including combinatorial and substitution algorithms), the design exploration process discovers design conditions and via gradual parametric experimentation characterizes what an optimal design looks like. Once this is known, the final solution can then be found through a convergent design optimization algorithm. The framework is detailed below and is based on five modules and seven steps carried out in a sequential manner as shown in Figure 1.

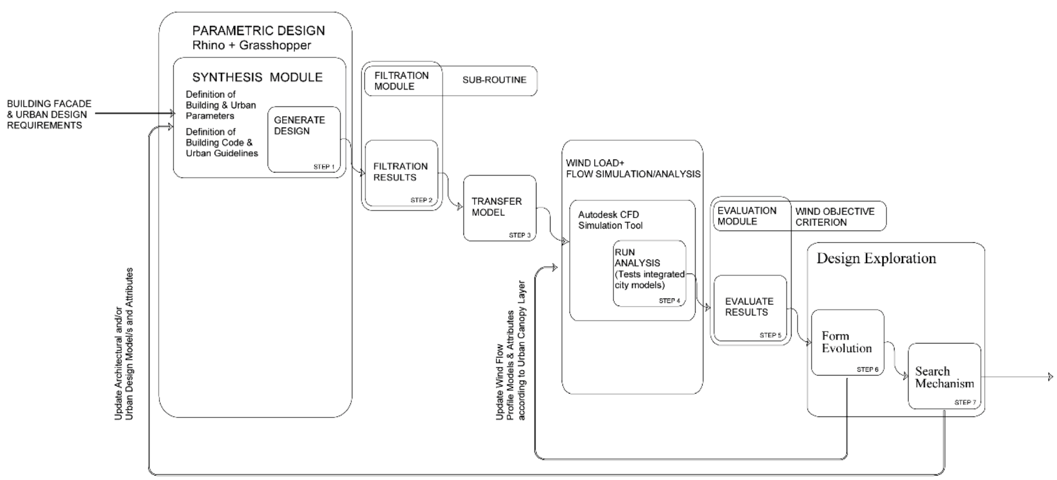

Figure 1 Performance-based Framework for Wind-Related Hazards in the Form Exploration of Tall Building Envelop Designs

Design Generation: Consisting of objective functions, parameters and constraints. This module defines the objective functions and the boundary of design parameters and constraints. The system boundary is based on three sets of parameters and one set of constraints, namely: wind load and flow performance parameters, geometric parameters defining the criteria for the building envelope, urban parameters defining the criteria of the surrounding urban environment, and the topographical constraints defining slope categories). By assigning different values to the geometric and urban parameters, the values of the wind performance parameters are accordingly adjusted in parallel with the geometrical change of the tall building envelope. Consequently all possible design solutions can be generated. The flexible relations between geometries, wind load and flow performance can then be analysed by the subsequent module. The generative software Rhino/Grasshopper can be readily used as the parametric modelling tool and is suitable due to the flexibility of modelling rendering and design workflow. In addition, Genoform, a Grasshopper plug-in is adopted as a bi-directional approach to multi-objective problem solving. The model is a surface-based parametric rig composed of geometric primitives (points, polygons, and surface.

Filtration: Consisting of filtering functions that can evaluate the results of the Generation Module and compare results with regard to performance parameters derived from building codes and city development design guidelines. The objective of this module is to filter design solutions by discarding unmatched solutions that do not meet the appropriate wind load (building) and wind flow (urban) design criteria. Filtration Sub-Routine: An external constraints module extends the Filtration Module so as to consider other design constraints relevant to the tall building design brief, such as functional, layout, height and construction constraints, etc

Simulation & Analysis: Consisting of the simulation of the flexible relationships between geometry and wind load and wind flow performance outcomes of the filtered design solutions (resulting from the previous module). The simulation workflow enables the analysis of the impact of the wind load on and wind flow around both the geometrical parameters and performance variables with the visualisation of data points assisting in the confirmation of different performance locations throughout the test site on all X, Y and Z axes. Consequently, the change of performance parameters can be visualized within the system using this module. This assists the designer's understanding of the nature of wind load and flow at both building and urban scales. The Autodesk CFD Design Study Environment is used in this stage as this tool includes a range of simulation methods for analysing wind loads and flows. This stage therefore includes both building and urban CFD analysis. It enables the testing of model geometry relative to the building envelope in the context of the urban environment. Simulations are run for two general scenarios: (i) high winds in extreme weather conditions, and (ii) low winds in the case of stagnant air conditions

Evaluation: Consisting of comparative assessment. The Evaluation Module provides a quantitative assessment of the level of effectiveness of wind performance across design alternatives, comparing results from the previous module with wind performance objectives and criterion. This implies that there may be no single optimal solution but rather a whole set of possible solutions of equivalent or comparable quality (Abraham et al 2005). The main objective of this module is therefore to rank design solutions according to wind performance criteria at three levels and to assess performance across these levels, including the pedestrian (0-6m), podium (7-45m) and upper (above 46m) levels.

Design Exploration: Consisting of exploration processes which are aimed at evolving and searching for the most suitable design solution that satisfies the objective function (tested in the previous module) together with relevant compliance criteria (e.g., building code and design guidelines). This module includes a two-part exploration process, namely Form Evolution followed by Search Mechanism.

Form Evolution: develops the design solution via mutation of the fittest design solutions' parameters (building and urban) according to all 'performance levels', i.e., pedestrian (0-6m), podium (7-45m) and upper (above 45m) levels. The purpose of mutation is to produce new design properties and features which will allow the system to improve the design solutions' geometric form and performance whilst limiting the number of the feasible alternative design solutions using a proven fitness function identified as a result of the Evaluation Module.

Search Mechanism: works as a space search mechanism. The designer in this stage searches for the optimum design solutions within the domain of feasible crossbred design solutions using the results of the wind performance objective criterion. The aim of this module is to identify the fittest design from among the available designs solutions based on both the design performance and the wind performance criteria. The objectives of design exploration may be variable and not constant depending on design and context requirements relative to wind velocity, directions, and turbulence. However, if the target design solution does not fit the performance criteria, the designer can implement changes in the initial design parameters defined in the Generation Module based on the current results, and perform another run of the module.

5 Discussion

The paper briefly reviewed literature surrounding designing for urban resilience and highlights the approaches relative to existing building standards and urban city planning guidelines. The paper then presented building codes and city development design guidelines pertaining to the design of tall building envelopes for wind loads and urban wind flow requirements focusing on the Australian cities. The paper highlighted the lack of performance-based form simulation and design exploration approaches to tall building and surrounding urban resilience, which can account for both scales relative to the control of the effects of high and low wind conditions. The authors, therefore, propose a generative parametric framework based on building and urban parameters and wind performance criteria that can manage dependencies between building and urban wind flows; thus supporting the exploration of tall building envelope designs. The benefits of using the framework surround the performance-based feedback which is valuable to decision-making in the early stages of design so as to mitigate wind-related hazards. Further work is aimed at verifying the framework in a case study of Melbourne.

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International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

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 a combined architectural-urban design method focusing 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 requirements for 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.

Peer-review under responsibility of the organizing committee iHBE 2016

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

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Peer-review under responsibility of the organizing committee iHBE 2016
doi:10.1016/j.proeng.2017.04.169

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 [1]. 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 [2]. 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 [3]. 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

The intentions of wind loading provisions that are included in building codes such as Part 2 of the Australia and New Zealand Standard AS/NZS 1170.2:2011 [4], 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, with AS/NZ 1170.0:2002 [5] also specifying provisions for the cross-wind direction. 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 [6]. 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 [7]. Nevertheless, many standards, such as the AS/NZS 1170-2 and the US standard ASCE07-05 [8], 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.* [9] 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 [8] and AS/NZ 1170.2 [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 [10], which is aimed at characterizing wind loads for tall buildings and SI.5281-3 [11] 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 [12] 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 [13] 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 [14] 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 [15] 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' [16] 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 [17] 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 [18] 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 [18]. 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.*, [19] 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.* [20] define 'favorable' wind conditions as moderate winds of 2m/sec, and Penwarden [21] 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 [21]. 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' [22] 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.* [23] 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 [24] 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 [25]. 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 [26]. Jain *et al*. [27] 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 [8]) 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.* [27] 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.* [28] and then later developed by Ciampoli *et al.* [29]. 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 [30] 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.* [31] 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 [32]. Further, conventional building envelope design methods typically produce a small number of design alternatives [33]. 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 flow criteria, accounting for structural and urban parameters as shown in Table 2. The method uses generative parametric modelling and a two-stage performance analysis technique that enables the gap between the structural 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.

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.

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

Type	Parameters	Value
	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
Building	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 Density	≤12:1
	Street width and length(m)	Street Width 7.2m to 16.6m, Street length 100m to 200m
Urban	Building Block width and length	Width 70m, Length 100m to 200m
	Urban Porosity	N/A
	Building Separation	8m to 16m
	Velocity	1.5m/s to 2.5m/s
Wind	Turbulence (TKE)	Floating Value
	External Pressure Coefficients	≤ +0.48 Kn/m2

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.

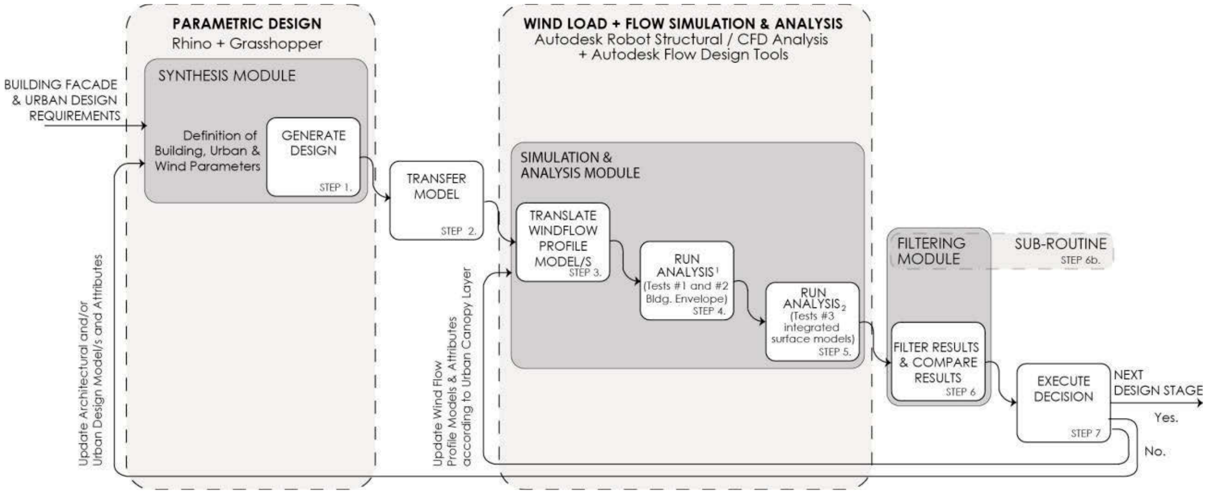

Fig 1. Three modules using a seven-step process for integrating architecture and urban design with wind flow performance design.

- *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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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-

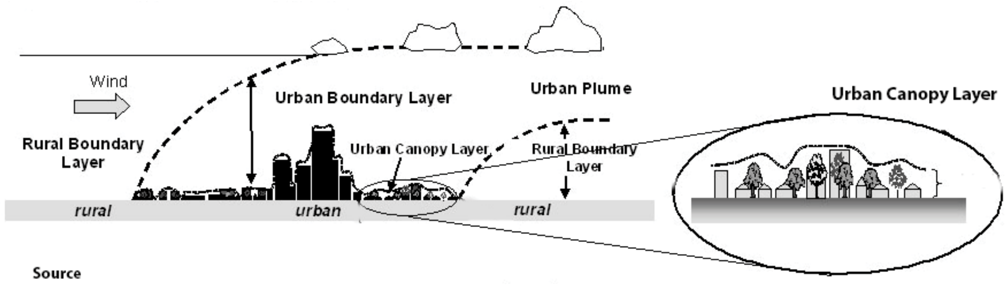


Figure 1
Main components of urban atmosphere (source: Voogt, 2004). Two-layer classification of architectural and urban MDO.

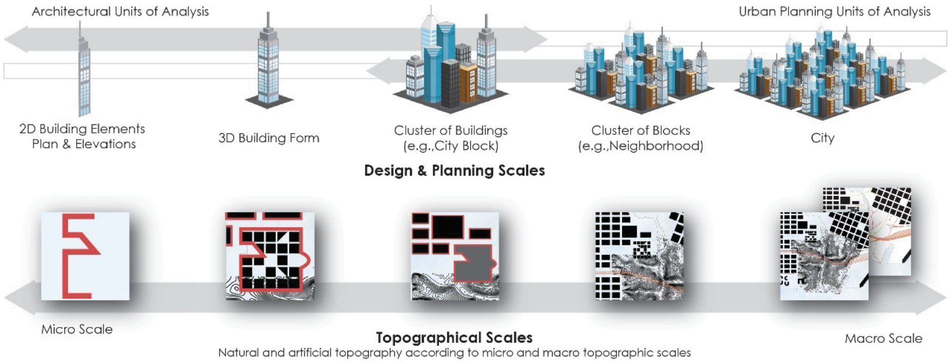
ban scales may ultimately result in poor design performance in terms of how the physical features of each scale impact on the wind flow profiles intended to be realised by the building design and or urban plan.

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 simula-

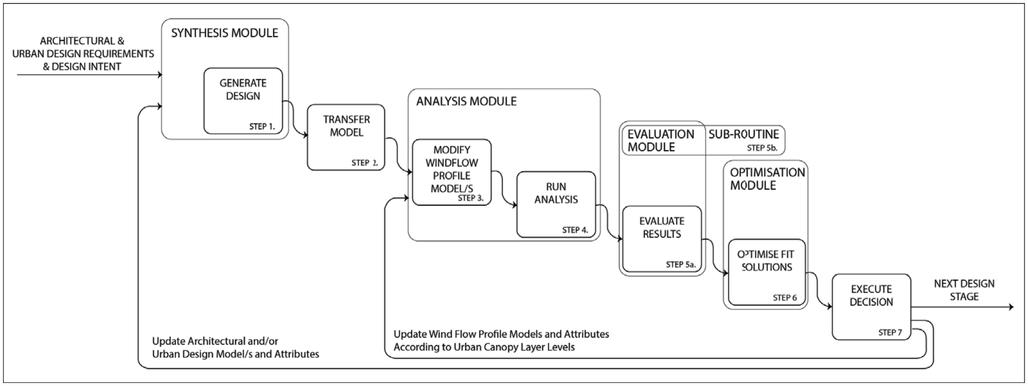


Figure 3
The seven step process for integrating architecture and urban design with wind flow simulation.

tion results.

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:

$$\lambda p = \frac{Ap}{At} \quad (1)$$

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.

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

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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