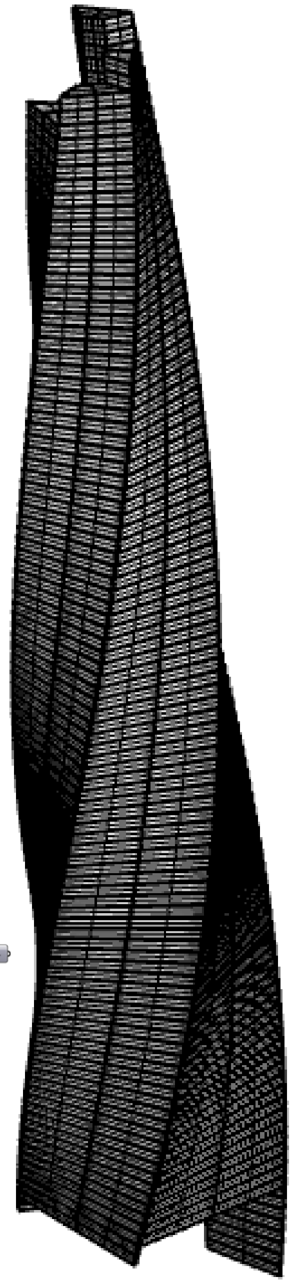

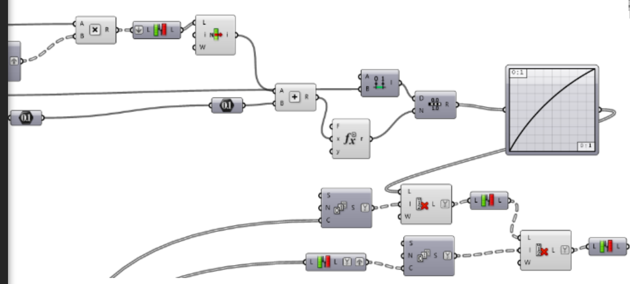

PhD DISSERTATION

# EVALUATION OF THE COMBINED EFFECT OF VEGETATION AND NATURAL VENTILATION IN NEARLY ZERO ENERGY MULTI-STOREY BUILDINGS – nZE(ms)B

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# UNIVERSITÀ DEGLI STUDI DI PALERMO

Dottorato in Architettura, Arti E Pianificazione

Dipartimento di Architettura

(ICAR/10) – Architettura Tecnica

# Evaluation of the combined effect of vegetation and natural ventilation in nearly zero energy multi-storey buildings – nZE(ms)B

(In cotutela con University of Lisbon, Portugal)

IL DOTTORE
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CICLO XXXII
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U LISBOA | UNIVERSIDADE DE LISBOA

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*A thesis submitted in partial fulfilment of the requirements of a double degree doctorate program in*

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Thesis Submitted: February 2020

Period: 2017-2020

# ABSTRACT (ENGLISH)

Cooling load is the main cause of high energy consumption for tall buildings in tropical climates while the construction of tall buildings[1] is an unavoidable practice due to land scarcity in metropolitan cities. In this regard, the use of natural ventilation (NV) in tall buildings can help reducing the energy consumption. However, this solution can also bring the problem of polluted air that may enter the space to be ventilated. If the air is passed through a system that can absorb pollutants and add more oxygen to the air, the problem may almost be solved. Building integrated vegetation (BIV) systems can help solving this problem. So, if the air entering buildings passes through dense vegetation, it may not only be cleaned but also cooled due to evapotranspiration effect of plants. Furthermore, the choice and location of vegetation can increase or decrease wind speed. Incorporation of the successful implementation of these green strategies lead to the design of nearly zero energy multi-storey buildings (nZEmsB).

A successful implementation of these strategies for an optimized outcome in terms of reduction in cooling load and the performance of NV is evaluated through computational fluid dynamics (CFD) software. A conventional method is to design the building using passive strategies i.e. NV and BIV, and then evaluating the design using a CFD tool to evaluate the efficiency of combined effect of NV and BIV. If the simulation results are not optimal, the design has to be modified and the simulation process has to be repeated. However, this is a time taking approach as the design of a tall building itself is a complex process and any wrong decision regarding spatial planning, overall building configuration and choice of BIV systems may become the reason for the failure of an implementation resorting to this passive technique.

The concept of optimization in Architecture, has brought a novel perspective for the designers to achieve the better design solutions in reduced time. There are many optimization models and tools available for the energy efficient design of buildings, however there is almost no research available regarding the optimization tools available for designing tall buildings incorporating a combination of NV and BIV systems. This research provides an optimization model for finding the optimal design choice for tall buildings using NV and SG as a cooling technique in hot and humid climates.

The deliverables of this research are a decision support framework for the development of the optimization tool, a generative tool, that is capable of developing 3D models of tall buildings with the geometrical characteristics (found in literature) suitable for the best implementation of NV and SG to reduce the cooling load in hot and humid climate; integration of a CFD simulation tool to the generative tool resorting to RhinoCFD for the evaluation of effectiveness of NV; and an optimization algorithm, based on evolutionary algorithms.

This Model is developed using visual programming and scripting on Grasshopper/ Rhino3D. The model does not require users to have in depth knowledge of computational fluid dynamics and still can inform the designer regarding the best design option. It will assist designers to make informed decisions for achieving effective natural ventilation design through building

[1] Terms “Tall buildings”, “high-rise buildings” and “multi-storey buildings” represent same meanings in this dissertation as tall/high-rise buildings are special type of multi-storey buildings.

form, orientation, space planning along with allocation of SG at an early stage of design. The results will contribute to the development of energy efficient and energy independent communities.

# ABSTRACT (ITALIAN)

Il carico di raffreddamento è la causa principale degli elevati consumi energetici di edifici alti nei climi tropicali, mentre la costruzione di edifici alti è una pratica comune ed inevitabile a causa della scarsità di suolo presente nelle città metropolitane. Mediante l'impiego della ventilazione naturale (NV) negli edifici alti è possibile abbattere i consumi energetici. Tuttavia, tale soluzione può comportare il rischio di penetrazione di aria inquinata negli ambienti da ventilare. Se il flusso d'aria in entrata attraversa un sistema in grado di assorbire gli agenti inquinanti e aggiunge un quantitativo di ossigeno maggiore all'aria, tale rischio potrebbe essere quasi totalmente risolto. Sistemi di vegetazione (VG) integrata agli edifici (building integrated vegetation) possono contribuire alla risoluzione di tale problema. Quindi, se il flusso d'aria entrante negli edifici attraversa un sistema costituito da fitta vegetazione, questo potrebbe non solo essere ripulito, ma anche raffrescato grazie all'effetto di evapotraspirazione delle piante. Inoltre, la scelta e il posizionamento della vegetazione può aumentare o diminuire la velocità del vento. L'incorporazione dello sviluppo di queste strategie ecologiche conduce alla progettazione di edifici multipiano a energia quasi zero (nZEmsB).

Una corretta applicazione di queste strategie, per l'ottimizzazione dei carichi di raffrescamento e delle prestazioni della VN, viene valutato attraverso un software computation fluid dynamics (CFD). Un metodo convenzionale è quello di progettare l'edificio impiegando strategie passive es. NV e VG, e poi analizzare la progettazione attraverso CFD per valutare l'efficienza dell'effetto combinato di NV e VG. Se i risultati della simulazione non sono ottimali, il progetto deve essere modificato e il processo di simulazione deve essere ripetuto. Tuttavia, si tratta di un approccio che richiede tempo poiché la progettazione stessa di edifici alti risulta essere un processo complesso e scelte non corrette in merito alla pianificazione spaziale, alla configurazione generale dell'edificio e alla scelta dei sistemi BIV potrebbero vanificare la corretta attuazione della suddetta strategia passiva.

Il concetto di ottimizzazione in Architettura, ha condotto i progettisti verso una nuova prospettiva ottenendo la migliore soluzione progettuale in tempi ridotti. Esistono molti modelli e strumenti di ottimizzazione per la progettazione di edifici ad alta efficienza energetica, tuttavia non sono presenti in letteratura molti studi effettuati su strumenti di ottimizzazzione della progettazione di edifici alti che incorporano sistemi combinati di VN e BIV. Questa ricerca fornisce un modello di ottimizzazione utile ad individuare la scelta progettuale più adatta per edifici alti che prevedono l'uso di ventilazione naturale e sky garden come tecnica di raffrescamento in climi caldi e umidi.

I risultati di questa ricerca sono un framework di supporto per lo sviluppo di uno strumento di ottimizzazione, uno strumento generativo, che è in grado di sviluppare modelli 3D di edifici alti con le caratteristiche geometriche adatte alla migliore implementazione di sistemi VN e BIV per ridurre il carico di raffrescamento in climi caldi e umidi; integrazione di uno strumento di simulazione CFD con lo strumento generativo che ricorre a RhinoCFD per la valutazione dell'efficacia di VN; un algoritmo di ottimizzazione, basato su algoritmi evolutivi.

Questo modello è stato sviluppato utilizzando la programmazione visiva e lo scripting su Grasshopper/Rhino3D. Il modello non richiede che l’utente abbia una conoscenza approfondita della fluidodinamica computazionale e può, quindi, indirizzare facilmente il progettista in merito alla migliore soluzione progettuale. Tale modello sarà di supporto ai progettisti nelle fasi iniziali del progetto per ottenere un efficiente progettazione della ventilazione naturale studiando la forma dell'edificio, l'orientamento, l’organizzazione dello spazio e l’integrazione di tetti verdi. I risultati contribuiranno allo sviluppo di comunità energeticamente sicure e indipendenti dall'energia fossile.

# ABSTRACT (PORTUGESE)

A carga de refrigeração é a principal causa do alto consumo de energia em prédios altos localizados em climas tropicais, sendo que a construção de prédios altos é uma prática inevitável devido à escassez de terrenos e pressão imobiliária nas cidades metropolitanas. Nesse sentido, o uso de ventilação natural (NV) em edifícios altos pode ajudar a reduzir o consumo de energia. No entanto, tal solução também pode fazer entrar ar poluído no espaço a ser ventilado. Se o ar passar por um sistema capaz de absorver poluentes e adicionar mais oxigénio ao ar, tal poderá constituir uma contribuição para a resolução do problema. Assim, a aplicação de sistemas de vegetação integrada (BIV) pode ajudar a resolver o problema. Se o ar que entra nos edifícios passar por uma vegetação densa, poderá não apenas ser limpo, mas também arrefecido devido ao efeito de evapotranspiração das plantas. Além disso, a escolha e a localização da vegetação podem aumentar ou diminuir a velocidade do vento. A incorporação bem-sucedida de tais estratégias verdes permitiu o desenvolvimento de projectos de edifícios altos e com quase zero de consumo energético (nZEmsB).

Para uma implementação bem-sucedida destas estratégias, a fim de obter resultados otimizados em termos da redução da carga de refrigeração e ventilação natural avalia-se o desempenho através do software computation fluid dynamics (CFD). Como método projectam-se edifícios usando estratégias passivas, isto é, NV e BIV, e depois avalia-se o projecto recorrendo a uma ferramenta CFD para avaliar a eficiência do efeito combinado de NV e BIV. O projecto é repetido até que os resultados da simulação sejam optimizados. No entanto, tal abordagem é demorada, pois o projecto de um prédio alto é um processo complexo e qualquer decisão incorreta em relação à organização espacial, à configuração geral do edifício e à escolha dos sistemas BIV podendo tornar-se o motivo do fracasso da implementação.

O conceito de optimização em arquitectura trouxe uma nova perspectiva para os projectistas obterem melhores soluções de projecto em menor tempo. Existem muitos modelos e ferramentas de optimização disponíveis para o projecto de edifícios com eficiência energética, no entanto, quase não há pesquisas disponíveis sobre as ferramentas de optimização disponíveis para projectar edifícios altos que incorporam uma combinação de sistemas NV e BIV. Esta pesquisa fornece um modelo de optimização para encontrar a opção ideal de projecto para edifícios altos recorrendo a ventilação natural e jardins suspensos (sky gardens) como técnicas de refrigeração aplicáveis em climas quentes e húmidos.

Os resultados deste trabalho são o desenvolvimento de uma ferramenta de optimização como modelo de suporte à decisão, uma ferramenta geradora capaz de gerar modelos 3D de edifícios altos com as características geométricas (de acordo com as encontradas na literatura) adequadas à melhor implementação de sistemas NV e BIV com o objectivo de reduzir a carga de refrigeração em contextos climáticos clima quentes e húmidos; integração de uma ferramenta de simulação de CFD de complemento à ferramenta geradora que utilizao RhinoCFD para a avaliação da eficiência da ventilação natural; e um algoritmo de optimização, baseado em algoritmos evolutivos.

Este modelo é desenvolvido com o recurso a programação visual e textual no ambiente Grasshopper / Rhino3D. O modelo não exige que os usuários tenham um conhecimento

profundo de dinâmica dos fluidos computacional (CFD) e pode ainda informar o projectista sobre as melhores opções de projecto, ajudando os projetistas a tomar decisões informadas com o fito de alcançar um projecto eficaz quanto à ventilação natural optimizando a forma da construção, orientação, organização espacial, juntamente com a inclusão de jardins suspensos e ainda na fase inicial do projecto. Os resultados contribuirão para o desenvolvimento de comunidades mais eficientes e independentes de energia.

# DEDICATION

*I dedicate my dissertation with love to my mother (Late)* ***Hamida Bano*** *and Father* ***Mirza Muhammad Ibrahim,*** *their continuous prayers and believe in me enabled me to achieve my dream*

# ACKNOWLEDGEMENT

The whole journey of this research had been challenging for me. I faced one of the biggest trauma of my life when my beloved mother passed away on Feb 13, 2019, due to brain stroke. I am forever indebted to her for her continuous belief and support that enabled me to achieve this milestone. **Mom! You are missed.**

I would like to pay a heartfelt thanks to my supervisor **Prof. Rossella Corrao**, for her consistent support and guidance throughout my research. Her supervision enabled me to carry out my graduate studies in an area that truly interested me at the University of Palermo. The experience and exposure I gained under her supervision, made me a better professional and will be helpful to me for years to come.

A special thanks is also due to my supervisor **Prof. José Nuno Beirão.** It has been an honor to be his Ph.D. student. He has taught me, both consciously and unconsciously, how good computational design is done. I appreciate all his contributions of time, ideas, and motivation to make my Ph.D. experience productive and stimulating. The joy and enthusiasm he has for his research were contagious and motivated me, even during tough times in the Ph.D. pursuit. I am also thankful for the excellent example he has provided as a successful supervisor and professor.

I would like to pay thanks to the **Italian government** and the **University of Palermo** for providing funding to carry out this research. I also want to thank all my colleagues in **Design and Computation Group** (DCG) at the **University of Lisbon**, with whom I have shared not only the moments of deep anxiety but also of big excitement. It was a great sharing laboratory with all of them.

I am particularly grateful for the assistance given by **Shakil Ahmed** and **Andrew Carmichael** (team members of **Concentration, Heat and Momentum Limited**) regarding the provision of license for RhinoCFD for the use of this tool to execute this research work.

I am beholden to my father, my siblings, extended family members, friends and colleagues for motivating me to get back to my research work again and again after every tough time and finishing the incomplete tasks. In this regard, I would like to mention my family members, **Sumera Mughal, Samina Bano, Nadra Mughal, Sidra Mughal Farheen Mughal, Mirza Muhammad Asif, Mirza Muhammad Arif**, & My dearest brother **Mirza Azhar** who have always been there for me and never been reacted when I claimed my thesis would be finished ‘in the next two months’ for nearly a year. It is my good fortune to be blessed with such a loving family.

I am very grateful to **Rukhsana Siddique, Muhammad Fawad, Zakir Ullah** and **Adil Ahmad** who have given me their friendship, moral support and guidance whenever things would get a bit discouraging.

On the same note I would like to thank **Anber Rana** for listening, offering me advice, supporting me, putting up with my odd hours and being one of my friends that I can afford to be stupid with. I am also very grateful to her for her amazing sense of respect when helping me with the editing of the thesis.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AES | Annual Energy Saving |
| BIV | Building Integrated Vegetation |
| CAD | Computer Aided Design |
| CFD | Computational Fluid Dynamics |
| EA | Evolutionary Algorithm |
| FF | Fitness Function |
| FFD | Fast Fluid Dynamics |
| GA | Genetic Algorithm |
| GD | Generative Design |
| GT | Generative Tool |
| GM | Generative Model |
| HVAC | Heating, Ventilation and Air conditioning |
| NV | Natural ventilation |
| nZEB | nearly Zero Energy Buildings |
| nZEmsB | nearly Zero Energy multi-storey Buildings |
| OM | Optimization Model |
| RG | Random Generator |
| SG | Sky Gardens |
| UHI | Urban Heat Island |
| VG | Vegetation |

# PREFACE

One article and four conference papers have been published from this PhD research, parts of which have directly or indirectly been included in the thesis. Complete references of these papers are provided below:


1. Mughal, H. (2017). Seminar: “Local Climate Change and Urban Mitigation Techniques to Counterbalance It”, University of Palermo, Italy, March 2017. Infolio (ISSN 1828-2482), 73–75.

   Available at: http://www.unipa.it/dipartimenti/architettura/.content/Infolio/34_infolio.pdf

2. Mughal, H., & Corrao, R. (2018). Role of Sky Gardens in Improving Energy Performance of Tall Buildings. International Conference on Seismic and Energy Renovation for Sustainable Cities (SER4SC) (ISSN 2071-1050). Catania, Sicily – Italy.

   Available at: https://iris.unipa.it/retrieve/handle/10447/278846/541504/Pagine%20da%20SER4SC%20Proceedings-ESTRATTO.pdf

3. Mughal, H., & José, B. (2019). A Workflow for the Performance Based Design of Naturally Ventilated Tall Buildings Using a Genetic Algorithm (GA). 37th ECAADe Conference + XXIII SIGraDi Conference. Porto, Portugal.

   Available at: http://papers.cumincad.org/cgi-bin/works/paper/ecaadesigradi2019_183

4. Mughal, H., & Beirão, J. (2019). Potential of Natural ventilation for achieving low-energy buildings in tropical climate: An overview. First International Conference on Progress in Digital and Physical Manufacturing (ProDPM’19) (ISBN 978-3-030-29041-2). Leiria, Portugal.

   Available at: https://link.springer.com/chapter/10.1007/978-3-030-29041-2_14

5. Rana, A., & Mughal, H. (2019). The effect of balconies on energy efficiency of multi-unit residential buildings: a state of art review. 6th International Conference on Energy and Environment Research. Aveiro, Portugal.

   Available at: https://www.researchgate.net/publication/336305552_The_effect_of_balconies_on_energy_efficiency_of_multi-unit_residential_buildings_a_state_of_art_review

# CONTENT

# *Introduction*

*This is the first part of the thesis that delivers an overview of the thesis outline. It introduces the research goal, research question, hypothesis, main objectives to achieve the goal, the challenges of the development process, methodological approach to carry out research, research structure and the contributions of the outcome of the research.*

# 1 RESEARCH INTRODUCTION

## 1.1 Background

Rate of energy consumption in almost all sectors of life is threatening since the demand is exceeding the supply capacity and continues to rise. Construction industry, in this regard, is found to be the most belligerent one as it requires energy supply from the beginning of the construction process till the maintenance of the existing structure. In Europe, buildings account for 40% of global energy use and 36% of $CO_2$ emission (European Parliament and Council, 2010).

Furthermore, rapidly increasing population in metropolitan cities due to economic pressure cause land scarcity which in turn requires vertical construction i.e. tall/high-rise buildings[2] (United Nations, 2018). Heating, ventilation and air conditioning (HVAC) system is accounted for almost half of the energy load of a building.

The demand for comfortable indoor environment using HVAC systems especially in tall buildings has got a gradual increase of 20-40% of global energy consumption, by both commercial and residential sector in developed countries (Pérez-Lombard, Ortiz, & Pout, 2008). This increase in energy demand seems to be continuing even with a higher rate in coming years. The situation may get worse in hot climate due to increased ambient temperature by urban heat island (UHI) effects in dense urban zones (Santamouris, 2015) compared to the neighbouring suburban or rural areas (Mughal & Corrao, n.d.; Pérez-Lombard et al., 2008; Santamouris & Kolokotsa, 2016) causing high energy demand for cooling (Taslim, Parapari, & Shafaghat, 2015).

In order to achieve the goals of having comfortable indoor environment, reduced carbon footprint and reduced energy demand traditional building design must be shifted to the sustainable & energy efficient design that is a step towards nearly zero energy building design (nZEB)[3] (Gil-Baez, Barrios-Padura, Molina-Huelva, & Chacartegui, 2017; Grigoropoulos, Anastaselos, Nižetić, & Papadopoulos, 2017). With reference to the design of tall buildings in hot climate, passive cooling techniques should be adopted to cut down the energy consumption by mechanical ventilation systems. For this purpose, the use of natural ventilation (NV) is found to be the most effective and sustainable strategy (David & Brian, 2008; A. Wood & Salib, 2013). It does not only reduce the energy consumption but also renovates air in indoor spaces providing a healthy environment (Gonçalves, 2010).

[2] Although the research focuses on the optimization of multi-storey buildings, but the term "multi-storey" is generic term and does not characterize the height limit or range. These buildings can be as low-rise as two or three story high or as high-rise as a tall, mega tall or super tall building. So, the type of multi-storey buildings addressed in this research are "tall/high-rise buildings" being a special type of multi-storey buildings.

[3] Nearly zero energy building (nZEB) is defined as a very high energy performant building with very low energy demand (that is covered by available renewable sources) and reduced carbon footprint (D'Agostino & Mazzarella, 2019). In tropical climate the climatic conditions allow the designers to implement NV as a passive strategy to reduce the energy demand for cooling (Babak Raji, Tenpierik, & Dobbelsteen, 2016). Use of NV is found to be a successful strategy to achieve nZEB design, since the buildings using NV not only have low energy demand but also provide high indoor air quality and have very reduced carbon footprint (Gil-Baez et al., 2017; Grigoropoulos et al., 2017; Haslam & Farrell, 2014).

On the other hand, tall buildings may disconnect the occupants residing at higher floors with the environment. This disconnection can be reduced by bringing in vegetation spaces at different levels/heights where people can socialize and feel connected to nature. These green elevated spaces are called sky gardens (SG) (Liu, Ford, & Etheridge, 2012). Studies by Ip (Ip, 2013), Mohammadi et al. and Mughal et. al (2018) have shown that SG do not only provide recreational and social space but if properly located, they may help in improving the performance of NV in the building by channelizing optimized air flow (Ip, 2013; Mohammadi & Calautit, 2019; Mughal & Corrao, 2018). They are also helpful lowering down the temperature of ambient air due to evapotranspiration effect of plants and purify the air from pollution before letting it inside the building spaces (Chan, 2005; Ip, 2014).

However, optimizing spatial design of a tall building using the aforementioned strategies i.e. NV and SG is a complex process, since the design needs computational fluid dynamics (CFD) simulation (A. Chronis, Stefopoulou, & Liapi, 2018; Lau & Tsou, 2009), before the design solution is defined. The purpose is to evaluate if the design is capable to provide comfortable indoor environment, otherwise the design parameters are changed, to be re-evaluated again and again until optimal results are obtained (Emanuele, Alessandro, Ivan, & Yi, 2013).

Moreover, shifting the whole building ventilation system from mechanical to natural is risky and may end up failing if proper consideration of an accurate design process is not being done from the early design stage. Doing all this work can be tiresome and frustrating for the designer. Building energy performance assessments are complex multi-criteria problems. Appropriate tools that can help designers explore design alternatives and assess the energy performance for choosing the most appropriate alternative are scarcely available and definitely needed (Bergin, Asl, Menter, & Yan, 2014). However, there is limited study being done on the development of optimization tool based on CFD simulation (Cichocka, Browne, & Ramirez, 2017). There is almost no study being done for the development of an optimization tool that can optimize a building design enhancing the effectiveness of NV by integrating SG.

Hence the proposal justifies the need for developing an optimization framework especially made for the spatial design of energy efficient tall buildings with emphasis on natural ventilation and vegetation. This is a step towards nearly zero energy multi-storey buildings (nZmEB). The study aims at developing a time efficient tool that provide energy efficient design of tall buildings through the effective use NV and SG in hot and humid climate.

## 1.2 Initial considerations to carry out research

In order to define the typology of the buildings used in this study, following aspects are considered.

### 1.2.1 Climate

The study started with the consideration of a specific climate, in this case, tropical (hot and humid) climate. This climate was chosen since its conditions are most favourable and in need for the implementation of cooling strategies like NV and BIV. Singapore has these climatic conditions i.e. hot, humid and windy and therefore, the first application of the model was done by using weather data of Singapore. Applications to similar weather conditions in other locations shall in principle follow the same methodology and apply the same tools.

### 1.2.2 How "tall" is multi-storey?

Although the research focuses on the optimization of multi-storey buildings, the term multi-storey does not characterize the height limit or range. Multi-storey buildings can be as low-rise as two or three stories high or as high-rise as fifty stories high or more. So, the type of multi-storey buildings addressed in this research are tall buildings being a special type of multi-storey buildings. Tall building does not have a specific universal definition, however, in every design code or law of a region it must have followed a specific criterion to be termed as "tall building". The height of tall buildings is measured in terms of number of floors or in meters depending on the design code or laws followed in a region (Al-Kodmany, 2018a).

According to U.S National Fire Protection Association 101®, Life Safety Code 2012 edition, a building with height more than 23 meters is termed as high-rise building (Ahrens, 2016). According to ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) Technical Committee for Tall Buildings, a building having height 91 m/300 ft or more is termed as "tall building" (Ellis & Torcellini, 2005).

In lack of a better definition, the concept of a tall building for this study is subjective to the criteria defined by Council of tall buildings and urban habitat (CTBUH), (2019). According to CTBUH, if a building fulfils one or more criteria mentioned in

**Table** *1*, it will be considered a tall building. A thumb rule, however, is that a building having 14 or more stories, or a building with a height 50 meters (165 feet) or more can be termed as a threshold for a "tall building". If the height of tall building exceeds 300 meters and 600 meters , it is termed as "mega tall building" and "super tall building" respectively (CTBUH, 2019b; Gerometta, 2009). The criteria for considering a building as tall is shown in

**Table** *1*.

Table 1 Criteria for tall building (Oldfield, 2019; Skyscrapercentre.com/ctbuh.org, 2019)

| Criteria | Description |
|---|---|
| **Urban context** | If a building having 14 floors is in a city with supertall buildings i.e. Chicago, Hong Kong etc., it may not be considered as tall building. The same building is considered as tall building if located in a provincial European city or suburb. |
| **Proportion** | If the building is slender enough to have the appearance of tall building than it may also be referred as tall. |
| **Technology** | If the technologies used in buildings are same as the ones being used in tall buildings, than it may be termed as "tall building" e.g., Home Insurance Building (1885), is considered as tall building due to the use of curtain wall , having height 55 meters. |

The building height taken for this study to represent a tall building is measured in number of floors and it will be referred as a "tall building", if having number of floors equal to 14 or more. However, the developed optimization model/tool in principle and for the purpose may assume other values for number of floors.

### 1.2.3 Urban context

The optimization model is decided to be free of compulsion of a specific context in order to make it versatile for the future development of this work. The idea of not choosing a specific urban context at this stage is that the behaviour of wind with and without surrounding buildings in the same climatic conditions is very different and for real life design projects these urban contexts always vary. If the optimization has to be carried out for a particular site, it is much easier to develop a 3D-model of the urban context and then connect it with the optimization model rather than the development of an algorithm that should be capable to create many types of urban context that may not be accurate as well.

### 1.2.4 Building use

Tall building can be characterised by their usage and thus they may be single function i.e. office, residential or mixed use. The optimization model was developed to be applied to the design of office buildings, although the model may also be the basis for adaptation to the design of mixed use or residential buildings.

## 1.3 Research gap

Vertical construction is inevitable in metropolitan cities due to land scarcity and real estate pressure caused by the rapid growth of population (Safarik, Ursini, & Wood, 2018). However, this solution itself brings a lot of environmental impacts, specifically with reference to tropical climate, specifically the high energy consumption by HVAC systems due to the increased cooling load caused by the high ambient temperature leading to a high carbon footprint. Optimized design for high-performance tall buildings through the incorporation of passive cooling strategies, specifically by introducing NV and SG, in hot climate, may solve this issue. However, the optimization framework requires the assessment of successful incorporation of these strategies in tall buildings. This is a complex process as increasing building size increases the complexity of fluid dynamics at micro and macro scale and requires computational techniques for assessment and a specific workflow for the provision of optimum design solutions. There is not much work available regarding the optimization framework that incorporates computation fluid dynamics technique for the production of optimum designs of tall buildings (Cichocka et al., 2017). Hence there is the lack of

- Study investigating the effect of a combination of NV and SG on the performance of tall buildings.
- An optimization tool that can help designers achieving an energy efficient and healthy design of tall buildings based on passive technologies in minimum computation time.

## 1.4 Goal

To guide the designer for the early stage design of tall buildings with reduced cooling load by incorporation of NV and SG in tropical climate.

## 1.5 Research problem and hypotheses

The research problem addresses three main issues with reference to the design of multi-storey buildings in tropical climate and their expected mitigation strategies. **Table 2** points out (1) the need for optimize the floor space area, (2) the need of adding SG and NV as strategy for mitigating heat island effects, and (3) optimizing cooling strategies resorting to SG and NV as a means to cool down air temperature and insert it in indoor spaces at adequate wind velocity for providing a comfortable environment. So, there are more than one criterion to be fulfilled as a requirement of an optimized design, summarizing: maximize building capacity, reduce the air temperature and channelizing the comfortable wind speed.

This thesis addresses two essential hypotheses. The first states that building energy performance can be improved by resorting to SG and NV. The second hypothesis states that there is a workflow capable of optimizing building energy performance through a multi-objective optimization technique that can be applied at an early design stage.

Table 2 Issues , Causes and proposed mitigation techniques to apply for the development of nearly zero energy tall buildings

| Issues | Cause | Mitigation |
|---|---|---|
| **Demand for tall building construction** (United Nations, 2018) | Fast urbanization (United Nations, 2018) | Increase the efficiency of the building capacity[4] by increasing the functional space for the users (Oldfield, 2019) |
| **Gradual rise in ambient temperature** (Santamouris, 2016) | Urban heat island (UHI) effect and climate change (Akbari et al., 2016; Santamouris & Asimakopoulos, 2001; Schiano-Phan, Weber, & Santamouris, 2015) | UHI mitigation through incorporation of green strategies i.e. vegetation SG[5] (Ip, 2013; Mahmad & Zulkefli, 2013; Babak Raji, Tenpierik, & van den Dobbelsteen, 2015) |
| **High cooling load** (B. S. Lin, Yu, Su, & Lin, 2013; B. Raji, 2018) | Energy demand for cooling through HVAC system(Pérez-Lombard et al., 2008) | Reduce cooling load through passive cooling strategies i.e. SG and NV through reducing indoor air temperature and optimum wind velocity (Aslan & Sev, 2014; Gonçalves, 2010; Holmes & Hacker, 2007; Mughal & Corrao, n.d.) |

## 1.6 Objectives

The overall objective of this research is to develop a design support tool for the early design stage of tall buildings by the incorporation of existing and advanced NV techniques and SG to reduce the cooling load. Specific objectives of this research are the following

1. **To perform a state-of-the-art literature review**; regarding NV in tall buildings, incorporation of BIV and NV in tall buildings, existing optimization tools and techniques to incorporate NV in tall building.
2. **Development of an optimization framework:** This is the schema for the whole optimization system devised to respond to the research problem. This model is divided in

[4] The efficiency of a building capacity to accommodate the users is measured through net-to-gross area of the floor. Net area is the useable floor area i.e. the floor space excluding lobbies, staircase etc, while gross area is total floor area. As the number of floors increase, the efficiency of building capacity decreases (Oldfield, 2019).

[5] Incorporation of vegetation in buildings is just a contribution to the mitigation of heat island effect. This type of mitigation requires urban space design strategies also in order to be absolutely effective. When applied to buildings this strategy is just a contribution. However, it is an essential strategy regarding the building sustainable behavior without which not much could be done (Santamouris, 2015).

several parts:

- ✓ **Generative model:** The generative model is composed of (1) a parametric design system able of developing parametric designs of 4 high-rise building morphotypes, and (2) a (random) genetic code generator. The parametric system generates sets of solutions based on genetic codes.
- ✓ **Evaluation model:** The evaluation model is composed of (1) a fitness function comprising the results of (A) a CFD analysis and (B) a shape optimization function. The CFD analysis evaluates wind speed and air temperature drop produced by the SG.
- ✓ **Evolutionary model:** Composed by an evolutionary algorithm. This model has (1) a selection algorithm which selects the 50% best fit according to the results retrieved from the fitness function; (2) a genetic operation module that does random crossover on 10% of the selected population plus 10% mutation (to avoid getting stuck on local optimums); (3) adds 30% new randomly generated individuals (generated by the generative model); and (4) loops the systems until no expressive improvements result from the evaluation model.

## 1.7 Research assumptions and challenges

The focus of this study is tropical climate where the cooling loads are high while the climatic condition favours NV and incorporation of BIV in the buildings.

- While talking about NV process in tall buildings as a passive strategy, urban context plays a great role since prevailing wind direction and speed are greatly affected by the urban context. Orientation also becomes part of the study as it can play a key role in the successful implementation of cross or single sided ventilation. However, in this study the 3D-Model analysis is done without considering any specific context. The reason is that the tool needs to be generic at this stage so that later, a proper Grasshopper plugin may be developed to create multiple contexts.

- NV systems and their utility in tropical climate is not exactly an unknown subject. It is recognized as a highly important feature for new buildings but the main problems regarding their implementation are related to social habits. For instance, the way people use the spaces, following mistaken assumptions regarding the use of ventilation ends up harming the quality of the inner environment rather than improving it. Solutions where humans are not allowed to control their environment are many times criticized as too authoritative giving the argument that people like to feel in control of their environment and that they have the right to have that control. Other criticisms point in the opposite direction stating that it is common that people do not agree on a standard for comfort in the space they share and that they many times end up fighting an individual choice. That is the reason why solutions can be best applied on commercial/office buildings.

- Definition of the algorithms require careful consideration of programming language. Being an architectural designer, the most efficient language is using visual scripting for their visual interactive qualities. That can be done using Grasshopper plugin to Rhino3D as it provides visual interaction while choosing the design parameters during the development process emulating common design workflows.

- Grasshopper has many existing plugins that can be beneficial for the development of the whole tool. However, there are limitations. The longest script on Grasshopper can be shorter, smarter, more efficient, flexible and much faster in python or other scripting language.
- The selection of the simulation tool is challenging when it comes to CFD. Integration of CFD tool in computational design has only three best approaches available; RhinoCFD, Butterfly through Openfoam and Fast Fluid Dynamics (FFD). These approaches still have also limitations (A. Chronis, Dubor, Cabay, & Roudsari, 2017). This study makes the use of two approaches out of these three.

## 1.8 Significance and application of the study

The research fulfils the gap of the limited studies regarding the optimization of NV and BIV in tall buildings that limits the ability of decision-makers (engineers, architects, designers) of evaluating design decision impacts at early design stages. Some work is available for NV but almost no work considers the combined effect of NV and BIV.

This study provides an optimization tool and a framework for the development of a potential plugin for the software Grasshopper. This tool is capable of helping designers at early stage of design to develop a 3D-Model of tall building with an optimized overall building shape and spatial plan for tropical climate. It guides the designer in form finding while improving performance through the combination of NV and SG reducing cooling load towards a set of optimized solutions. The methodology can be followed as a reference to develop optimization tools to optimize other performance parameters i.e. daylight optimization, for buildings. It may contribute to the development of energy secure and energy independent tall buildings, and to alleviate energy poverty[6] especially in remote communities.

## 1.9 Research structure

This research study is composed of the following phases:

- First phase focuses on collection of data and literature survey regarding
  - ✓ Existing optimization tools and techniques.
  - ✓ Zero energy standards.
  - ✓ NV process and its implementation in tall buildings as a passive strategy in hot climates.
  - ✓ Types of BIV systems and their effectiveness in tall buildings as a green strategy in hot climates.
  - ✓ identification of knowledge gaps in the research field.
  - ✓ study of some cases of tall buildings located in tropical climate. with successful implementation of NV and BIV to learn from their pioneering implementations.
- Second Phase involves the development of the optimization Model. At this stage, identified knowledge gap is used to develop and modify existing architectural elements for a nearly

[6] It is a specific form of poverty that results in range of issues related to people's health and wellbeing due to thermal discomfort in indoors and stress caused by high energy bills ("What is energy poverty? | EU Energy Poverty Observatory," 2019).

zero-energy building design. An initial optimization model is developed that is applicable to multi-storey building that will make use of existing scientific knowledge and cases for the development of 3D models of nearly zero energy tall buildings. This phase follows the following steps

- ✓ Decision of geometric variables to develop 3D-model using generative tool.
- ✓ Development of generative tool with visual programming on Grasshopper/Rhino. The framework for generative tool will make use of existing building typologies based on airflow paths to develop a set of parametric typologies that were previously analyzed for their ventilation performance.
- ✓ Development of algorithm to integrate a CFD tool (RhinoCFD) into the Grasshopper platform, so that the models can be evaluated directly on Grasshopper.
- ✓ Algorithm for the fitness function is developed to rank the evaluated models
- ✓ Development of evolutionary algorithm.
- ✓ Development of an algorithm for database. This algorithm opens the excel file and writes the genetic codes of the developed model and corresponding fitness.
- ✓ Automatization of the whole system.

## 1.10 Thesis format

Thesis report is composed of into four parts and which are shown in **Figure 1**.

- Introduction: This part comprises of **chapter#1** that gives the overview of all the research and introduces the reader with the reasons to carry out this study and to the outcomes of it.
- Methodology: This part comprises of **chapter#2** that describes the methodology to carry out phase#1 and phase#2 followed the author to achieve the final goals and objectives of this study
- Literature Review: This part is composed of two chapters. **chapter#3** contains state of art review of various topics related to the thesis. **chapter#4** consists of case studies.
- Development: This part describes the development process of the optimization model and its potential significance and contributions towards the fields of architecture. It is divided into two chapters. **chapter#5** describes the development of Generative Model while **chapter#6** elaborates the whole optimization model. Thesis is enclosed with Discussion and Conclusion of the research.

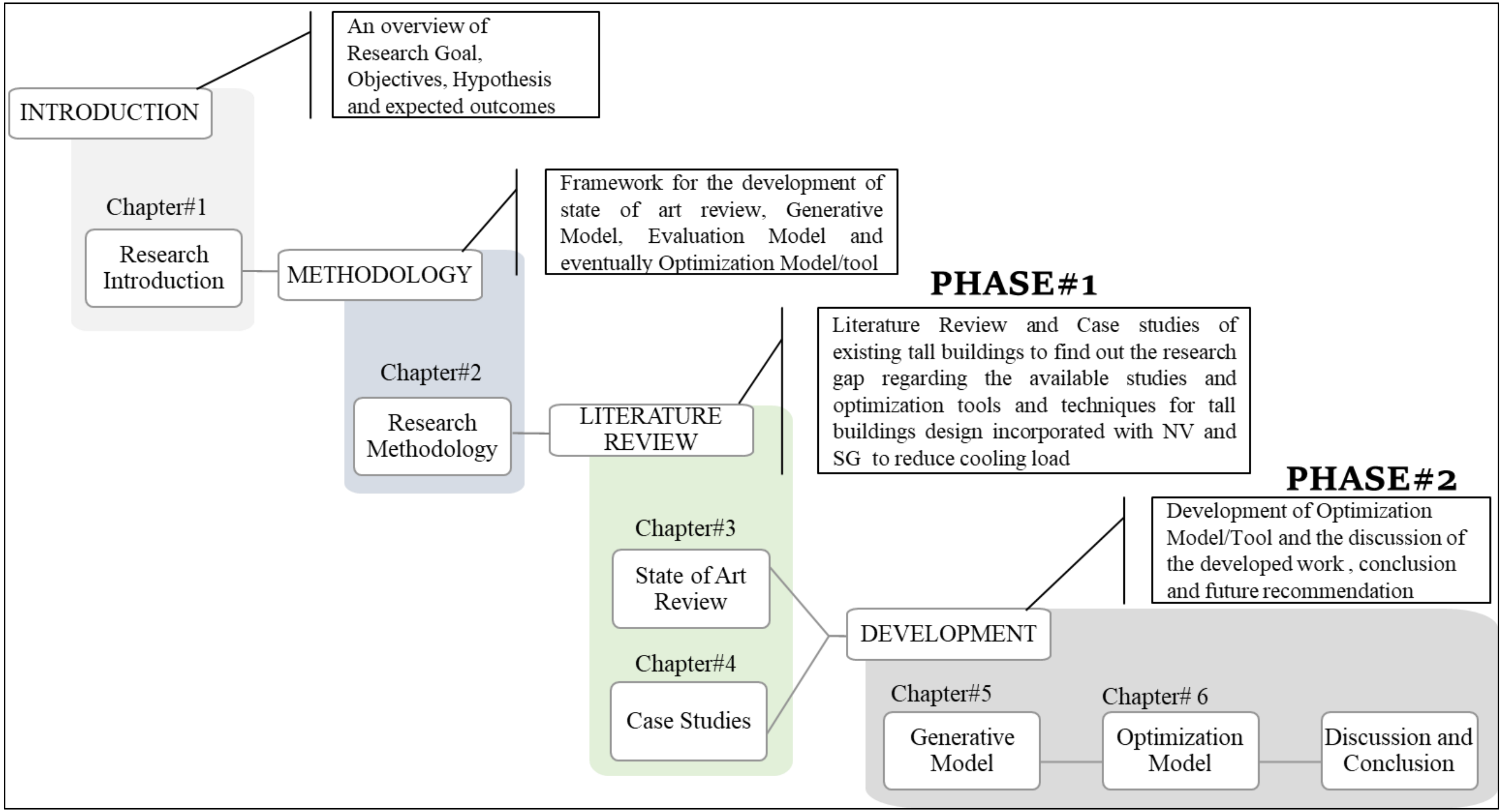



Figure 1 Thesis format

# *Research Methodology*

*This part of the thesis gives a detailed overview of the methodological approach followed to achieve the goal of research. The phases to accomplish all the objectives are demarcated through workflow diagrams.*

# *2 RESEARCH METHODOLOGY*

This chapter gives an overview of the methodology for the development of optimization Model (OM) for the evaluation of potential of NV in tall buildings through the incorporation of SG in hot climates. The methodological approach taken in this study is a mixed methodology based on both qualitative and quantitative approaches. Phase#1 corresponds to the qualitative approach in which already developed research work i.e. peer review articles, conference proceedings, books, thesis, technical reports and online cases of tall buildings have been reviewed to find out the research. It has been hypothesized that the findings of these studies may make a strong base for the second phase. While phase#2 involves the implications of the outcome of phase#1 in order to achieve the final goal through the objectives defined in the first part of the thesis.

## 2.1 Phase#1. Data collection & literature survey

Methodology for phase#1 and its expected output are shown as follows.

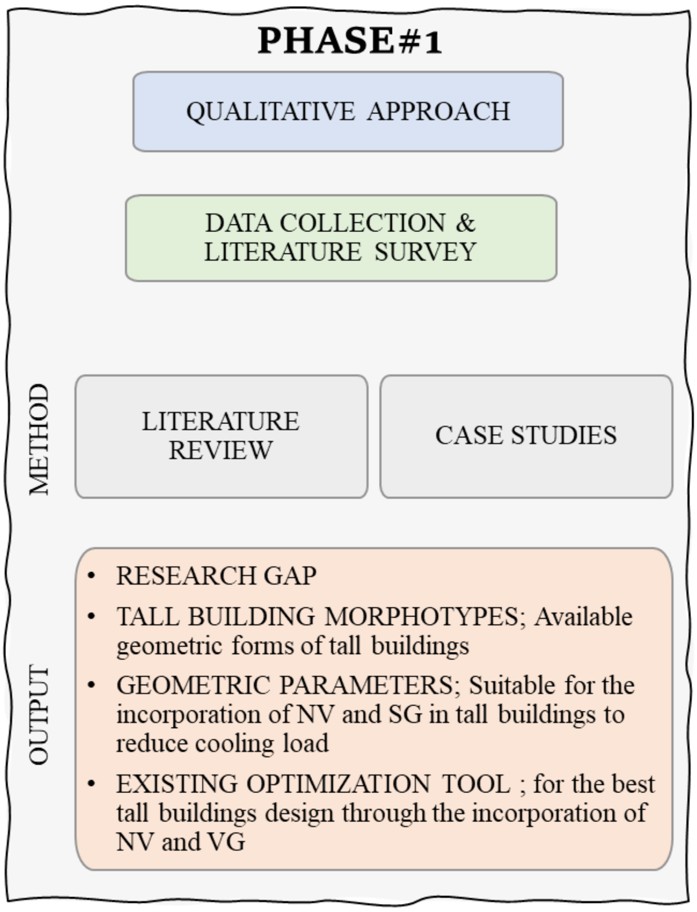



Figure 2 Methodology for pha

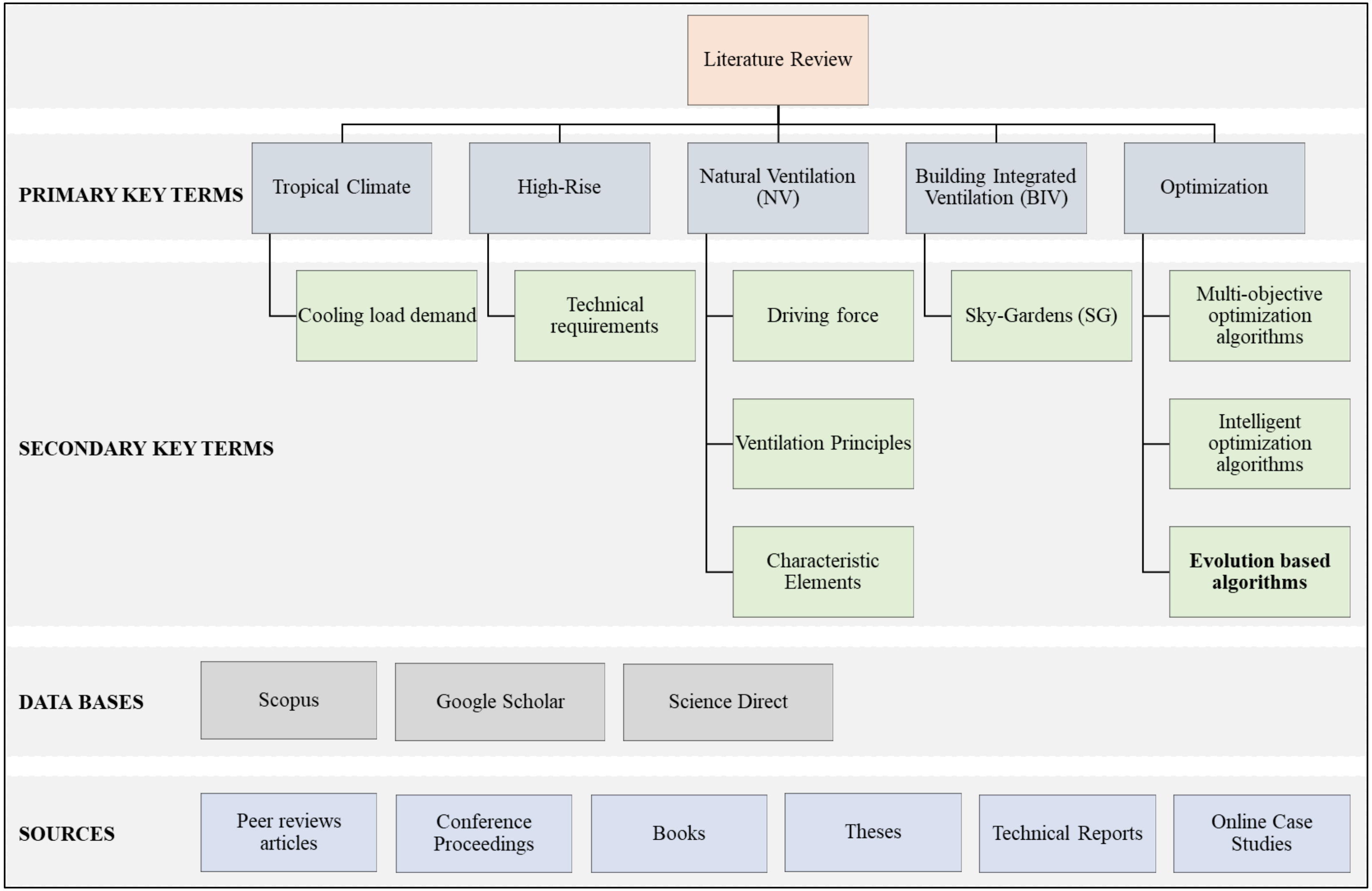



Figure 3 Methodology for literature review

### 2.1.1 Literature review

This phase includes the state-of-the-art review of previous scientific research regarding the implementation of NV and VG in tall buildings. The geometrical characteristics and design parameters of tall buildings for the successful implementation of these strategies are identified in this section. Existing optimization tools available for the successful implementation of NV and VG in tall buildings are investigated and research gap is identified. The workflow to carry out this review of literature is shown in

**Figure** *3*.

### 2.1.2 Case studies

In order to elaborate the impact of identified design characteristics of tall buildings (through findings in literature review) for an effective implementation of NV, ten buildings are chosen.

The goal is to identify the potential of green strategies, design features and geometrical characteristics on the energy performance of these buildings. The methodology to carry out case studies has been shown in **Figure 4.**

The selection criteria for the selection of these cases is based on building height, building use, climate and applied cooling strategies. This criterion defines the building typology. While the geometrical characteristics (of the tall buildings having the potential of reducing cooling load through NV and BIV) define the building morphology (Huybers, 2002). Thus, it is possible to hypothesize that the tall building (morphology + typology) morphotypes derived from these case studies will have the potential of successful implementation of NV and BIV to reduce the cooling load in tropical climate.

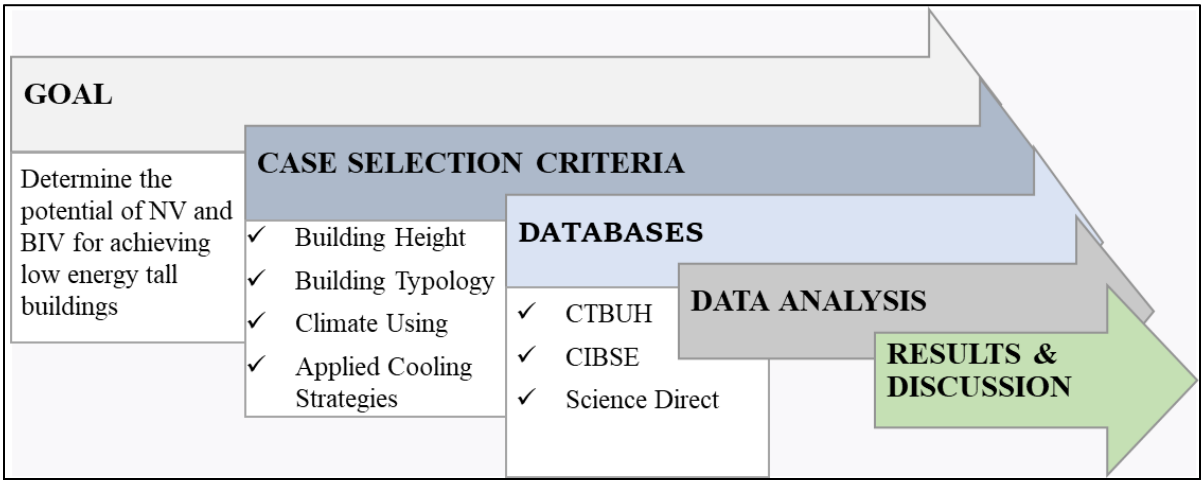



Figure 4 Methodology for case study

The data regarding post construction energy performance, geometrical characteristics and other passive and active techniques used to make these case buildings energy efficient was collected. For this purpose, many journal/conference papers and books specifically by Council of Tall Buildings and Urban Habitat (CTBUH) and the database of Chartered Institution of Building

Services Engineers (CIBSE) were studied. These are the world's huge resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities. Further literature regarding these case studies was gathered through Science direct platform. A sample data sheet is provided in **Table 3**.

The effect of use of NV and VG on the energy efficiency has been noted. The collected data is further analyzed to take out the findings that is supposed to be the base of the development part of research. For the database regarding case studies, a datasheet format was devised that is divided into many sections. The format of datasheet for the case study is composed of nine sections and each section is explained as follows:

1. **Name of building**; This section presents the name of building and logos assigned to the case study based on the incorporation of type of ventilation and building integrated vegetation (BIV) system. These logos are provided in **Figure 5**.

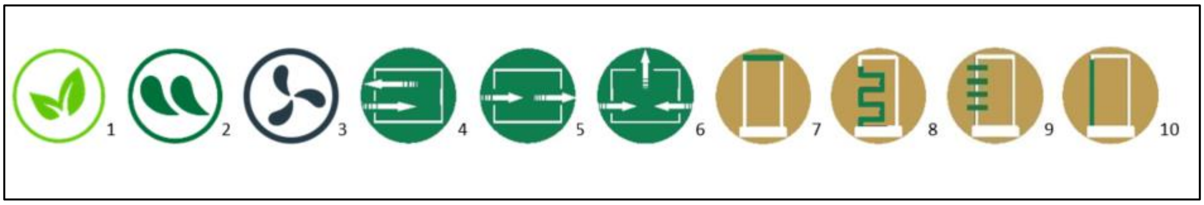



*Figure 5 Logos assigned for case studies*[7]

2. **Building information**: This section describes the basic information regarding case study (e.g. height of building, number of floors, architect of the building, completion year, building type), climate of the place and geographical context (e.g. site context and site typology) and orientation. The geographical data is mainly extracted from the google map tool. Data regarding the number of floors and height of the buildings was extracted from the building drawings and from the descriptive details of buildings provided at the designer's websites.

3. **Climatic data**: This section provides the necessary information regarding the climatic data of each case study region under consideration. The data includes the numerical and graphical description of certain parameters i.e. geographical position of the case building, prevailing wind direction, mean annual temperature, average day time temperature during the hottest months, average day time temperature during the coldest months and mean annual precipitation. These parameters are very important in order to learn the direction of wind and its temperature variation during the year so that it can be understood whether the strategy of using natural ventilation may work efficiently for this building and in this climate or not working.

4. **Building integrated vegetation (BIV) system**; This section gathers the information regarding the type of BIV system incorporated in the building under consideration and its purpose. It may help understand whether the selected system serves the purpose of

[7] 1 represents natural ventilation; 2 represents hybrid ventilation; 3 represents mechanical ventilation; 4 represents single sided NV; 5 represents cross NV; 6 represents stack effect; 7 represents roof garden; 8 represents Sky Gardens; 9 represents vegetative/green balconies; 10 represents green wall

insulation and aesthetics only or it also has some effect on the performance of natural ventilation. Hence, this information may help the designer for selection of BIV system for a similar case.

5. **Ventilation system**: This section gathers the information regarding of type ventilation system being used in a case study and how much it is participating in energy efficiency process.
6. **Energy performance of building**; This section highlights the percentage of annual energy saving for heating and cooling by the case building compared to a conventional air-conditioned building of the same sized and typology, typical annual energy consumption for lighting & electricity and typical annual energy consumption for heating/ cooling. These values are usually post construction simulation results and the source is written in the reference section of the format.
7. **Design strategies for the effectiveness of NV & BIV systems;** This section highlights the presence of favourable design strategies (according to literature review) being adopted to enhance the effectiveness of NV and BIV in tall buildings in tropical climate for reducing energy load.
8. **Architectural elements for the effectiveness of NV & BIV systems;** This section indicates the presence of favourable architectural element (according to literature review) being adopted to enhance the effectiveness of NV and BIV in tall buildings in tropical climate for reducing energy load.
9. **Source:** This section reports the source of data collection.

Table 3 Datasheet for case studies

| **NAME OF BUILDING** | | | |
|---|---|---|---|
| Logo | | | |
| **BUILDING INFORMATION** | | | |
| Building location | | Architect/Design Team | |
| Completion year | | Site Context | |
| Building type/s | | Site Typology | |
| Building height (m) | | Climate Type | |
| No. of floors | | Orientation | |
| **CLIMATIC DATA** | | | |
| Geographical position | | | |
| Prevailing wind direction | | | |
| Average wind speed (m/sec) | | | |
| Mean annual temperature | | | |
| Average day time temperature ($^{o}$C) | Hottest months (June, July, August) | | |
| | Coldest months (Dec., Jan., Feb.) | | |
| Difference between Day/Night temperature (%) | Hottest months (June, July, August) | | |
| | Coldest months (Dec., Jan., Feb.) | | |
| Mean annual precipitation (mm) | | | |

| | | |
|---|---|---|
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | |
| Type of BIV system | | |
| Location on the building | | |
| Surface area of green coverage ($m^2$) | | |
| **VENTILATION SYSTEM** | | |
| Ventilation type | | |
| Natural ventilation principle | | |
| Approximate percentage of the year natural ventilation can be utilized | | |
| **ENERGY PERFORMANCE OF BUILDING** | | |
| Annual energy saving for (%) | Heating and Cooling | |
| | Lighting & Electricity | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | |
| Segmentation | | |
| Location of air shaft | | |
| Overall building shape/form | | |
| Plan depth | | |
| Plan shape | | |
| Shape of air shaft | | |
| High ceiling height (to enhance stack effect) | | |
| Night-time ventilation | | |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | |
| Wing wall | | |
| Wing roof | | |
| Double skin façade/Rain screen/Brise-soleil | | |
| Wind catcher | | |
| Lobbies | | |
| Operable window | | |
| Shading devices | | |
| **SOURCE** | | |
| References | | |

## 2.2 Phase#2. development of optimization tool

This Phase makes use of the outcome of the scientific research and case studies done in first phase of research as a scientific base for the development of optimization model (OM). Optimization is a process to find the values of input for developing the best solution.


Figure 6 Optimization

A variety of optimization algorithms are available for finding the optimum solution for design problems, which are efficient and accurate e.g. direct search and model-based algorithms. However, for architecture design problems, genetic algorithm is found to be the most widely practiced optimization method. Genetic algorithm is inspired by Charles Darwin theory of natural selection (Schwehr, 2010). According to this theory only favorable traits (adaptable to the environment) can survive in long term and the selection of these traits is done by natural selection process to produce next generation (Eiben & Smith, 2003; Granadeiro, Pina, Duarte, Correia, & Leal, 2013).

This phase demonstrates the implementation genetic algorithm for the developed optimization model, advantages and disadvantages associated with this model and conclusion of the whole research together with the future recommendation. **Figure 7** shows the methodology used to carry out the research in for this phase.

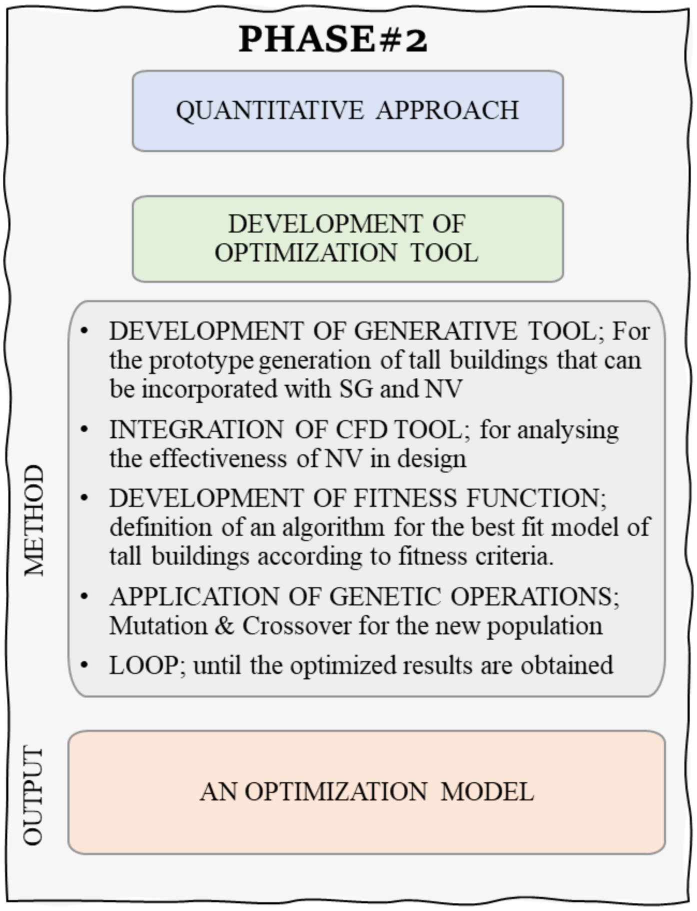



Figure 7 Methodology for phase#2

The development of generative model (GM)[8] involves the development of a generative algorithm for the generation of 3D models of tall buildings with multiple geometric external forms and arrangements of floors at horizontal level as well as on vertical level to create an overall spatial diversity of form using a variety of 'genetic codes'. We call 'genetic codes' here to the arrangement of input variables needed for each design variation. The models produced by the genetic code are then put into an optimization loop, starting from a randomly generated population and then evaluating the set of models using a performance evaluation software, selecting the best half, doing some genetic operations (crossover or mutation) on a small part of the population as explained ahead, adding some additional randomly generated designs and

[8] Generative model may also be termed as generative tool in this study, as it can used solely for the exploration of tall building 3D-models for various design purposes.

repeating this procedure until the evaluations stabilize on a high performance level. This is roughly the description of an evolutionary procedure (Marzban, Ding, & Fiorito, 2017) based on Darwin's law of survival of the fittest (Back, 1997; Câmara, 2015; X. S. Yang, 2014).

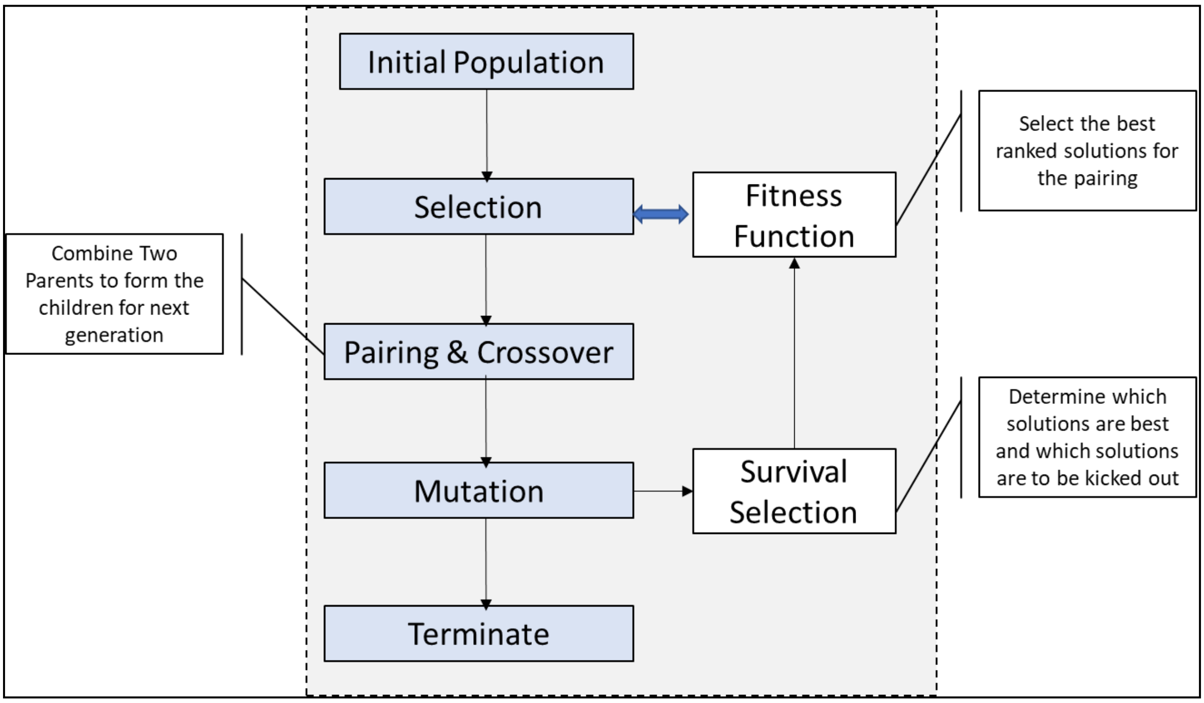



Figure 8 Generic evolutionary optimization model (B. Wang & Malkawi, 2015)

It is considered to be the most suitable for the complex architectural problems because of the following facts:

- the elimination (that is based on the fitness criteria), does not allow every random chromosome to evolve to participate in the next computing loop so every next generation is better than the previous one (Fasoulaki, 2007)..
- It is parallel method for finding solutions as it works on whole population for evaluation and selection simultaneously (Fasoulaki, 2007).

### 2.2.1 Development of a generative model (GM)

GM should be capable to develop 3D-Models of tall buildings with the geometrical characteristics guided through the outcome of case studies and literature review. Each model has unique set of chromosomes, termed as genetic code.

**Figure 9** shows the methodology adopted for the development of Generative tool. It involves three stages – (i) Decision of input variables[9] that involves the selection & classification of building morphotypes and geometrical characteristics of 3D model of tall building (definition

[9] Input variables are geometric characteristics of tall buildings, commonly used for enhancing the effectiveness of natural ventilation and reducing the cooling load. It involves the classification of tall building morphotypes and associate such morphotypes with typical geometric features needed to elaborate a generic parametric model.

of a genetic code for all morphotypes), (ii) the definition of the generative algorithm[10] able to generate all the variations of the identified morphotypes: and (iii) Output, in the form of 3D model generation[11] and their characteristic genetic code (Granadeiro et al., 2013).

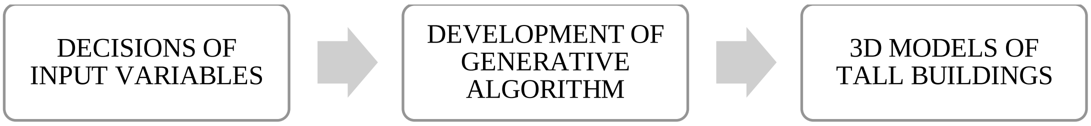



Figure 9 Workflow for the development of generative tool

### 2.2.2 Evaluation model

#### *2.2.2.1 Integration of a CFD simulation tool*

that can analyses the NV process of the 3D-Model developed by the generative tool and provide the results that can be stored in working directory in excel sheets.

#### *2.2.2.2 Development of fitness function*

Fitness function is the function to be optimized. This function takes the solution as an input and produces the fitness of the solution as an output (in other words ranks the solution). In the proposed model fitness function takes the geometrical characteristics of the models and the results obtained through CFD simulation and rank the model as an output, from worst to best result assigning values 0 to 10, where 0 means worst and 1 represents best. The fitness criteria are decided to be:

- Optimum wind velocity
- Optimum air-temperature
- Maximum gross floor area

### 2.2.3 Evolutionary model

Last step is the implementation of evolutionary process through, selection of the best fit genes, application of genetic operations i.e. Mutation and crossover for the generation of new population of better genes and Looping the whole process until the best fit results are obtained (X. S. Yang, 2014). The workflow for this model is shown in **Figure 10**.

[10] generative algorithm is programmed on "Grasshopper" that is a visual parametric programming interface and its output can be visualized on "Rhinoceros" as 3-D Model visualization interface. Grasshopper provides the opportunity to use graphical algorithm editor integrated with Rhinoceros 3D modelling and does not require previous knowledge of programming or scripting allowing designers to easily develop the needed geometry generators.

[11] multiple prototypes of 3D Models of tall buildings with different forms and shapes including different levels or floors are developed by varying the input variables that were identified on the first stage.

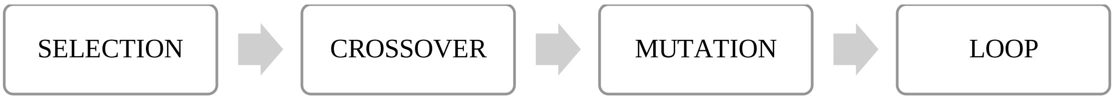
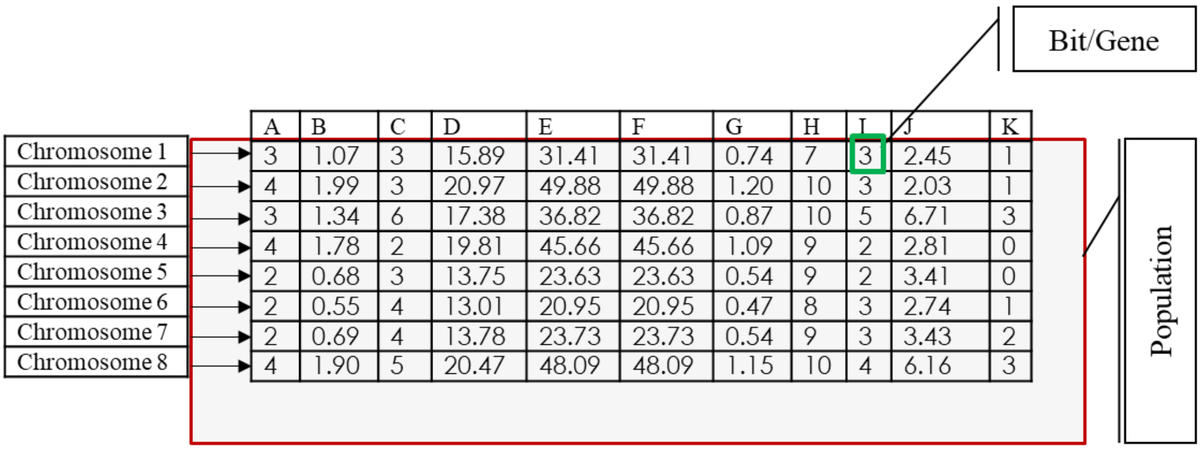



Figure 10 Genetic operators

Genetic Operations makes the use of database of genetic codes of tall building models to perform the genetic operations and inform the generative algorithm to produce the model that can be best fitted as compared to the older ones.

In order to understand the evolutionary process, it is important to know the terminology and how these operators are performed. Total number of genes of candidate solutions (i.e. a set of phenotypes or individuals) are termed as population. Every individual has a set of properties composed of string of genes that is termed as chromosome while each gene in the string of chromosome represents one property of the individual (in this case it is geometrical property). According to this theory the input variables generating the models are called population (Eiben & Smith, 2003). The case shown in the **Figure 11** is having a sample of eight individuals/tall building model and a population of 88 genes. Every individual is having a chromosome and the string of chromosome is composed of 11 genes. These genes represent the geometrical characteristics of tall building. These strings of chromosomes are termed as genotypes and the tall building models having these genotypes are termed as phenotypes shown in **Figure 12**.




| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chromosome 1 | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| Chromosome 2 | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| Chromosome 3 | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| Chromosome 4 | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| Chromosome 5 | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |
| Chromosome 6 | 2 | 0.55 | 4 | 13.01 | 20.95 | 20.95 | 0.47 | 8 | 3 | 2.74 | 1 |
| Chromosome 7 | 2 | 0.69 | 4 | 13.78 | 23.73 | 23.73 | 0.54 | 9 | 3 | 3.43 | 2 |
| Chromosome 8 | 4 | 1.90 | 5 | 20.47 | 48.09 | 48.09 | 1.15 | 10 | 4 | 6.16 | 3 |

Figure 11 Gene pool/population of a set of random solutions; an example to explain terminology

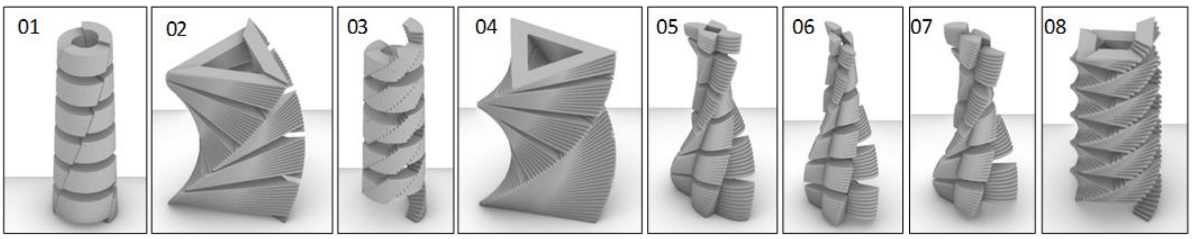



Figure 12 Phenotypes corresponding to the genotypes presented in Figure 9.

### *2.2.3.1 Selection*

After the evaluation of initial population through fitness function, the best fit individuals are selected for pairing, crossover and mutation to make new population. The evolution theory suggests that the new population should be better according to fitness function than the previous generation as it is inheriting the best genes.

### 2.2.3.2 Crossover

Swapping parts of the genetic code of the solution with another in chromosomes or solution representations. The main role of this operation is to provide mixing of the solutions and convergence in a subspace. Commonly used types of Crossover are:

✓ ***One-point crossover***

In this one-point crossover, a random crossover point is selected and the tails of its two parents are swapped to get new off-springs.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Parent 1 | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| Parent 2 | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| Child 1 | 3 | 1.07 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| Child 2 | 4 | 1.99 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |

✓ ***Multi-point crossover***

Multi point crossover is a generalization of the one-point crossover wherein alternating segments are swapped to get new off-springs.

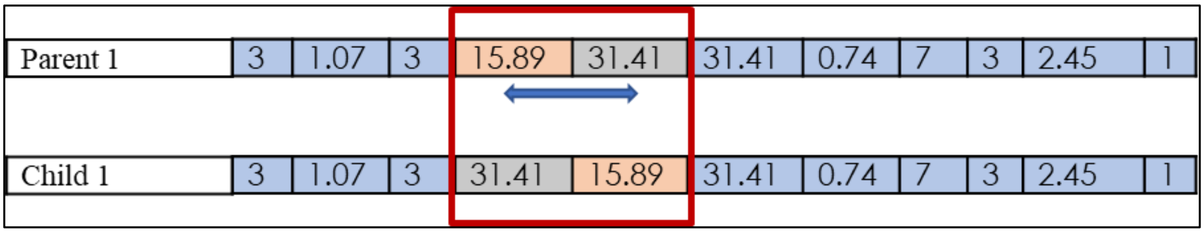
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Parent 1 | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| Parent 2 | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| Child 1 | 3 | 1.07 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.45 | 1 |
| Child 2 | 4 | 1.99 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.03 | 1 |

### 2.2.3.3 Mutation

The change of parts of genetic code of one solution randomly, which increases the diversity of the population and provides a mechanism for escaping from a local optimum. Commonly used types of mutation are:

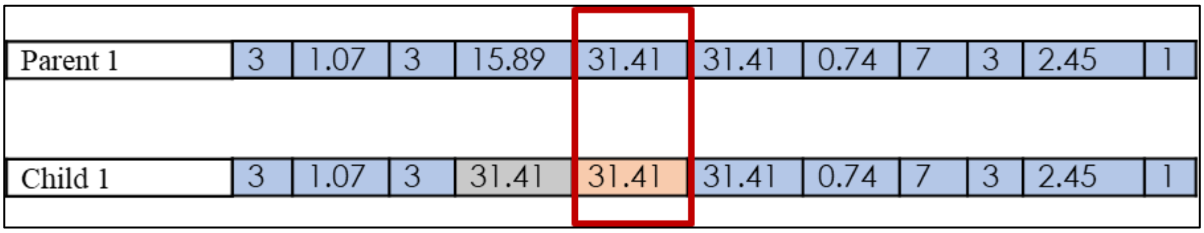
✓ ***Swap mutation***

In swap mutation, we select two positions on the chromosome at random, and interchange the values.




- ***Bit flip mutation***

In this bit flip mutation, we select one or more random genes and flip them.




### *2.2.3.4 Loop*

After the selection process of new population according to the fitness function, it is decided whether the solution is best or worse among the set of solutions/ considered population. If the whole population is extremely bad, only best of the extremely bad solutions are selected, hence the need to perform as much iterations as possible become important to get the optimum solution. The more the number of the iteration the better will be the solutions because selection will always move away the worst ones. This process continuous to go on and on in a loop until the best solutions show no more improvement.

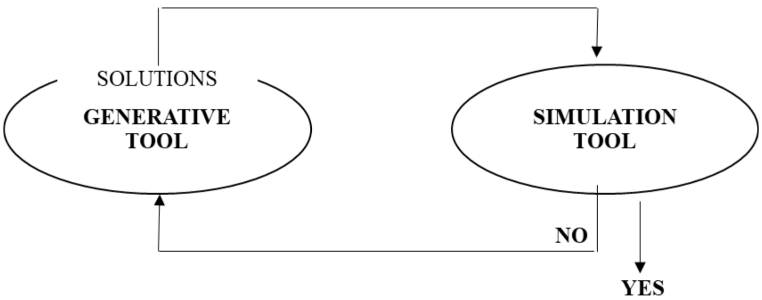



Figure 13 Loop of optimization model

Hence the eventual proposed optimization model comprising of Generative tool (GT) and evolutionary algorithm as shown in **Figure 14**.

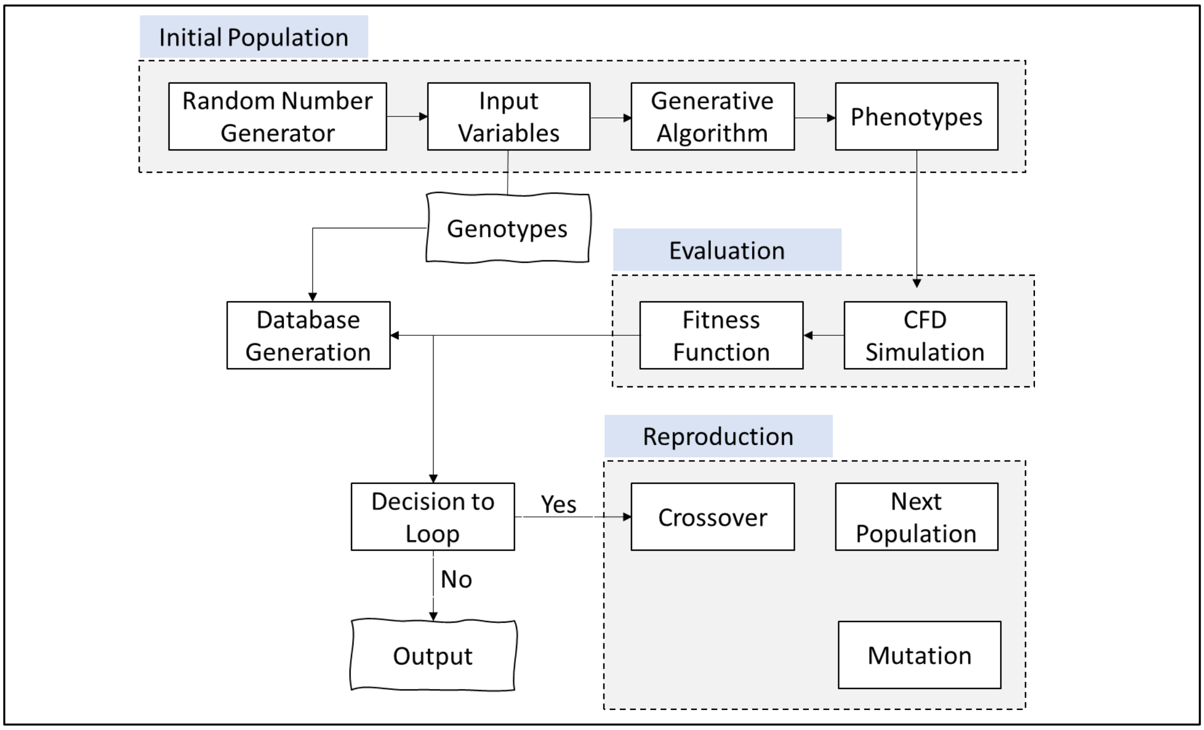



Figure 14 Proposed optimization model

## 2.3 Tools

**Tools Used** for this whole process are provided in **Table 4**.

Table 4 Tools used for developing generative models

| Tool | Application | Description | Ref. |
|---|---|---|---|
| Rhinoceros | Visualizing 3D Model and CFD simulation results | Rhino is CAD platform for 3D-modelling. It is, however, more than just a modeller. It has a rich ecosystem of plugins and an open set of development tools, thus rapidly becoming the development platform for the curious designers (architects and engineers). | ("Rhinoceros," 2019; Tedeschi, 2014) |
| Grasshopper | Visual Programming | Grasshopper is a graphical algorithm editor integrated with Rhinoceros. It does not require programming or scripting skills, but still allows developers and designers to develop form generation algorithms without writing code. It is the most suitable algorithmic tool for architects who do not have computer programming languages background. | ("Rhinoceros," 2019; Tedeschi, 2014) |
| RhinoCFD | CFD simulation | RhinoCFD is a computation fluid dynamics tool for simulation of design solutions and is compatible with the CAD environment of Rhino3D. It helps the designers to simulate their models without leaving the Rhinoceros environment. | (A, Dyer, Glynn, & Michel, 2017; Ahmed, Carmichael, Glynn, & Michel, 2019) |
| Microsoft Excel | Database of simulation results, genetic codes and optimization results | Integration of excel in Grasshopper for reading and writing database is a new feature. New plugins like "Lunchbox" make use of excel as a moderator to exchange the data between grasshopper and excel. | (Miller, 2019) |

# *Literature Review*

*This part of the thesis is composed of chapter#3 and chapter#4. In this part, a state-of-the art literature review of suitable strategies i.e. natural ventilation (NV) and building integrated vegetation (BIV, for tall building in tropical climate to reduce the cooling load is performed. Important aspects that need to integrate these two passive strategies in tall buildings are determined using case studies of existing buildings located in tropical climate. Need for optimization tools to generate a building geometry based on NV and BIV is determined.*

*A conference paper has been written from chapter#3 by the author in "International Conference on Seismic and Energy Renovation for Sustainable Cities (SER4SC)" under the title "Role of sky gardens in Improving Energy Performance of Tall Buildings."* (Mughal & Corrao, n.d.)

*A conference paperer has been written from chapter#4 by the author in ProDPM'19 Conference Proceedings "Progress on Digital and Physical Manufacturing" under the title "Potential of Natural ventilation and Vegetation for achieving low-energy tall buildings in tropical climate: An overview"* (Mughal & Beirão, 2019b)

# 3 LITERATURE REVIEW

Tall buildings are not only symbolic of modern urban landscape but also help accommodate high occupancy demands of residential and commercial areas. High urban population density in cities and in mega cities have to accommodate a huge number of tall buildings to meet the needs of the increasing urban population. It is projected that the world urban population will be 66% by year 2050 (United Nations, 2018); therefore, the need for tall buildings will continue to increase with time. Sometimes, tall buildings construction can be driven by reasons other than low-land availability that may include associated profit, prestige and/or creativity (Hamilton et al., 2017). Despite a number of economic and social benefits associated with tall buildings, a number of negative environmental impacts such as use of high amounts of energy and negative impacts on human health can occur if these buildings are not properly designed (Gifford, 2007). Therefore, the focus of designers and planners should not only be on producing beautifully designed tall building but on production of optimally designed sustainable building that is both visually appealing and environment friendly (Liming, Haque, & Barg, 2008).

Globally, buildings account for 40% of end-use consumption and major portion of the carbon emissions from buildings is associated with the operational energy use (Atmaca & Atmaca, 2015). Heating and cooling systems of the building are the major consumers of this energy. Bastide et al., (2006) showed that for a standard building, heating, ventilation, air-conditioning (HVAC) systems account for 50% of the total operational energy. As world temperature rises the cooling load demands will increase. This demand will be especially critical for tall buildings located in tropical climate regions. Hence, it is essential that tall buildings in tropical climate are made energy efficient as soon as possible to reduce the carbon emission and impact on environment.

Sometimes, tall buildings construction can be driven by reasons other than low-land availability that may include associated profit, prestige and/or creativity (Hamilton et al., 2017). Despite a number of economic and social benefits associated with tall buildings, a number of negative environmental impacts such as use of high amounts of energy and negative impacts on human health (Gifford, 2007) can occur if these buildings are not properly designed. Therefore, the focus of designers and planners on tall buildings is not only in producing beautiful designs but to optimize design ensuring that the building is able to fulfil their intended purpose with a sustainable use of energy and other resources.

In order to achieve carbon mitigation targets and achieve long-term sustainability goals it is essential to make energy efficient buildings. Buildings can be made greener by use of energy efficient strategies (example: better building envelope or more efficient lighting). Studies have shown that taking energy efficiciny initiatives from the earliest design stage results in higher energy and resource savings (Deru et al., 2003). **Figure 15** shows how the energy saving potential decreases during different cosntruction stages of a building. The degree of effort needed to achive these savings also increase with time.

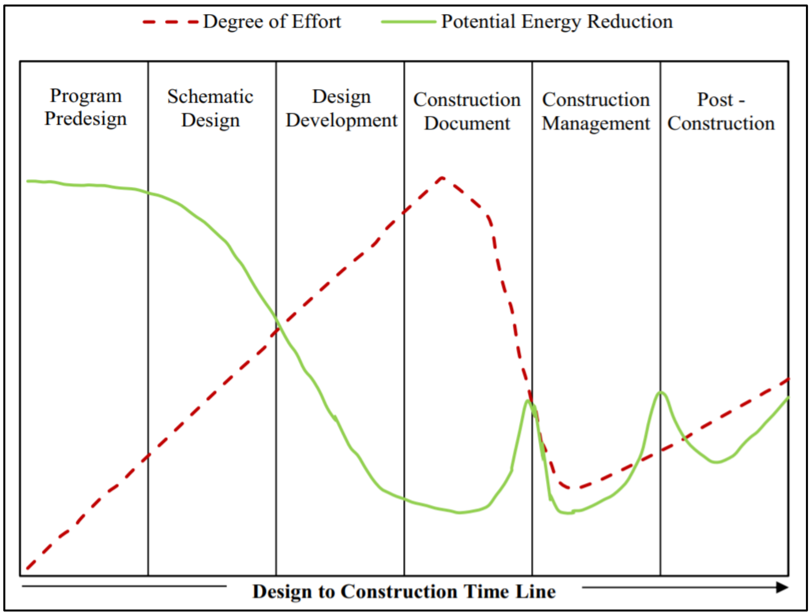



Figure 15 Potential energy savings at different stages of a building construction (X. Chen, Yang, & Wang, 2017)

Climate is an important parameter that effects the energy performance if a building. Attia et al., (2013) investigated the importance of climate conditions for making building design decisions. Technical and architectural solutions can be used to improve energy performance of buildings. Thermo-physical properties of building envelope are especially important for obtaining comfortable indoors and improved energy performance in tall buildings located in tropical climate (Manioğlu & Yilmaz, 2008). However, improvement of these properties through improved architectural design is a complex process. This complexity is due to high humidity levels and daytime temperatures that increase indoor temperatures much higher than comfortable temperature limits defined by ASHRAE (26$^{0}$C) (Hyde, 2012; M. Al-Tamimi, Syed Fadzil, & Wan Harun, 2011).

The most promising strategy for tropical and subtropical climates is natural ventilation (NV) and should be incorporated into the building design (Haase & Amato, 2006). Due to climate change, naturally ventilated buildings located in hot climates can face problems such as higher over-heating hours and need for longer duration for open windows in the winter months in mild and cold climates (Carrilho da Graça & Linden, 2016). Implementation of vegetation in tall buildings can help decrease the effect of climate change locally (i.e. at building scale) together with a decrease in the carbon footprint while producing healthier living spaces for building users at a reduced cooling load (Babak Raji et al., 2015).

The outcome of this chapter is a detailed theoretical background needed for developing an understanding of natural ventilation (NV), sky gardens (SG) and their use in tall buildings located in tropical climate. The information gathered from this state-of-art review is essential for achieving the research objectives provided in introduction chapter.

## 3.1 Passive strategies for tall buildings

Tall buildings can be made sustainable by making use of exising active and passive stratgies (**Table 5**). In recent years, the importance of passive stratgies has increased due to the lower investment and energy saving potential. Since, the buildings located in tropical climate are subject to high humidty and temperatures all year round special attention needs to paid to the type of stratrgy employed for obtianing an energy efficient building with comfortable indoors.

Table 5 Active and passive strategies for tall buildings (X. Chen, Yang, & Lu, 2015)

| Type | Description | Examples |
|---|---|---|
| Passive | Passive strategies enable building energy saving by better designed building envelope features | • Change in building layout<br>• Geometry<br>• Envelope materials |
| Active | Active strategies enable building energy savings by use of more energy efficient building systems | • Energy efficient heating, ventilation, air-conditioning (HVAC) systems<br>• Energy efficient hot water production<br>• Energy efficient lighting<br>• Building services application |

Passive strategies are defined as energy saving strategies that are based on architectural elements such as building layout, building geometry, thermos-physical features of envelope, proper construction that include air-tightness and infiltration (X. Chen & Yang, 2016). Application of passive strategies in tall buildings have proven to save energy (X. Chen et al., 2017). These strategies have also been proposed as an energy reducing measure in a number of green building guidelines such as LEED, BEAM, BREEAM (Lee, Yik, & Burnett, 2007). Application of some passive strategies such as green roofs and ground cooling have limited benefits for tall buildings due to smaller roof and site coverage (X. Chen & Yang, 2018). Studies have shown that there is need to improve passive strategies for buildings located in tropical climate. Focus of these strategies should be on improving the air interacting with building envelope so that comfortable indoors are obtained (Garde, Adelard, Boyer, & Rat, 2004; TURIEL, CURTIS, & LEVINE, 1984).

Buildings located in tropical climate are subject to long daytime temperatures; hence, higher cooling loads need to be addressed. For such climates, natural ventilation (NV) has been found to be most effective passive cooling strategy that enables comfortable indoors with lower dependence on mechanical systems (Haase & Amato, 2006; Nguyen & Reiter, 2014). Tall buildings present in tropical regions average temperature and air movements remain constant throughout the year (Mirrahimi et al., 2016). Hence, NV strategy can be applied for buildings subject to such constant conditions.

A set of bioclimatic principles have been introduced for high-rise building in tropical climate by Yeang, (1997) who used a series of high-rise buildings to test these principles to achieve two main goals i) Occupant comfort and ii) energy reduction. Based on these tests he has suggested a predesigned checklist for the design of high-rise buildings in tropical climate. These principles include Building plan shape and depth (shapes with reduces resistance to the incoming wind i.e. and narrow plan depth), Incorporation of NV, Location and shape of air shaft/central core (should located along the facade in order to provide a buffer space), incorporation of BIV systems (Green wall, green balconies, roof garden, vegetated terraces and sky gardens), balconies and terraces with the incorporation of sky gardens/ Sky courts, Lobbies located on external façade (to reduce the need of artificial light), environment interactive external façade(providing transitional space), Curtain wall location at north and south so that maximum heat and sun can enter in winter while can be avoided in summer through designed shading devices (Ismail, 2007).

Hence, in order to achieve thermal comfort as well as energy load in tall buildings located in tropical climate, all the above principles should be adapted. These parameters help reducing the energy load, but the most important principle is the incorporation of NV and sky courts are these strategies' complement each other for reduced energy load

and all the other principle help improving the performance of these two strategies(S. F. Alnusairat, 2018; S. Alnusairat, Jones, & Hou, 2017).

## 3.2 Natural ventilation strategy

Ventilation is defined as the intentional process of providing fresh and clean air to a to be ventilated and removing stale air from it. This mechanism can be achieved through

natural, mechanical or a combination of natural and mechanical (Hybrid) system (Allard, Santamouris, & Alvarez, 1998; Asfour, 2015).

Table 6 Types of ventilation in buildings

| Type | Definition | Impacts |
|---|---|---|
| Natural | The naturally ventilated building is the type of building in which the building air exchange is driven by the natural force of wind or temperature (Liddament, Axley, Heiselberg, Li, & Stathopoulos, 2006) | • NV system can be maintenance free (Delsante & Vik, 2002) |
| Mechanical | The mechanical devices are used to force air in and out of the building (Prajongsan, 2014) | • Improved control over the air flow |
| Hybrid | The building equipped with a hybrid ventilation system, which is a two-mode system capable of providing a comfortable indoor environment using natural and mechanical forces according to the dynamic indoor and outdoor environment (Heinonen & Kosonen, 2000) | • Higher energy savings compared to mechanical ventilation (Lim, Yun, & Song, 2015)<br>• Amenity to occupants to interact with nature outside (Lim et al., 2015)<br>• Uncertainty related to thermal comfort in NV is removed (Karava, Athienitis, Stathopoulos, & Mouriki, 2012) |

When the exchange of the air is taken place through the designed openings i.e. windows, ventilators, central air shaft due to natural fluid dynamics characteristics of the wind/air, it is termed as natural ventilation (NV) (The Chartered Institution of Building Services Engineers (CIBSE), 2014). This approach is becoming more important strategy as it is passive and cheaper unlike mechanical ventilation that requires installation, operational and maintenance cost together with the fact that it is not even healthy strategy. Furthermore, occupants give preference to natural ventilation and natural light through window and balcony. However, if this strategy has to be applied to the building successfully, it should be planned an designed from the early stage of the design (Asfour, 2015; The Chartered Institution of Building Services Engineers (CIBSE), 2005). If properly designed and successfully implemented, NV can bring the many benefits i.e. increased user satisfaction, reduced energy consumption, reduced carbon footprint, cooling building structure, comfortable indoors, improved productivity and improved air quality that result in reduction in health issues that can occur due to mechanical ventilation system e.g. sick building syndrome.

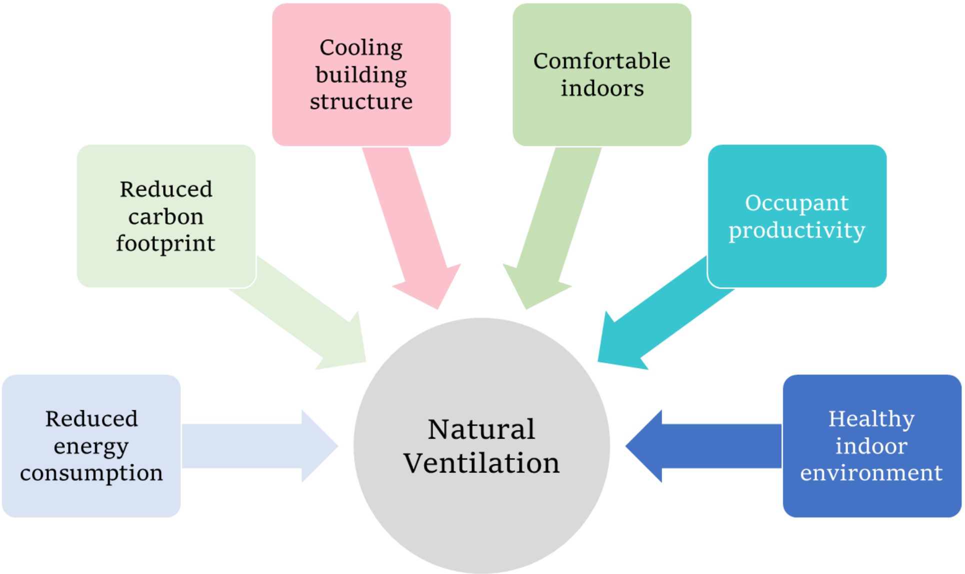



Figure 16 Advantages of natural ventilation

Despite these benefits, some challenges are also associated with NV. The biggest problem is change in outdoor environment that can result to insufficient performance of building to provide comfortable indoors. Hence a strict weather constraint needs to be used when designing NV in tall buildings.

According to Haase et al. (2006) NV is found to be the best cooling strategy for building in tropical and subtropical climatic regions. However, climate change and UHI effect in hot climatic region are triggering an additional increment in rise of temperature of outdoor air (Carrilho da Graça & Linden, 2016), so there is great need to integrate an additional cooling technique e.g. vegetation (VG), at least at micro level i.e. building

scale , to not only reduce the temperature of the air coming inside the building but also to purify it before letting it enter inside the building (Babak Raji et al., 2015).

### 3.2.1 Measuring natural ventilation

Natural ventilation for a building can be defined by consideration of three main aspects: (1) Driving forces; (2) Ventilation principle and (3) characteristic elements.

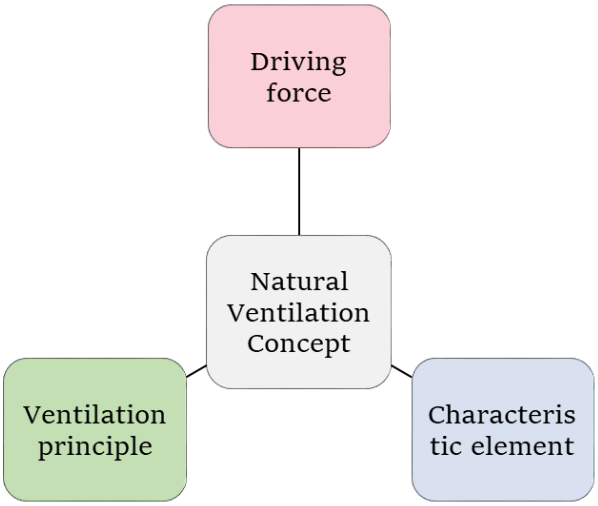



Figure 17 Natural ventilation concept (Kleiven, 2003)

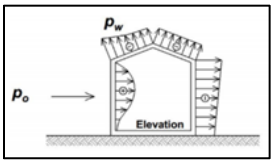
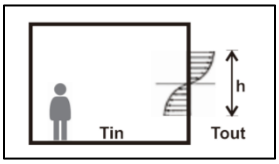
Table 7 Three aspects of natural ventilation (Kleiven, 2003)

| **Aspect** | **Description** | **Types** |
|---|---|---|
| Driving Force | Force that allows air movement, so ventilation takes place. | • Wind<br>• Buoyancy<br>• Combination of both |
| Ventilation principle | The principle used to govern the driving force. | • single-sided ventilation<br>• cross ventilation<br>• stack ventilation |
| Characteristic elements | Elements of the building that are used to realize natural ventilation | • wind towers<br>• wind scoops<br>• chimneys<br>• double façades<br>• atria<br>• embedded ducts |

#### *3.2.1.1 Driving forces*

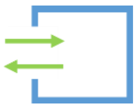
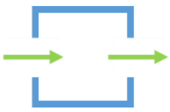
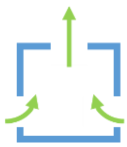
Natural ventilation mechanisms are based on the change in pressure between the indoor and outdoor. The difference allows the movement of air in and out of building (Awbi, 2007). Two driving forces: (1) wind force and; (2) buoyancy or stack govern the pressure difference (Kleiven, 2003) in natural ventilation.

Table 8 Driving forces for natural ventilation

| **Type** | **Graphical** | **Definition** |
|---|---|---|
| Wind Force |  | Wind driven ventilation occurs as a result of various pressures created on the building envelope by wind. These pressure differences drive air into the building through openings in the building envelope's windward side, and drive air out of the building through openings in the building envelope's leeward side (Kleiven, 2003; Prajongsan, 2014) |
| Buoyancy force/Stack |  | Thermal buoyancy or Stack driven ventilation occurs when there is a density difference between the internal and external air, which again is caused by temperature differences between the inside and outside. Thermal buoyancy is sometimes referred to as the stack effect or the chimney effect(Prajongsan, 2014) |

### 3.2.1.2 *Ventilation principles*

Table 9 Natural ventilation types-based on ventilation principles

| **Type** | **Graphical** | **Definition** |
|---|---|---|
| Single-Side |  | Single-sided ventilation is the principle when natural ventilation enters and leaves a building either from the same opening, or from another opening(s) that is situated on only one side of the ventilated space (Awbi, 2007; J. Chen, 2018) |
| Cross-Ventilation |  | Cross ventilation or two-sided ventilation is a principle whereby air enters into a room (or a building) from an opening(s) on one side, sweeps through the indoor space and leaves the room through an opening(s) on another side (which is located either on the opposite wall or the adjacent wall) (Awbi, 2002; J. Chen, 2018) |
| Stack Ventilation |  | Stack ventilation is a useful principle when the required indoor air movement cannot be achieved solely by wind effect. In such situations stack effect can be used as an additional driving force (J. Chen, 2018; Prajongsan, 2014) |

### 3.2.1.3 *Characteristic elements*

Architectural elements for the implementation of natural ventilation in tropical climate are

**Courtyards:** these are also termed as light well or void when it comes to tall building. They have opening at the bottom and on the top so the air get inside through the bottom opening and reached the top to exhaust (Kotani, Satoh, & Yamanaka, 2003).

**Atrium:** Just like courtyard, it is also characterized as the central feature of the high-rise building that may help channelize the air flow through the building, it may however be located along the façade of the building (Ismail, 2016). It takes the warm air from the adjacent floors and exhaust it. Just like courtyards/voids/ lights wells it works due buoyancy force and mostly is channelizing stack ventilation (Holford & Hunt, 2003).

**Windows:** these are the opening, with various sizes and shapes on the building façade. The air is exchanged in a space inside the building through these openings. They work usually on wind-driven ventilation principle however sometimes NV through windows occur due to buoyancy affect depending on the location of the window on the façade. both driving forces i.e. wind and buoyancy are affective for this element and the wind is channelized through cross, single sided or stack ventilation depending on the location of exhaust window (Kleiven, 2003).

**Balconies:** these are private outdoor spaces located at various floor levels above the ground floor. It is generally using single sided ventilation and is driven by wind force. Balconies reduce the wind pressure on the façade by the amount depending on its size and location (Omrani, Garcia-Hansen, Capra, & Drogemuller, 2017).

**Wind catcher:** These are the elements just like voids/light shell/ atrium with a height from 5 to 33 meters, however the flow of air for ventilation is opposite in this case as they capture wind from external top air stream and induce it into the building and courtyard. The openings of these elements can be one sided to six sided and use stack affect to channelize the wind (Montazeri & Azizian, 2008).

### 3.2.2 Parameters governing natural ventilation

The feasibility and efficiency of acceptability of enactment of NV in the tall building design in tropical climate regions highly depends on the inputs: climate conditions, windows opening schedule, materials of construction, urban context, and number of Occupants and their behavior (Elotefy, Abdelmagid, Morghany, & Ahmed, 2015a; Oropeza-Perez & Ostergaard, 2014; A. Wood & Salib, 2013). These parameters are deliberated below.

#### *3.2.2.1 Climate*

Climate is very important for the best implementation of NV, as in hot climate the summers are longer and so the NV strategy may work in such climates longer period of the year causing reduced annual energy consumption. Furthermore, the direction and speed of wind, air temperature and humidity are important parameters to for the implementation of this strategy.

In hot and humid climate, effectiveness of NV for energy saving can be achieved using low heat capacity construction material. This combination will help reducing indoor air temperature. While in hot dry climate a combination of high heat capacity material and natural ventilation is most suitable one for reduction in energy consumption. Hence, not just climate, choice of material of construction is also important in enhancing the effectiveness of NV (Oropeza-Perez & Ostergaard, 2014).

#### *3.2.2.2 Occupants behaviour*

Occupants behaviour towards the usage of natural ventilation and their comfort is very important in terms of implementation of NV strategy successfully in the design. For instance, in a residential building, occupant is given free choice in case of hybrid ventilation system and it is usual practice that microclimatic conditions force the occupant to switch to the mechanical ventilation for achieving the best comfort levels. There is more trend to use the natural ventilation in hot and humid climate than in cold one. Best implementation of NV has been seen in office buildings (Elotefy, Abdelmagid, Morghany, & Ahmed, 2015b).

#### *3.2.2.3 Urban context*

The urban area having high-rise buildings receive less solar radiation and shaded by the nearby buildings which cause less energy consumption for cooling. Above the canopy layer, tall buildings loss entrapped heat during the nights and hence the top floors have lower indoor air temperatures, causing a reduction in cooling load (Elotefy et al., 2015b). Furthermore, a dense urban area will have a complex air flow pattern and if the tall building is surrounded by tall buildings (for instance, urban areas in Singapore) and hence a simple design strategy may not guarantee the best implementation of NV. The accurate implementation of NV to achieve reduced cooling load depends on the urban context. Considering only surrounding buildings is not enough while analyzing the influence of urban context. It is usually the texture of three layers of surrounding buildings that effects the wind flow patterns near the site. In case of wide canyone, few surrounding buildings or one layer of surrounding building is enough for the consideration. This is the advantage of using NV in tall building that the downstream buildings around the site don't usually effect the wind patterns and speed (Tong, Chen, & Malkawi, 2016). Furthermore, the shape/form of the surrounding buildings and their geometrical relationship with the street pattern will affect the wind velocity and wind flow patterns (Etheridge, 2008).

#### *3.2.2.4 Orientation of building*

Orientation of the building for the effectiveness of NV to reduce cooling load plays a vital role. There must be considerations of wind directions and sun path while defining the orientation. The decision of orientation can have significant impact on the energy performance of building envelope as well, as it can be used to increase or decrease the intake of direct sunlight into the building through openings. In tropical climate the orientation that reduces the direct intake of sunlight is considered the best to have reduced cooling load (M. Al-Tamimi et al., 2011).

that could have impact on building envelope energy performance, as it can be used to minimize the direct sun radiation into the buildings through windows, building openings as well as external opaque walls.

## 3.3 Building integrated vegetation (BIV)

Building integrated vegetation (BIV) is termed as a system to accommodate the vegetation at different vertical positions of the building. It may be located at roof, walls, balconies and at intermediate floors and is termed as Roof Garden (RG), Green Wall (GW), Green Balconies (GB) and sky gardens (SG) respectively shown in **Figure 18**.

Figure 18 Left to right i) green wall (GW); ii) green roof/roof garden(GR); iii) green balconies (GB); iv) indoor sky garden (SG)

BIV is found to be a promising solution for energy saving and purification of air (Babak Raji et al., 2015). describes the most common types of BIV systems along with associated strengths and weaknesses.

A number of studies found environmental benefits of incorporating BIV systems in high rise buildings. Thermal comfort through the reduction in indoor air temperature (**Table 10**) by evapotranspiration and shading effect of plants (Babak Raji et al., 2015; Zaid, Perisamy, Hussein, Myeda, & Zainon, 2018). Franco et al. (2012) did a wind tunnel testing and found that the combination of wind and vegetation enhance the cooling effect in indoors. Indoor air quality (IAQ) through the purification of air by the reducing $CO_2$ and addition of $O_2$ together with the screening of pollutants and dust particles from the air (Babak Raji et al., 2015; Zaid et al., 2018).It also provides wind barrier effect and thus controlling the discomfort at the higher floors occupants who want to use NV (Pérez, Coma, Martorell, & Cabeza, 2014) If used as window shading it will help increasing the incoming daylight and will reduce the glare effect. At the same time, it provides insulation effect due to the presence of multiple layers of BIV systems i.e. air layer in the plant layer and substrate layer (Substrate layer refers to the soil structure that carries the plant). These characteristics of BIV systems may eventually affect the electricity demand (Ip, 2013; Pérez et al., 2014).

### 3.3.1 Cause and effects of BIV systems

Three main phenomena; evapotranspiration, Shading and Insulation effect of BIV systems contribute to the seasonal energy saving as well as on the wellbeing of occupants. These benefits of BIV systems and their cause are described in **Table 11.**

Table 10 Types of building integrated vegetation systems and their advantages and disadvantages

| **Type** | **Sub types** | **Example** | **Advantages** | **Disadvantages** | **Ref.** |
|---|---|---|---|---|---|
| Green Walls | Green Façade | It includes climbing plants directly and indirectly connected to the façade | • Reduction in heat fluxes & temperature fluctuations on building envelope | • Limited plant selection/climate adaptability. | (Manso & Castro-Gomes, 2015; Babak Raji et al., 2015) |
| | Living Walls | Living walls consist of modular pre-cultivated panels or bio filter walls | • Humidification<br>• temperature reduction<br>• Reduction in UHI effect<br>• Mitigation of air pollution<br>• Rainwater Management | • Long-term maintenance | |
| Roof Garden | Extensive | A vegetated roof with thickness of growing medium around 6–20 cm | • Reduction in UHI effect<br>• Rainwater Management<br>• Extend the life of roofing<br>• Control peak storm water runoff from large roof areas<br>• Add amenity space on previously unused roofing space<br>• Heat flux through the roof structure is reduces by 60%.<br>• The risk of glare for the surrounding buildings is reduced<br>• Noise Reduction | • Initial high construction cost<br>• Roof leakage problems<br>• High maintenance cost<br>• Drainage and filter layers of the green roofs are fabricated with 40% recycled polypropylene while manufacturing process of these materials cause pollution.<br>• Management issues during construction due to lack of co-operation and collaboration between different fields (architectural, Civil, Environmental engineers and residents). | (Hien, Yok, & Yu, 2007; Babak Raji et al., 2015; Shafique, Kim, & Rafiq, 2018) |
| | Intensive | A vegetated roof with thickness of growing medium around 20–100 cm | • Reduction in heat fluxes & temperature fluctuations on building envelope | | |
| Green Balconies | | As horizontal planting a vegetation in balconies | • Reduction in UHI effect<br>• Mitigation of air pollution<br>• Rainwater Management | | (Babak Raji et al., 2015) |
| Sky gardens (SG) | Indoors | Indoor Vegetated (Trees or potted plants in soil substrate) spaces like atrium located at any height above the ground level are termed as Indoor SG | • Air Purification,<br>• Humidification<br>• temperature reduction<br>• Wellbeing<br>• Provision of recreational space | | (Ip, 2013; A. Wood & Salib, 2013; Yuhong & C.Y., 2011) |
| | Outdoors | Sky gardens located at rooftop level and usually placed on an external structure with some distance to the roof of the building are called outdoor SG. These may also include sky bridges. | • Reduction in heat fluxes & temperature fluctuations on building envelope | | |

Table 11 Various studies indicating the cooling effect of BIV systems in various climatic conditions and urban context

| **Location** | **Climate** | **BIV Type** | **Temperature reduction** | | | **ES (%)** | **Methods/Tool** | **Findings** | **Ref.** |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Surface/Air** | **Indoors (Microclimate)** | **Outdoors (Macroclimate)** | | | | |
| Palermo, Italy | Temperate | Green roof, Green wall | | 4.8 °C. | 3°C | | ENVI-met EnergyPlus | Vegetation i.e. green roof and green wall in temperate climate region cause a reduction of temperature up to 3°C in the external spaces and 3.10°C- 4.17°C in indoor spaces. | (Luisa, 2014) |
| Cairo, Egypt | Hot-dry | Green roof | 14 °C | 0.4–1.4 °C | 0.05–0.6 °C | 5.2% | ENVI-met EnergyPlus | This study investigated the cooling effect of green roof in different urban context and climate. The results reveal an outdoor nighttime warming effect of not more than 0.2 °C which is most obvious with the semi-extensive while the outdoor and indoor cooling effect ranges between 0.05–0.6 °C and 0.4–1.4 °C, respectively depending on the green-roof type, urban density and time of the day. | (Morakinyo, Dahanayake, Ng, & Chow, 2017a) |
| Hong Kong | Hot-humid | | 10 °C | | | 3.1% | | | |
| Tokyo, Japan | Warm-humid | | 8.5 °C | | | 4% | | | |
| Paris, France | Temperate | | 7 °C | | | 1.5% | | | |
| Multiple cities<br>-Athens, Greece<br>-Beijing, China<br>-Hong Kong,<br>-Brası ́lia, Brazil<br>-Montre ́al, Canada<br>-Mumbai, India<br>-Riyadh, Saudi Arabia | Hot-dry<br>Hot-humid | Green roof, Green wall | 3.6-11.3°C | | 8.4°C | 32% to 100% | ECOTECT<br>CFD Code<br>WinAir4 | This study investigated the thermal effect of green roofs and green walls on the built environment both inside the canyon and at roof level. It also investigated the effects of this temperature reduction on outdoors thermal comfort and energy savings. | (Eleftheria & Phill, 2008) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Hot | Sky gardens | | 0.2-0.3°C peripheral config. | | | ANSYS FLUENT | This study investigated the reduction in air temperature due to the addition of trees, in sky gardens and according to this study an air temperature reduction is seen to increase with the width of sky garden and decreases with the height. | (Mohammadi & Calautit, 2019) |
| Netherlands | Cold | Green roof, Green wall | 0.52°C mean and 2.0°C max. | | | | ANSYS FLUENT | This study investigated the cooling effect of different vegetation systems on surroundings. According to this study avenue-trees contribute in temperature reductions at pedestrian level by 0.43°C- 1.6°C. Facade greening results in temperature reduction for a range 0.04°C and 0.3°C while roof greening does not show any significant impact. | (Gromke et al., 2014) |
| Penang, Malaysia | Hot | | 2-5°C | | | | Experimental Method | Vegetation in the tropical climate can contribute in local temperature reduction by a range of 2-5°C. | (Kim Huat, Fairuz Syed Fadzil, & Shuib, 2009) |

## 3.4 Combination of NV and SG systems

Research has found that the benefits of NV and BIV systems can result in larger environment benefits. There are a number of high-rise buildings that are focusing on using these two strategies (Babak Raji et al., 2015). **Table 12** shows the suitability of the combination of NV and BIV systems (Babak Raji et al., 2015).

There is very little research being done on the topic of energy performance of tall buildings incorporated with SG and particularly in combination with NV. However Niu (2004) suggested in his study that the incorporation of SG in tall buildings hot climate can definitely provide a better thermal comfort for the occupants during summers (J. Niu, 2004). While Alnusairat (2017) suggested the use of combination of Sky Courts/ sky gardens with natural ventilation in highrise buildings to reduce cooling energy consumption (S. Alnusairat et al., 2017).

Table 12 Suitability of BIV systems to enhance NV (Babak Raji et al., 2015).

| **BIV System** | **Summer Cooling** | | **Winter Heating** | **Suitability for NV**[12] |
|---|---|---|---|---|
| | **Evapotranspiration** | **Shading** | **Insulation** | |
| **Green Walls** | ✓ | ✓ | ✓ | ✗ |
| **Roof Garden** | ✓ | ✓ | ✓ | ✗ |
| **Green Balconies** | ✓ | ✓ | ✗ | ✓ |
| **Sky gardens** | ✓ | N/A | N/A | ✓ |

Table 13 Design criteria for BIV Systems

| **Benefit** | **Cause** | **Description** | **Ref.** |
|---|---|---|---|
| Cooling effect | Evapotranspiration | Plants used in BIV systems absorb solar energy and convert it to latent heat through evapotranspiration process. As a result of this process water vapor are released from the plants causing increase in the humidity of air and reduction in air temperature. | (Zaid et al., 2018) |
| Shading | Leaf area Index | BIV systems provide shading effect for the walls and to the balconies and thus block the direct sunlight causing reduced cooling load. | (Pais & Bertoli, 2019; Pérez et al., 2014; Zaid et al., 2018) |
| Insulation effect | Soil substrate, growing medium | The growing medium of plants have insulation properties and thus cause reduced energy consumption in hot as well as cold climates. | |
| Wellbeing and Comfort | Connection with nature<br>Buffer space<br>Insulation effect<br>Evapotranspiration effect | Indoor BIV systems provide acoustic and thermal comfort to the occupant as these systems are transition from outdoor to indoor and hence act like a buffer space. When the ambient air passes through plants, it gets cooled causing thermal comfort to the occupants in hot climatic conditions while in winter the same buffer space becomes a barrier to extreme cold weather due to the presence of substrate insulation effect. Furthermore, sound absorbing properties of plants make the indoor environment acoustically comfortable. It also has positive psychological effect on occupants due to their connection with the outdoor environment and nature. | |
| UHI Mitigation | Photosynthesis, | Plants use CO2 for the photosynthesis process and use solar energy. This process causes the reduction in surrounding air temperature and hence mitigating the UHI effect. | (Babak Raji et al., 2015; Zaid et al., 2018) |

Raji el al. (2015) found that, in order to achieve these bnefits the best orientation and selection of plants in the buildings located in tropical climate should be in a way that it should enhance

[12] Suitability to be used in a combination with NV as a cooling strategy

the wind velocity and shading effect. He also suggested the use of a combination of NV and indoor SG in tall buildings for tropical climate (Babak Raji et al., 2015). Since outdoor SG increase the wind velocity positively (Mohammadi & Calautit, 2019), hence are best to be incorporated in this context in tall buildings combined with NV to reduce cooling load. This high speed can be brought to an optimum level by adding trees and specific plants that can reduce the wind speed.

Osmundson T. (1999) and Pomeroy (Pomeroy, 2014) defined the SG as the vegetated spaces located at any level along the height in tall buildings. Main aim of these spaces is to provide adequate natural light, ventilation and a green space that can be used by the occupants of the adjacent floors for recreational and relaxation purpose. These spaces are also termed as sky courts and roof top gardens in literature. The vegetation, plants and trees in these spaces not only purifies the incoming air but also cools it down through evapotranspiration and shading effect of plants and acts as a buffer to the noise, dust particles etc. (Mughal & Corrao, n.d.; Pomeroy, 2014; O. Theodore, 1999).

Yuhong & C. Y. (Yuhong & C.Y., 2011)described the benefits of incorporation of SG in tall buildings at different levels bring different benefits i.e at rooftop Level it is not much helpful. It is different from GR as SG at this level is not directly related to building envelope, hence they do not provide same thermal benefits as RG. SG at this level may be termed as Sky Bridges or Rooftop Gardens. However, if incorporated at intermediate levels that is also termed as podium gardens/indoor SG/outdoor SG, the benefits are more as compared to the rooftop level. These benefits include reduction in UHI effect, mitigation of air pollutants and storm water management and if incorporated at large scale these can reduce significant amount of cooling load (Yuhong & C.Y., 2011).

Yang et al. (2004) investigated the airflow patterns around the high-rise buildings incorporated with SG and analysed the effect of wind direction, distance between buildings, height of the building and volume of SG on the effectiveness of NV in tall buildings. According to them the incorporation of SG in upstream buildings helps channelizing the affective air flow in downstream buildings (J. Yang et al., 2004).

Ismail (2007) suggested that the combination of sky gardens/Sky courts and natural ventilation can help increase the occupant satisfaction in tall buildings in tropical climate and it is a step towards bioclimatic design.

Wood et. al (A. Wood & Salib, 2013) analysed various case studies of tall buildings incorporated with SG and using NV as a passive strategy to reduce cooling load in cold climate and found that the efficiency of NV is positively affected due to the presence of SG with the incorporation of atrium at the centre on building plan/shape. Some of the studies with their respective %age of annual energy saving is shown in **Table 14**.

## 3.5 Typical features of naturally ventilated buildings

The design considerations at different levels that are found to be helpful in literature for the effectiveness of NV in tall buildings are given as follows:

Table 14 Example of tall buildings using a combination of SG and NV for reducing cooling load (Mughal & Corrao, n.d.; A. Wood & Salib, 2013).

| Building | Plan shape and depth | Location of sky garden | Position of atrium/air shaft | AES (%) |
|---|---|---|---|---|
| **Commerzbank,** Frankfurt (Germany) | Compact triangular shape with round corners and narrow plan depth | On central atrium and on the top of coupled with radial arrangement of offices | Centre | 63% |
| **Manitoba hydro place,** Winnipeg (Canada) | Compact triangular shape with wide plan depth | South facing winter gardens (2-storey and 6-storey stacked sky gardens) | On the North facade | 73% |
| **Post tower,** Bonn (Canada) | Compact oval shape with narrow plan depth | Series of four stacked sky gardens on the top of each other | Centre | 79% |
| **30 St Marry axe,** London (United Kingdom) | Compact circular shape with narrow plan depth | 2-storey and 6-storey stepped, spiralling sky gardens | Centre | N/A |

### 3.5.1 Horizontal design

***Building shape/form*** with least value of drag coefficient[13] are found to be the best for effectiveness of natural ventilation in tall building as this shape helps avoiding vortex excitation and thus the discomfort faced by the occupants due to high wind pressure and speed. In this regard oval/circular floor plan shapes and narrow plan depth are highly adopted for effectiveness of NV (Baghaei Daemei, Khotbehsara, Nobarani, & Bahrami, 2019; Elshaer, Bitsuamlak, & El Damatty, 2015). More over façade pressure is distributed evenly on the façade if building form is twisted and circular (B. Wang & Malkawi, 2015).

### 3.5.2 Functionality attribution

The reduction in energy consumption can also be achieved by placing the functions having high cooling requirements at upper floor levels, as the air temperature above the urban canopy is lower (Elotefy et al., 2015b).

### 3.5.3 Vertical design

External opening/ Porosity/ Segmentation & Central sir shaft: In hot and humid climates, natural ventilation can be improved through the stack effect using a central atrium accompanied with external opening/segmentation. The windward and leeward openings should be kept at different levels in order to increase ventilation through the stake effect (Elotefy et al., 2015b). **Figure 19** illustrates this concept.

***Incorporation of building integrated vegetation (BIV):*** Various studies have found that BIV systems are an effective way to enhance building air quality and reduce the cooling load through enhancement of natural ventilation. sky gardens is one of the types of BIV system that is especially useful in increasing the wind speed by a maximum of 10 m/s along with lowering down the temperature of the ambient air coming inside the building (Mohammadi & Calautit,

[13]The drag coefficient is the resistance of an object in a fluid environment i.e. air and water. A low drag coefficient implies that the object has less resistance towards incoming fluid while higher values of drag coefficient means the object tends to stop the fluid motion with higher resistance (McCormick, 1979).

2019). Implementation of this concept is explained in (Mughal & Beirão, 2019b).

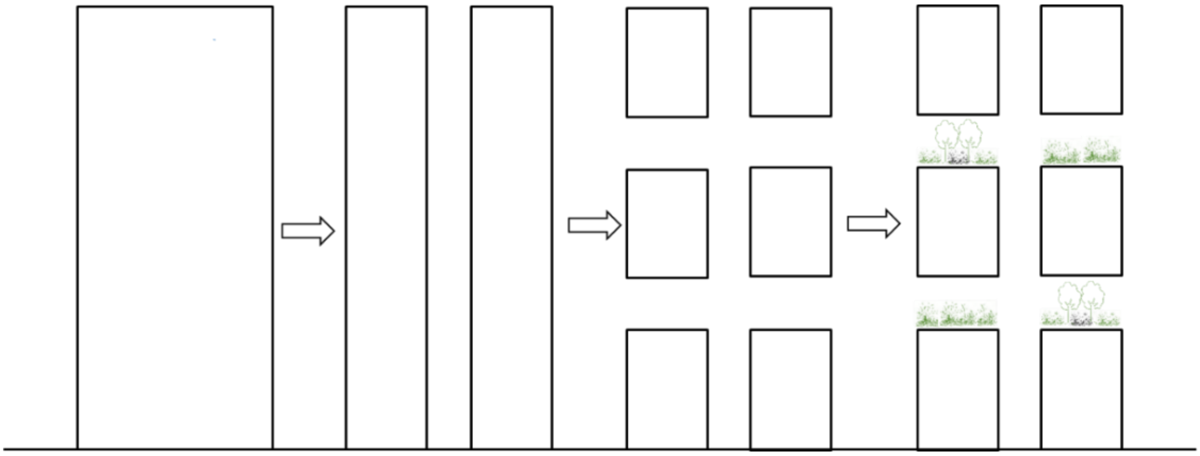


Figure 19 Integration of segmentation in tall buildings (left to right)

## 3.6 Optimization in architecture

Introduction of parametric design techniques have revolutionized various aspects of engineering and manufacturing processes (DİNO, 2012; Stavric & Ognen Marina, 2011; Tedeschi, 2014). Architects use these techniques in the initial phases of their design creation process to propose multiple solutions. Architectural parametric design coupled with novel assessment techniques helps the designer in enhancing the global understanding of the performative qualities of the design (Park, Elnimeiri, Sharpe, & Krawczyk, 2004; Stavric & Ognen Marina, 2011). This deeper comprehension and acknowledgement of the design objectives and performative aspects aids designers to make decisions and find solutions. Integrating a performance analysis tool to the parametric modelling can therefore bring out great advantages in finding adequate solutions in less time, informing the designers regarding performance quality at early stages of design. This whole process is termed as optimization (D'Aquilio, Sileryte, Yang, & Turrin, 2016; Magnier & Haghighat, 2010; Virta, 2016).

Challenges in the architectural industry are cantered on energy saving, cost-effectiveness, improving safety and occupant comfort. To address these challenges, optimization towards high-performing architectural design solutions is needed. As described earlier, optimization process is usually done on the basis of some performance criteria and this criterion is evaluated through simulation process (D'Aquilio et al., 2016). Optimization in architecture is a multifaceted process and, due to such complexity, cannot be done using traditional gradient based methods. They require, rather a stochastic approach and one of most widely used is the Genetic/evolutionary algorithm (Magnier & Haghighat, 2010; Virta, 2016). It was first introduced by John Holland in 1960 (Sadeghi, Sadeghi, & Niaki, 2014). These algorithms are biologically inspired techniques (Rutten, 2013; Vierlinger & Bollinger, 2014). Swarm Intelligence (Cichocka, Browne, & Ramirez, 2015), Artificial Neural Networks (Yao, 1999) have been found to be useful computational optimization techniques applicable in the architecture field.

Optimization can be single objective or multi-objective optimization. Complex building simulations are possible through multi-objective optimization as many fitness criteria can be considered and are necessary for dealing with the architecture holistic complexity. When the one problem is being considered at a time e.g. reduction in cooling load etc., multi-criteria single objective optimization is used which includes weight sum of multiple criteria (Wortmann & Nannicini, 2017). Cichocka et. al. (2017) conducted a survey regarding the implementation of optimization in architectural practices on the designers of 34 countries and found that there is great need for muti-objective optimization than single-objective one. He further found that the most widely investigated aspects of design for optimization are related to daylight, structure and geometry.

An optimization algorithm always tries to look for global optimum solution specifically with reference to engineering problems. When the complex process that, the optimization algorithm no more tries to find a global optimum solution but sub-optimal solutions (Nguyen & Reiter, 2014; W. Wang, Rivard, & Zmeureanu, 2005).

Hence optimization models are composed of generative design tools/models that has numerous variables decided by the developer based on characteristics of the required solution. For instance, for shape/form optimization, these variables may include geometrical parameters (Shi & Yang, 2013).

### 3.6.1 Existing optimization algorithm

Optimization algorithms offer the possibility of finding optimal solutions for the building design in terms of energy efficiency and sustainability. Commonly used optimization algorithm in architecture is **(Figure 20)** black box optimization. The optimization problems which use numerical simulation process are optimized through black box method. It has three main classes; **(1)** metaheuristics, that is based on randomization and nature-based analogies for finding the solution e.g. genetic algorithm, **(2)** direct search method, that examines a series of individual design candidates in a fixed sequence of steps, and **(3)** model-based methods, that constructs an approximate model of the black-box function (Wortmann & Nannicini, 2017). These three types of algorithms are further classified into various types of algorithms.

Most optimization algorithms used in architecture are based on evolutionary algorithm specifically when a huge number of design solutions are to be optimized within allotted time (Belém, Alexandre, & Lourenço, 2019; Wortmann & Nannicini, 2017). Evolutionary optimization process in architecture, are basically composed of three steps sequentially looped together. These steps are (1) a generative system generating architectural solutions; (2) an evaluation algorithm evaluating performance criteria of the architectural solutions; and (3) a selection algorithm that selects the best fit solutions from the set of solutions produced. The algorithm runs a loop adding the best fit solution to a new generation of solutions that helps improving the solutions in each new cycle until further performative improvements in the solutions are negligible. (Mitchell, Forrest, & Holland, 1992).

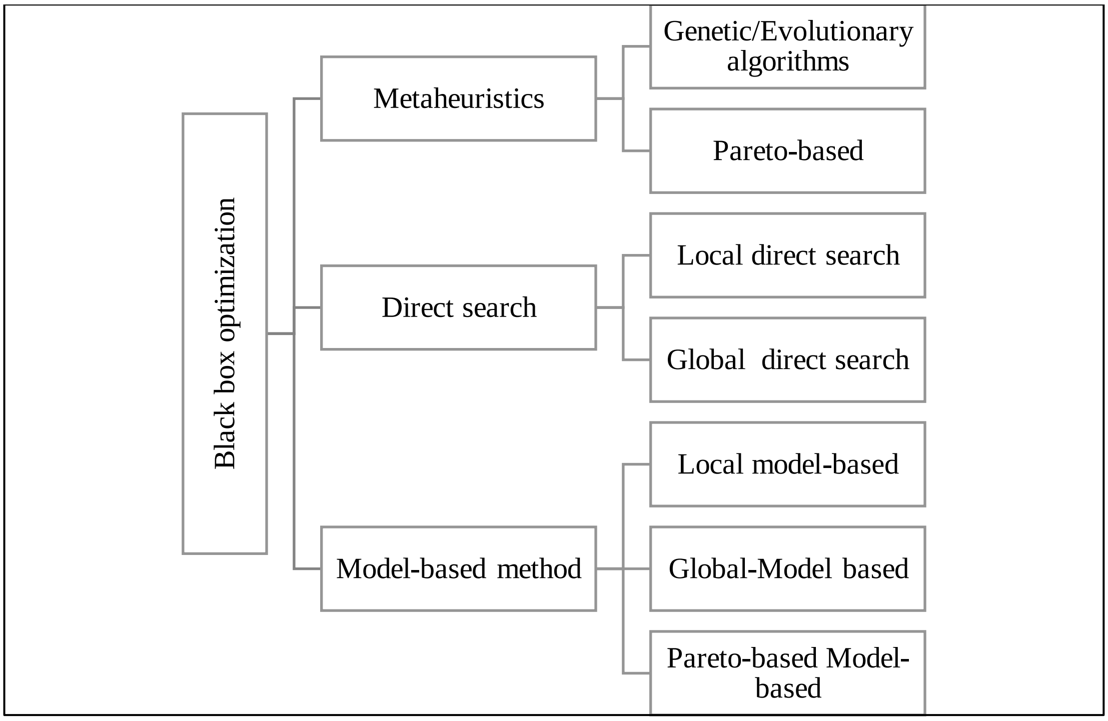



Figure 20 Commonly used optimization methods in architectural design (Wortmann & Nannicini, 2017)

Some optimization tools commonly used in design of building geometry are listed below in **Table 15**.

Table 15 Comparison of free existing famous optimization tools using EA (Belém et al., 2019; "Food4Rhino," 2019)

| **Plugins** | **Optimization Algorithm** | **Objective** | **Usage** |
|---|---|---|---|
| Goat | GA (Genetic Algorithm) | SO | Complicated |
| Octopus | SPEA (Strength pareto evolutionary algorithm) | MO | Easy |
| Galapagos | GA (Genetic Algorithm) | SO | Easy |
| Opossum | model-based RBFOpt and evolutionary CMA-ES | SO, & MO | Easy |
| Optimus | Joint Approximate Diagonalization of Eigen matrices algorithm (JADE) | SO | Complicated |

### 3.6.2 Available CFD simulation tools

Currently, most CFD solvers that are exposed to CAD environments have none or limited shape optimization capabilities. OpenFOAM, which is exposed to Rhinoceros3D through its plugin Grasshopper and the add-on Butterfly has only limited shape optimization methods, such as its integrated adjoint solver, which is also not exposed to Grasshopper. Other software, such as ANSYS Fluent have more extended optimization capabilities but the software is also not integrated with CAD and has limited use in the architectural industry, also due to its very high cost. RhinoCFD, which was used for the context simulations has no optimization capabilities (Angelos Chronis, Dubor, Cabay, & Roudsari, 2017; Angelos Chronis, Stefopoulou, & Liapi, 2018).

Table 16 Comparison of existing CFD simulation plugins for Rhino/Grasshopper ("ArchiDynamics Inc.," 2019; "Food4Rhino," 2019; Cham, 2019)

| APP/Plugin | Environment | Simulation Platform | Vegetation Evaluation | License | Validated | Installation Process |
|---|---|---|---|---|---|---|
| RhinoCFD | Rhino | Stand alone | ✓ | Free | ✓ | simple |
| ButterFly | Grasshopper | Openfoam | ✘ | Free | ✓ | simple |
| Swift | Grasshopper | Openfoam | ✘ | Free | ✘ | Complicated |
| Archidynamics | Grasshopper | Stand Alone | ✘ | Purchase | ✘ | simple |

There are very few optimization models available that incorporate CFD simulation tool and an optimization algorithm for the design of naturally ventilated tall buildings. Existing literature on this aspect is given in **Table 17**. Most of these studies are following evolutionary algorithm.

Table 17 Recent literature on optimization of tall buildings using natural ventilation

| Authors | Description | Design Variable | Optimization Algorithm | Programs/Tools |
|---|---|---|---|---|
| Stavrakakis et al.(2012) | Optimization of window-openings design for thermal comfort in naturally ventilated buildings | Window design<br>Window-to-door Ratio<br>Orientation | Artificial neural network (ANN) | MATLAB®<br>Thermal Comfort Index (TCI)<br>CFD |
| Elshaer et al., (Elshaer et al., 2015) | Aerodynamic shape optimization for corners of tall buildings using CFD | Aerodynamic shape optimization | Neural network (NN) | Commercial CFD package (STAR CCM+) |
| Wang and Malkawi (B. Wang & Malkawi, 2015) | Genetic algorithm-based building form optimization study for natural ventilation potential | External geometry of tall buildings | Genetic algorithm (GA) | Grasshopper<br>Pheonics 2011<br>Galapagos |
| Feng et al.(2016) | Physical and numerical simulation as a generative design tool | External geometry of tall buildings | Simulation based optimization | CAD package<br>Grasshopper<br>STAR-CCM+ |
| Marzban et al.(2017) | An evolutionary approach to single-sided ventilated façade design in residential buildings | | Genetic algorithm (GA) coupled with pareto front | MATLAB® |
| Chronis et al.,(2018) | Integration of CFD simulations in computational design for harnessing the natural ventilation performance of typical atrium spaces in Athens, Greece | localized retrofitting interventions to increase the air quality of the courtyards and the ventilation performance of the buildings | Genetic algorithm (GA) | FFD<br>RhinoCFD<br>Java applet |
| Grygierek and Ferdyn-Grygierek (2018) | Multi-objective optimization of the envelope of building with natural ventilation | Types of windows<br>Size of windows<br>orientation | multi-objective genetic algorithm-NSGA-II | MATLAB®<br>Energy Plus |
| Estrado(2019) | Optimization of complex geometry buildings based on wind load analysis | External geometry of tall buildings | Genetic algorithm (GA) | Grasshopper/Rhino3D<br>Butterfly<br>Opossum |
| (D'Aquilio et al., 2016) | Simulation of natural ventilation in large sports buildings | temperature and airflow patterns | Computational Optimization | Grasshopper/Rhino3D<br>CONTAM 3.1<br>EnergyPlus through Honeybee plugin |

### 3.6.3 Design variables and objective function

Optimization of building design encompasses a great number of design variables and objective function as shown in **Figure 21**. Design variables are the parameters that are input for the design solution while the design objective is basically the criteria for the comparison of output. The design variables corresponds to geometrical parameters of building, envelope material and energy systems while the objective functions/ fitness function are referred to the performance indicators for user comfort, energy efficiency, economic and environmental efficiency(Ascione, Bianco, Mauro, & Vanoli, 2019).

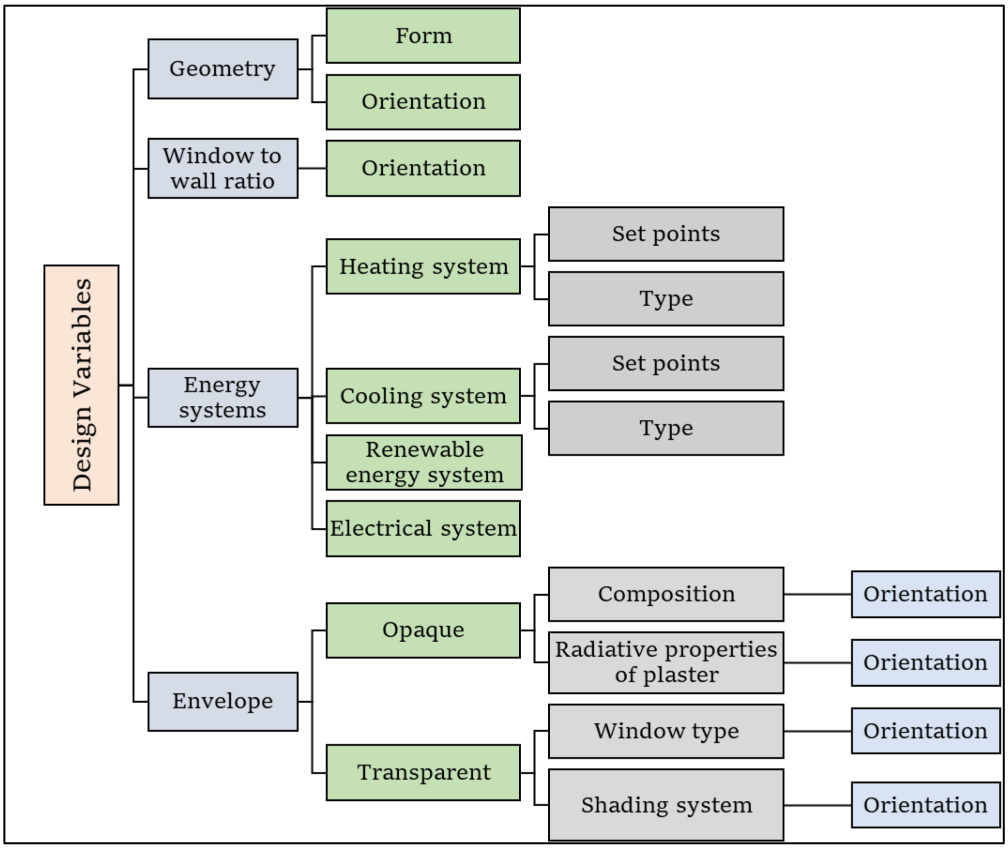



Figure 21 Building energy optimization possible objective functions (Ascione et al., 2019).

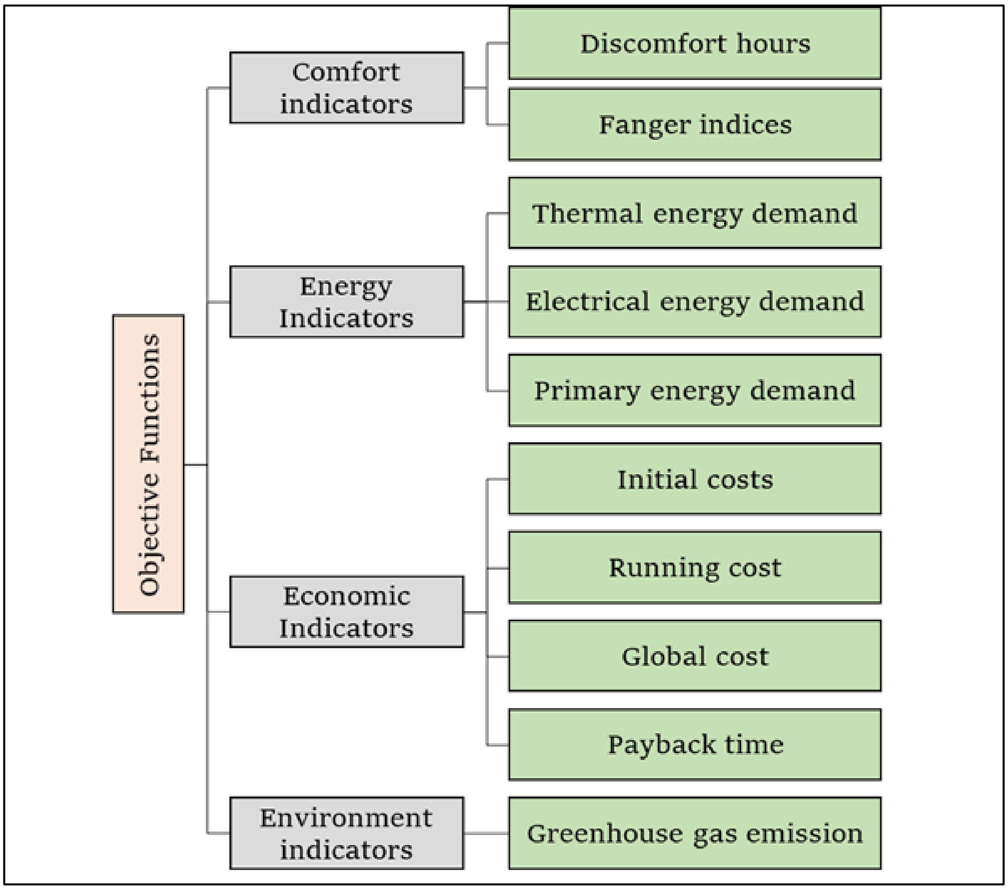



Figure 22 Building energy optimization main design variables (Ascione et al., 2019).

### 3.6.4 Design variables for naturally ventilated tall buildings in tropical climate

Although the process of natural ventilation and its effectiveness for the reduction of cooling load remains same for both low rise and high-rise buildings (Oldfield, Trabucco, & Wood, 2009) but tall structures are prone to high wind loads and speeds that cause vortex excitement resulting in extreme discomfort for the occupants.

Hence the design of tall buildings with the incorporation of NV becomes challenging when it comes to the envelope or façade of the building due to high wind loads and wind pressure (David & Brian, 2008; Liu et al., 2012). The situation is worsened if the building shape/form are more like bluff bodies. Typically, bluff bodies are shapes with sharp corners, such as rectangular plan buildings, however, circular structures are also considered bluff since at high Reynold's numbers pressure drag dominates. While drag is the capacity of object to resist air flow. In this regard Streamlined bodies (i.e. aeroplane wings) are more appreciated, as they allow the air flow to smoothly re-join after separation (Estrado, 2019).

This effect of wind load and pressure can be decreased by bringing the certain and already explored geometrical variation to the tall structures. In this regard the optimization of the overall building for and shape can be done at early design stage to reduce the effect of this discomfort caused due to vortex and high wind speeds (Estrado, 2019; Irwin, 2009). These variations involve:

- **Softened corners:** It refers to rounding, chamfering, or stepping back the corners of the floor plan of the building. This solution is adopted to reduce the drag coefficient and thus the high pressure generated by the wind resulting in reduced vortex excitation (vortex lowers down the wind speed behind the building).These should ideally extend about 10% of the building dimension (Asghari Mooneghi & Kargarmoakhar, 2016; Elshaer et al., 2015; Estrado, 2019; Tanaka et al., 2013; B. Wang & Malkawi, 2015) . An example of application of this strategy is Taipei 101 tower in Taiwan (Irwin, 2008; Li et al., 2011).

- **Innovative envelope:** Innovative envelope refers to as intelligent, adaptive or responsive façade. These involve material, components and systems that change their behavior according to the indoor and outdoor parameters resulting in reduced wind loads and energy consumption (David & Brian, 2008; Elshaer et al., 2015; Romano, Aelenei, Aelenei, & Mazzucchelli, 2018; Vongsingha, 2015). Some successful examples these systems application in tall building are i) Al Bahar Towers Abu Dabi, UAE using Responsive facade system as a curtain wall, ii) Media-ICT building in Barcelona using smart material i.e Ethylene Tetrafluoroethylene Polymer as and adaptive system and iii) Terrence Donnelly Centre for Cellular and Biomolecular Research building is incorporated with Canada using Intelligent building skin as an adaptive system (Shahin, 2019). Another example of innovative envelope double skin façade (Elotefy et al., 2015b).

- **Porosity/Segmentation:** It refers to introduction of openings through the building so that the air can flow through and disrupt or weaken high wind pressure causing extreme discomfort near the façade or on the building envelop. This concept is also termed as segmentation. It offers the least risky approach for envelope design of non-residential tall buildings, provided the aerodynamic effects can be reliably accounted for (David & Brian, 2008; Etheridge, 2008; Liu et al., 2012; A. Wood & Salib, 2013). A successful implementation of this strategy can be seen in 432 Park Avenue tower in New York City by Rafael Viñoly Architects (Macklowe, 2015).

- **Varying cross-section shape & tapering and setbacks:** If the building width is varying along the height, it causes reduction in wind load in the façade and the discomfort (Elotefy et al., 2015b). These shapes can enhance building aerodynamics for a more efficient use of natural ventilation. (Asghari Mooneghi & Kargarmoakhar, 2016; Tanaka et al., 2013; Zhao & He, 2017). An example of implementation of this strategy is Burj Dubai, Dubai, UAE (Baker, D. Stanton, & Lawrence, 2008).

Table 18 Classifying issues and solutions in optimization of tall buildings

| **Issue** | **Challenges/Barriers** | **Opportunities/Solutions** |
|---|---|---|
| Integration of CFD tool with the optimization algorithm | Integration of CFD software in optimization models is very important regarding high performance architectural design, however this subject still needs to be explored (A. Chronis et al., 2017, 2018). | three least complicated approaches available for the architects to work in Grasshopper/Rhino are:<br>✓ RhinoCFD (Integrated with Rhino only)<br>✓ FFD (Integrated with GH /Rhino)<br>✓ Butterfly (Fully integrated with GH/Rhino)<br>✓ Among these the easiest approach is the use of RhinoCFD as it can be used by non-expert people. |
| Selection of optimization algorithm | According to the literature, most widely and successfully used optimization algorithm in architecture and engineering related problems is found to be evolutionary algorithm. However, the huge number of iterations make the optimization a time taking process. Furthermore, in case of MOO, the algorithm does not necessarily look for global optimal solution (Belém et al., 2019; X. S. Yang, 2014). | Available optimization plugins for Grasshopper i.e. Opossum, Octopus, Optimus etc. are making the work easier for architects in this regard. Furthermore, other optimization also be integrated the similar way, hence a huge amount of work is still needed to be done in this aspect for architectural design solutions. |
| Automatization of optimization process | This aspect is the most challenging one when it comes to develop an optimization tool. Visual programming is not enough in this case, other languages i.e. Python, C+ and JavaScript etc. are necessary (Celani & Eduardo Verzola Vaz, 2012). The process is complex because each design solution in architecture has its own requirement regarding performance analysis aspect. | Optimization tools for high performance architectural design are needed to be developed by the teams composed of architects, software developers and engineers. The model of objective function, however, should be designed by the architect and engineers.<br>Architectural courses should be redesigned with the addition of programming languages, building physics and computational design to equip the architects for the future world of computational design in architecture. |
| Lack of work done on optimization model regarding natural ventilated tall buildings | There are very few optimization models available for the natural ventilation design of tall buildings and the one that are available are complex for the designers who are not familiar with programming languages (**There are** very few optimization models available that incorporate CFD simulation tool and an optimization algorithm for the design of naturally ventilated tall buildings. Existing literature on this aspect is given in **Table 17.** Most of these studies are following evolutionary algorithm.<br>*Table 17*). | An optimization model/tool is needed to be developed that is easy to be used by a non-expert for the design of tall buildings to be incorporated with green strategies i.e. NV and BIV. |

## 3.7 Findings from literature review

Based on the literature review challenges and barriers related to the optimization of tall buildings with NV and SG. Four main areas were identified and the opportunities and solutions to barriers and challenges in optimization are expressed in

However, the benefits of BIV systems are not only limited to IAQ and thermal comfort and energy efficiency. it also has got psychological and social advantages which are:

- GW's act as sponge surface to control storm water (Ip, 2013).
- Vertical greenery i.e. GW's are fit to be incorporated into the existing buildings, increasing its value in terms of aesthetics and energy efficiency and saving the cost of demolition and reconstruction (Ip, 2013).
- SG's can be used for social gathering and recreational purposes by the adjacent floors occupants that makes the contact of the occupa nts with nature and eliminates the psychological threats. Furthermore, they can be used for the vegetation of local fruits and vegetables by the habitants (Chan, 2005; Mughal & Corrao, n.d.; Babak Raji et al., 2015; A. Wood & Salib, 2013).
- Adding SG to the different floor levels in Highrise buildings increases the urban green area that reduces UHI effect. Green surface channelizes quick airflow as ambient air after passing through vegetated surface cools down and takes the space left by the hot air quickly (Ip, 2013).
- Almost all types of BIV systems have similar effects on energy efficiency of the buildings and IAQ, however GW's have significant direct and indirect effect on the whole buildings while the effect of GR on IAQ is only confined to the adjacent floors. Direct effect refers to the purification of ambient air from pollutants and dust particles while indirect affect means reduced infrared emission due to the reduced wall surface temperature (Ip, 2013) .

From the research that has been undertaken by Cichocka et al., (Cichocka et al., 2017), it is found, that multi objective optimization techniques and tools are more necessary in the architectural practice than single objective ones. Moreover, it has been demonstrated that majority of practicing architects (93%) would like to understand the underlying optimization procedures and 54% would prefer to have full control over the optimization process, thus intuitive and easy to-understand optimization algorithms would be more suitable in the architectural practice. Furthermore, the interactive optimization methods and 'human in the loop' approach seem the most appropriate, as almost all of surveyors (91%) would like to select promising designs during the optimization process. These authors concluded that most of the optimization models/tools developed by researchers are focused on daylight, structure and geometry as designers and researchers are found to be more interested in these topics (Cichocka et al., 2017). However almost no research has been made regarding optimization of spatial planning to enhance natural ventilation as a strategy for energy saving.

# 4 CASE STUDIES

This chapter will analyse existing buildings to determine the most common geometric parameters governing design of high-rise buildings located in tropical climate. Literature review performed in chapter# 3 identified two most sustainable strategies for high-rise multi-storey buildings located in tropical climate as natural ventilation (NV) and use of vegetation (VG). This chapter explores the forms of buildings based on three main criteria: (1) design characteristics/ concepts; (2) architectural elements and (3) Annual energy saving (AES).

As described in chapter#2, the case studies data is collected based on four main parameters that effect-cooling load of tall buildings located in tropical climate. The four information categories are shown in **Figure 23**.

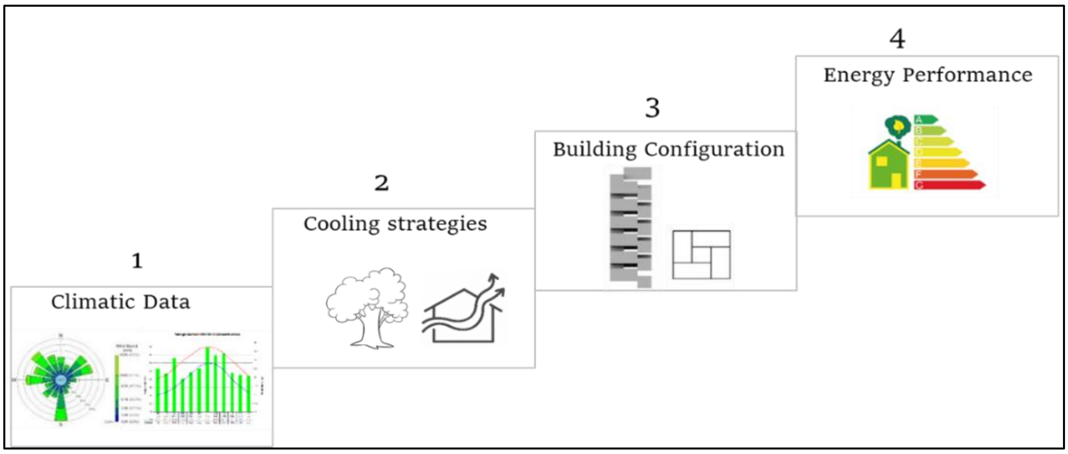



Figure 23 Type of information collection for case studies

In order to determine the geometric design parameters that govern energy use in high-rise buildings a two-step methodology was designed (**Figure 24**).

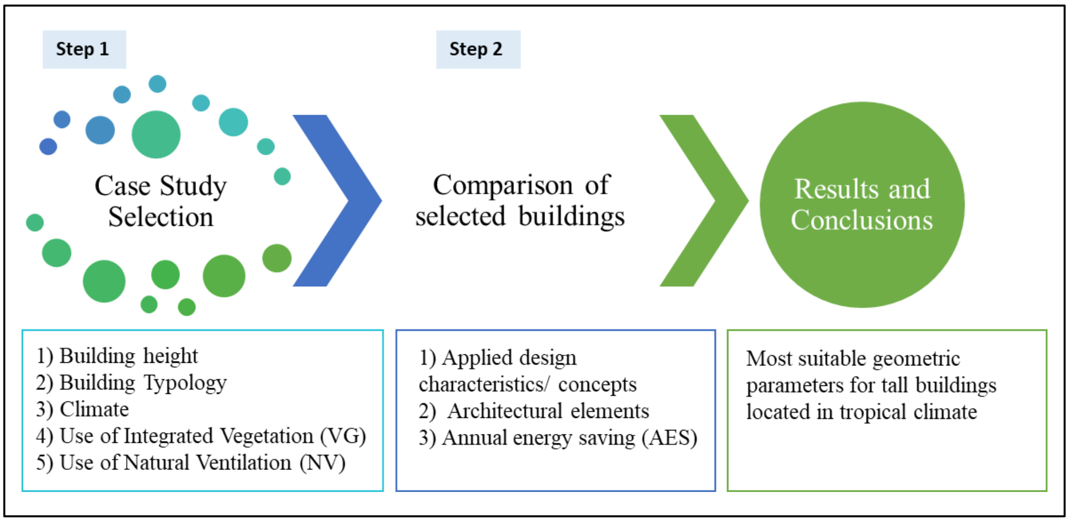



Figure 24 Selection and analysis of case studies

First step involved the selection of case studies based on 5 core criteria:

1. Building height
2. Building Typology
3. Climate
4. Incorporation of building integrated vegetation (VG)
5. Use of natural ventilation (NV)

In the second step, the criteria to compare the selected case studies were defined based on the literature review performed beforehand. Three main criteria for comparison considered are

1. Applied design characteristics/ concepts
2. Architectural elements
3. Annual energy saving (AES)

## 4.1 Selection criteria for buildings

Ten buildings have been selected according to the criteria given in **Table 19** A list of these buildings is shown in

**Table** *20*. The datasheets for these case studies are available in the appendices.

Table 19 Selection criteria of cases of tall buildings

| Criteria | Description |
|---|---|
| Building height | • 10 to 50 number of floors |
| Building Typology | • Office<br>• Residential<br>• Mixed-use building |
| Climate | • Hot and Humid i.e. Tropical |
| Incorporation of building integrated vegetation (BIV) | • Sky gardens<br>• Green wall<br>• Green balconies<br>• Roof garden |
| Use of natural ventilation (NV) | • Cross ventilation<br>• Single sided<br>• Stack affect |

Building height is considered in terms of number of floors according to tall building criteria as described in section 1.2.2 of the thesis. Different VG systems affect the energy efficiency of the building in different way. For this study it was important to see which BIV system may play a significant role in improving the NV phenomenon in the building. It has already been concluded that SG and NV are the best combination for this purpose. Most of the tall buildings are using a combination of natural and mechanical ventilation so even if one principle of NV is used in combination with mechanical ventilation, the criteria is fulfilled.

Table 20 Selected case study buildings

| 1 | 2 | 3 | 4 |
|---|---|---|---|
|  Menara Umno, Penang, Malaysia |  Torre cube, Guadalajara, Mexico |  1 Bligh street, Sydney, Australia |  Capitagreen, Singapore |
| **5** | **6** | **7** | **8** |
|  One Central Park, Sydney, Australia |  Skyville@Dawson, Singapore |  Skyterrace@Dawson, Singapore |  Magic Breeze Sky Villas, Hyderabad, India |
| **9** | **10** | | |
|  Solaris, Singapore |  Parkroyal on Pickering, Singapore | | |

## 4.2 Case study buildings

Energy performance of each building depends on its urban context and green strategies adopted to mitigate the high energy loads. Hence, it is necessary to study each building individually before making a comparison among them. The phenomenon of NV and the design strategies and architectural elements used in selected buildings for case study to reduce the cooling load are described in detail in the following section while the datasheets are provided in appendices.

### 4.2.1 Menara Umno

The UMNO Tower is 93.5 meters tall (21-storey). It was one of the tallest office buildings of in Penang, Malaysia, built in 1998. Penang is a tropical climate region and thus giving rise to the need to reducing cooling load in buildings. Thus, the focus of design was to use natural ventilation to reduce the cooling load and increase the indoor comfort level. The building uses mixed-mode or hybrid ventilation system (a combination of natural and mechanical ventilation) (A. Wood & Salib, 2013).

Although the building has centralized air conditioning system, all the corridors, elevator spaces, stairways and toilet zones located at the periphery of the building act as a buffer zone and are designed to be easily ventilated through natural ventilation. It has elongated plan shape and the orientation is in in a way that the elongated side is in parallel to the wind direction and thus offering less resistance to the incoming wind. Furthermore, from the site context it has been observed that there is no tall building located within 569.32 m from UMNO Tower, causing no obstruction for the wind to reach the building (Cynthia & Botiti, 2015). Following figure shows the orientation of the building with the wind flow inside the building.

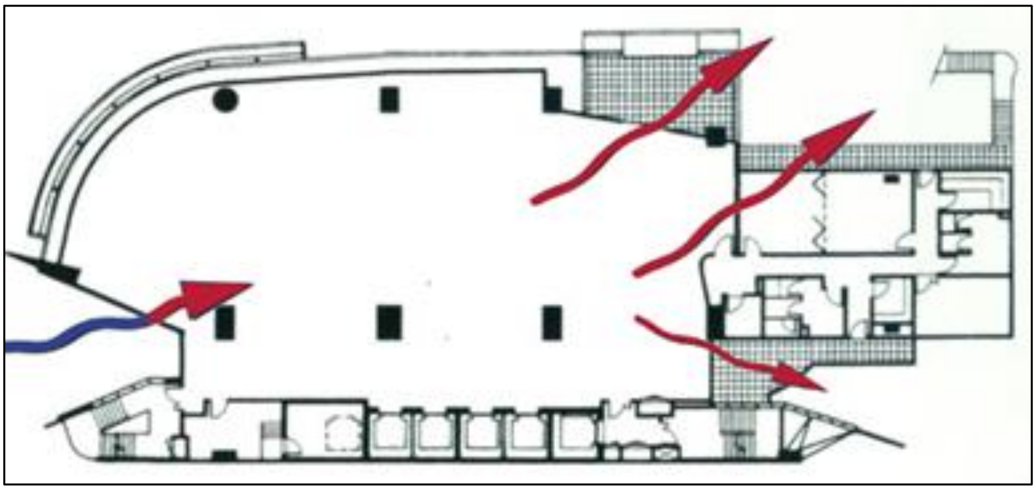


Figure 25 Plan of the building showing the sun path diagram (A. Wood & Salib, 2013)

The architectural elements used in this building to enhance the effectiveness of natural ventilation are full height windows, wing walls that direct the wind to special balconies zone with adjustable doors and panels, high floor to floor height (i.e. 3.85 meters) and height window to wall ration i.e. 0.8 for all facades except south façade to avoid direct sunlight in summer, service core facing east, narrow plan depth i.e. floor depth is 18 meters from window to the core, lobbies and sun shading panel/ devices (Ismail, 2007). All these elements contribute in reducing the energy consumption and thus an annual energy saving is found to be 25% (A. Wood & Salib, 2013).

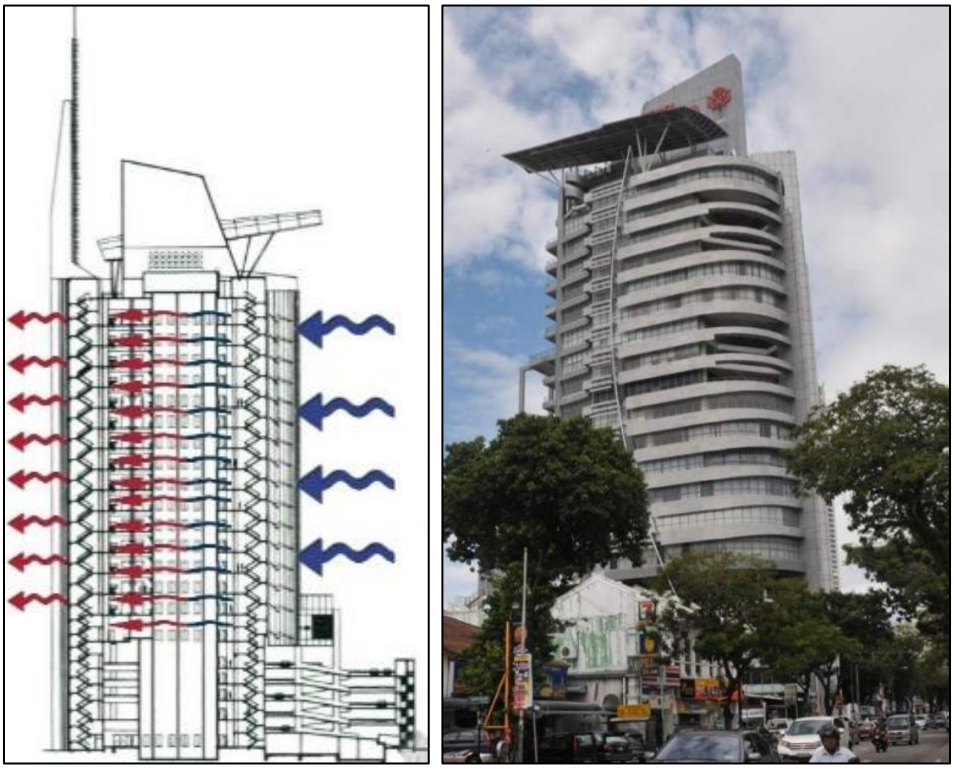


Figure 26 Ventilation process of Menara Umno involving cross ventilation (A. Wood & Salib, 2013)

### 4.2.2 Torre Cube

Torre Cube is 60 meters (17-Storey) tall office tower that is in Guadalajara, Mexico, characterized as a tropical climate region. It is found to be the only office building of this scale that is designed to use natural ventilation to ventilate the spaces in almost all the year. The building has symmetrical plan shape incorporated with three central concrete cores/ columns that support the whole structure of the building. Three funnel shaped office wings are cantilevered from these columns (B. Raji, Tenpierik, & Van den Dobbelsteen, 2014). The arrangement of these cores and office space can be seen from the following figure.

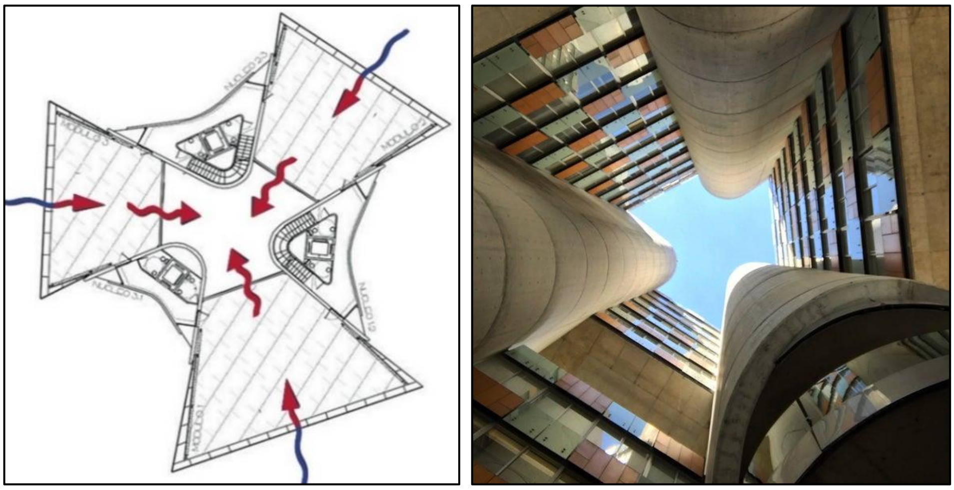


Figure 27 a) Plan of the building showing the airflow path & wind direction and sun path diagram (A. Wood & Salib, 2013); b) A view from the central air shaft (McManus, 2018)

The wind comes in the office space from sliding glass windows and is exhausted through the central shaft (that acts as lighting well as well as ventilation shaft) due to stack affect. Furthermore, the implementation of segmentation concept and incorporation of sky gardens (SG) also helps improving the ventilation process by cooling down the ambient air through vegetation of SG and channelizing this fresh cooled air in corridors (Aslan & Sev, 2014; A. Wood & Salib, 2013).

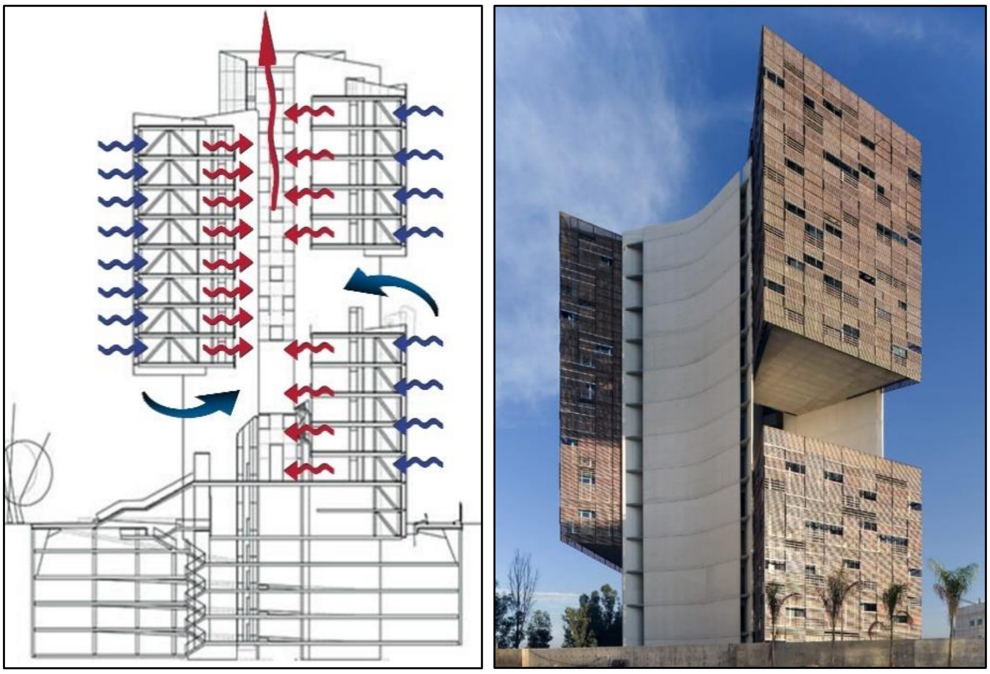


Figure 28 Ventilation process of Torre cube involving cross ventilation and stack effect (A. Wood & Salib, 2013); b) A view of the building  (Malagamba, 2005)

The architectural elements used in this building to enhance the effectiveness of natural ventilation (cross and stack) are central air shaft, narrow floor plan depth (12 meters), implementation of segmentation concept to enhance the stack affect, incorporation of SG to purify the incoming air, use of double skin façade with external rain screen/brise-soleil façade acting as a buffer for high wind speeds at height and inner skin with “floor to ceiling” high sliding windows. Shading through the external wooden lattice skin of double skin façade and low window to wall ratio contribute to reduced energy consumption (Aslan & Sev, 2014).

All these elements contribute in annual energy saving of this building that is found to be 100%. This building does not use any mechanical plant for heating or cooling (A. Wood & Salib, 2013).

### 4.2.3 1 Bligh Street

1 Bligh Street Tower is 139 meters tall (30-storey). It is an office building located in Sydney, Australia, built in 2011. Being in a tropical climate region gives the opportunity to use NV as a cooling strategy.  Thus, the design is comprised of mixed mode/hybrid ventilation system to reduce the cooling load and increase the indoor comfort level. (A. Wood & Salib, 2013). The shape of the plan is aerodynamic i.e. oval or circular plan shapes provide less resistance to the

incoming wind and avoid vortex.

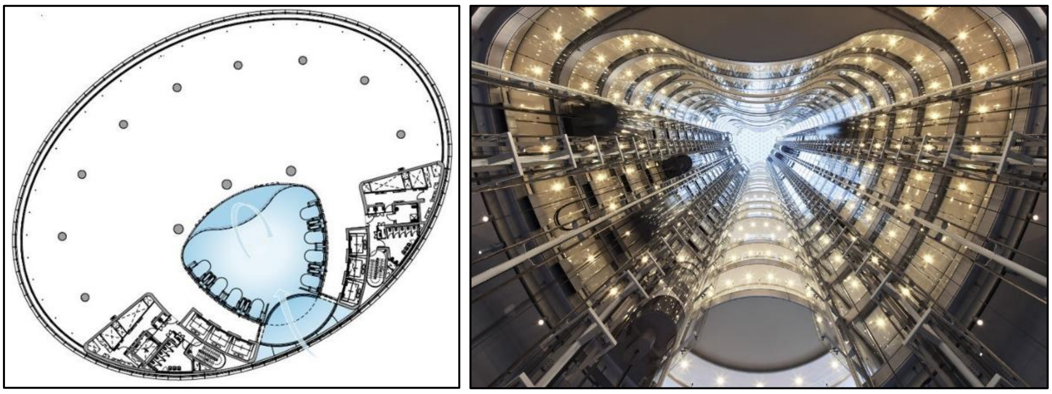


Figure 29 a) Plan of the building & wind direction and sun path diagram, b) View of central air shaft/atrium (A. Wood & Salib, 2013)

The architectural elements used in this building help reducing the cooling load by enhancing NV. Air shaft/ atrium located at the entrance point of each floor is covered at the top with the solar collectors which provides energy to the cooling systems to introduce fresh air inside building without additional running cost (heating consumption is also covered by the same system). The building is incorporated with double skin glass façade that has an air cavity (the enters the cavity from the bottom and leave from the top after heating up while providing buffer for the external heat to directly enter). Aerodynamic floor plan shape helps enhancing NV through the building. Three stories high lobbies surrounded by glass louvers allows cross and stack affect. Balconies facing atrium give rise to easy exchange of air between indoors and atrium (CTBUH, 2019a; Lochhead, Oldfield, & Lochhead, 2017; B. Raji et al., 2014).

Furthermore, incorporation of two sky courts, one on the 15th floor, one on the 30th floor and one of 10 m height in the form of a sky-roof and implementation of concept of segmentation also affect the NV performance (S. F. Alnusairat, 2018). The office spaces, however, are designed to be fully air-conditioned (CTBUH, 2019a; Lochhead et al., 2017; B. Raji et al., 2014).

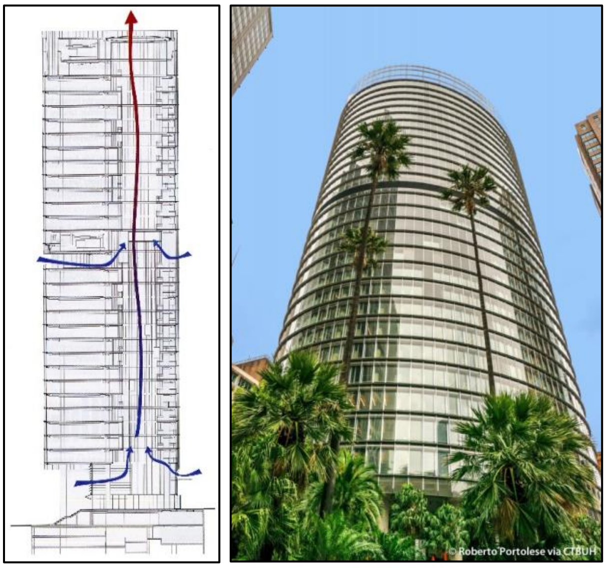



Figure 30 Ventilation process of 1 Bligh Street involving cross ventilation and stack effect (A. Wood & Salib,

2013); b) A view of the building (CTBUH, 2019)

The building uses Tri-generational system for heating, cooling and electricity generation. All these elements contribute in annual energy saving of this building that is reported to be 63% (A. Wood & Salib, 2013).

### 4.2.4 CapitaGreen/Market Street Tower

Capita Green/Market Street Tower is 242 meters tall (40-storey). It is an office building located in Singapore, built in 2014. HVAC system used in the building is mechanical. It is located in the business district of the city and thus surrounded by many other tall buildings. The location makes it difficult for the building to ventilate the spaces without mechanical means. Thus, the incorporation of wind scoop helps drawing cooler and clean air from the top. The air than passes through a void that cools it down through mechanical air conditioning system and penetrates it to the spaces (Al-Kodmany, 2018b).

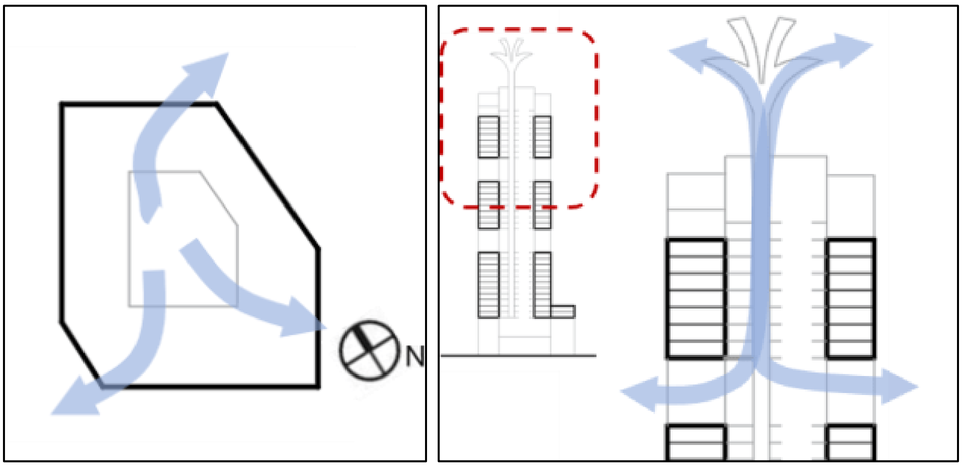



Figure 31 a) Plan of the building and b) Section ; showing the airflow path & wind direction from wind scoop to the spaces (The Λrchitecture Gazette, 2019)

The architectural features that contribute in reducing the energy consumption in this building are: floor-to-ceiling height (3.2 metres) that allows the incorporation of large windows reducing electricity consumption for lighting and gives the sense of openness, energy efficient double skin façade with high performance glass and façade greenery, implementation of segmentation concept and incorporation of SG at 5$^{th}$, 14$^{th}$ and 26$^{th}$ floor and roof garden and triple height Lobbies (Council on Tall Buildings and Urban Habitat, 2019).

All the mentioned features contribute in annual energy saving of this building that is reported to be 30% (Parakh, 2016).

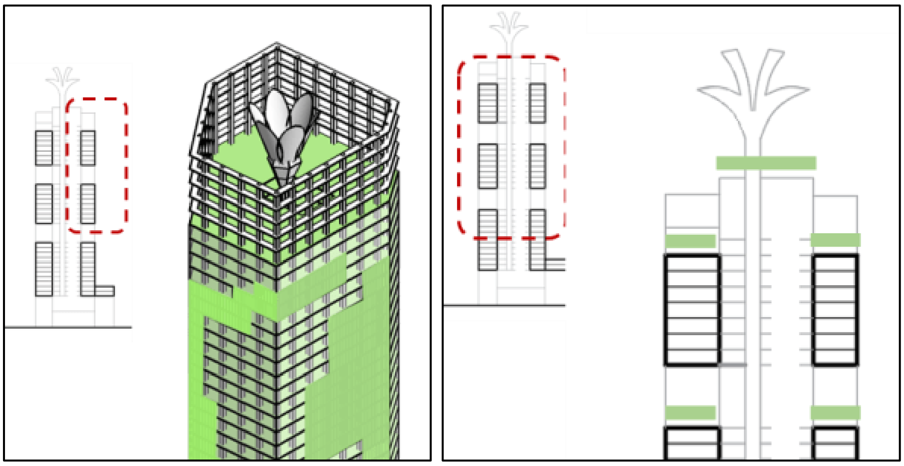


Figure 32 Vertical green spaces in façade and sky terraces integrated in building(The Λrchitecture Gazette, 2019)

### 4.2.5 One Central Park

One Central Park Tower is comprising of two towers, western tower is 84 meters high while eastern tower is 117 meters tall (13-storey). It is a mixed-use building located in the business district of Sydney; Australia built in 2013 (Nouvel & Beissel, 2014). The shape of the floor plan is rectangular and elongated. The orientation of the building favours the flow of incoming wind through it enhancing the cross ventilation (Nouvel & Beissel, 2014).

Ventilation system used in the building is hybrid. The design is intended to approach sustainable standards of residential building under the Australian Green Star rating system. The aim was to build an environmentally responsible structure that can contribute in reducing carbon footprint. This aim was achieved through the integration of five kilo meters long system of slab edge planters which provide the shading to reduce the cooling load. Additionally, these plants reduce the heat gain in the apartments by 20%. Other vegetation systems integrated with the buildings are living facades and green roof (A. Wood, Bahrami, & Safarik, 2014).

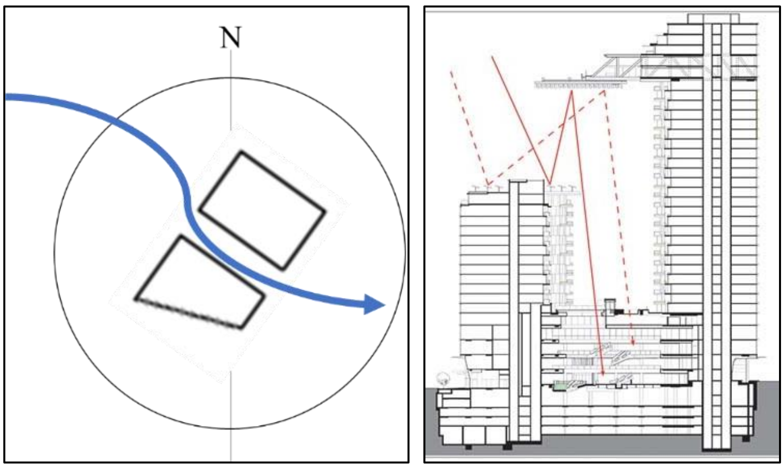



Figure 33 Plan of the building showing wind flow; b) daylight reflection through holiostat

Figure 34 A view of vegetated balconies and façade of building (S. Wood, 2008)

One of the defining features of this building is heliostat[14], cantilevered from the twenty eighth floor. It reflects the sunlight to the gardens and atrium reducing the energy required for lighting. This is all year light source for building and adjoined gardens. Other features include the heat sink created by adding a layer of water at the glass roof of atrium, 100 meters high sky garden, recycling of black water to use in toilets and washing, air conditioning and irrigation purposes.

All the mentioned features contribute in annual energy saving of this building that is reported to be 25% (Brian Fullen, 2015).

### 4.2.6 Skyville@Dawson

Skyville@Dawson Tower is 152 meters tall (48-storey). It is a residential building located in the downtown of Singapore built in 2015. The shape of the floor plan is rectangular and elongated. The orientation of the building favours the flow of incoming wind through it enhancing the cross ventilation in all apartments (Wong, Hassell, & Yeo, 2016).

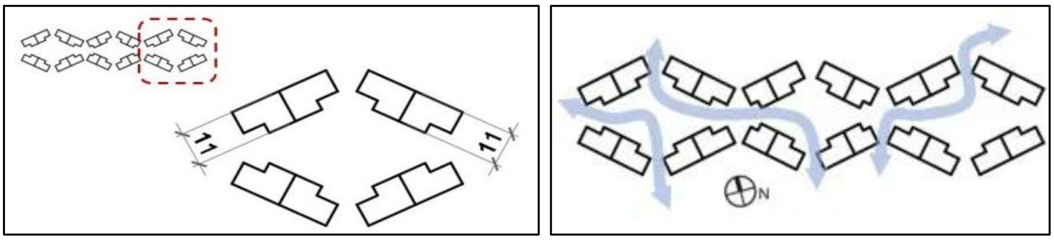



Figure 35 a) 11meters wide apartment blocks enable ventilation (Sharma, Aditi Bisen, & Yanming, 2018); b) Plan of the building showing the sun path diagram (Sharma, Aditi Bisen, et al., 2018)

The architectural features of this building to enhance the effectiveness of NV in the apartments and reduce the cooling load of the building are; narrow plan depth (11 meters), Operable windows, implementation of the concept of segmentation, incorporation of SG at every 12

[14] A heliostat is a plane mirror that reflects the sunlight to a targeted place for the compensation of direct sunlight. It is derived from Greek helios which means sun and stat that means stationary. This device was first invented by Willem 's Gravesande (1688-1742). (*A New and Complete Dictionary of Arts and Sciences*, 1763).

floors and a public garden on roof, horizontal and vertical shading systems, installation of photovoltaic panels at rooftop, covered balconies and monsoon windows[15] (Sharma, Aditi Bisen, et al., 2018). All the common spaces i.e. stairways, lobbies and lift are naturally ventilated while the apartments are fully naturally ventilated including kitchen and bathroom spaces (Generalova, Generalov, & Potienko, 2016; Samant & Menon, 2018).

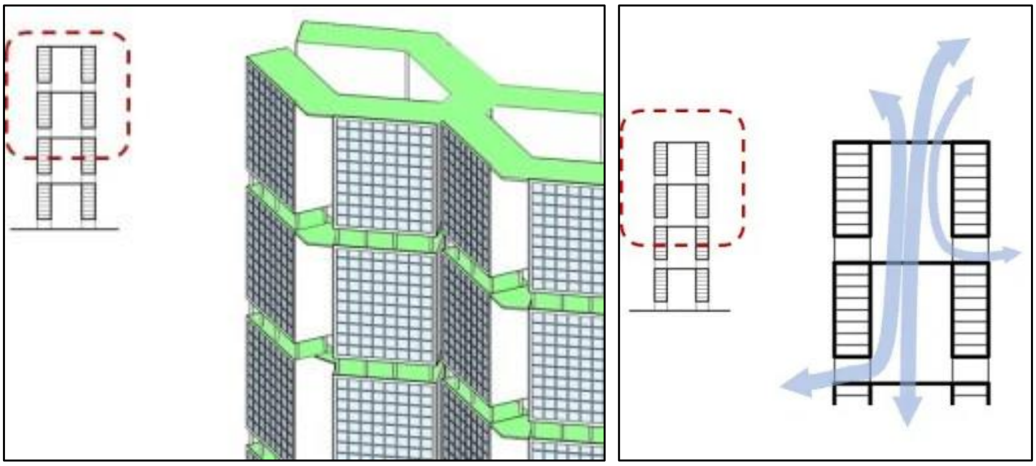


Figure 36 a) Sky gardens and rooftop garden used in Skyville@Dawson (Sharma, Aditi Bisen, et al., 2018); b) Natural ventilation based on stack affect (Sharma, Aditi Bisen, et al., 2018)

All the mentioned features contribute in annual energy saving of this building that is reported to be 55% (322,552 kWh/yr) (BCA, 2010).

### 4.2.7 Skyterrace@Dawson

Skyterrace@Dawson Tower is 142.3 meters tall (44-storey). It is a residential building located in the downtown of Singapore built in 2015. It is composed of five towers connected through a series of skybridges to engage the users with the surrounding. The shape of the floor plan is rectangular and elongated. The orientation of the building favours the flow of incoming wind through it and minimizes the solar gain in summer.


[15] These are the type of windows specially designed with shading so that the wind can be drawn into the building without letting the rain enter (Sharma, Aditi Bisen, et al., 2018).

Figure 37 a) Plan and wind flow through the building (Author); b) A view from ground floor (Sftey, 2019).

The green architectural features involve use of NV through elevated green sky terraces, operable windows and atrium, Elevated gardens, harvesting of rain water, generation of energy through rooftop solar array, shading systems to reduce the cooling load (Fredrickson, 2014).

Figure 38 Different views of BIV system used in Skyterrace@Dawson

All the mentioned features contribute in annual energy saving of this building that is reported to be 793,962 kWh/yr (BCA, 2010).

### 4.2.8 Magic Breeze Sky Villas

Magic Breeze Sky Villas is a residential building composed of 127 residential duplex units. Each residential unit has its own garden. The building is located in Hyderabad, India. The project is still under construction phase started in 2017. However, it is the part of study due to the interesting fact that the design of each residential units is based on “VAASTU” concept (Designboom, 2016). This is a traditional hindu architectural system according to which the architecture design is integrated with nature through geometrical patterns, symmetry and directional alignment (Sachdev & Tillotson, 2002).

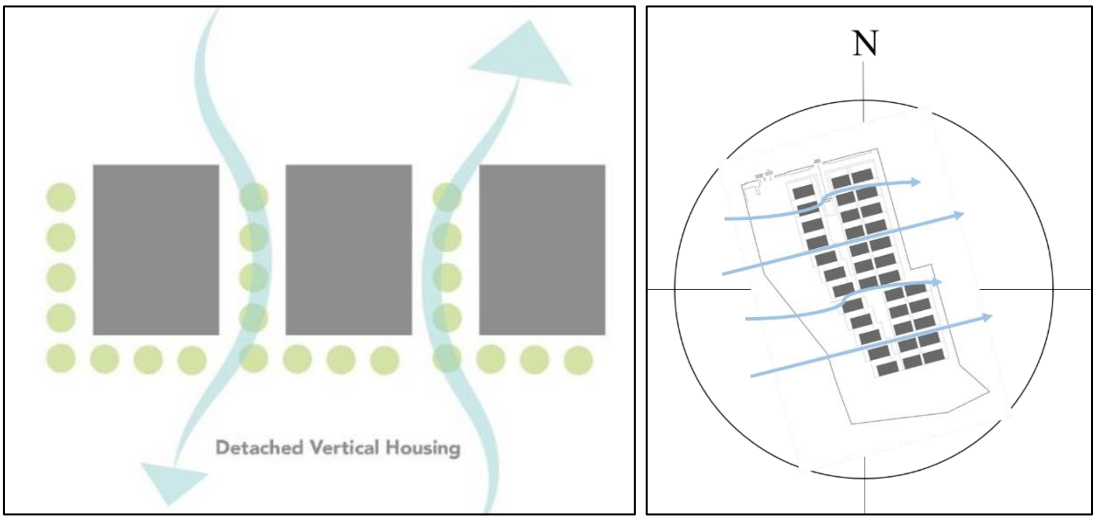



Figure 39 a) Arrangement of units with wind flow (Precht, 2016); b) Wind flow through the residential units

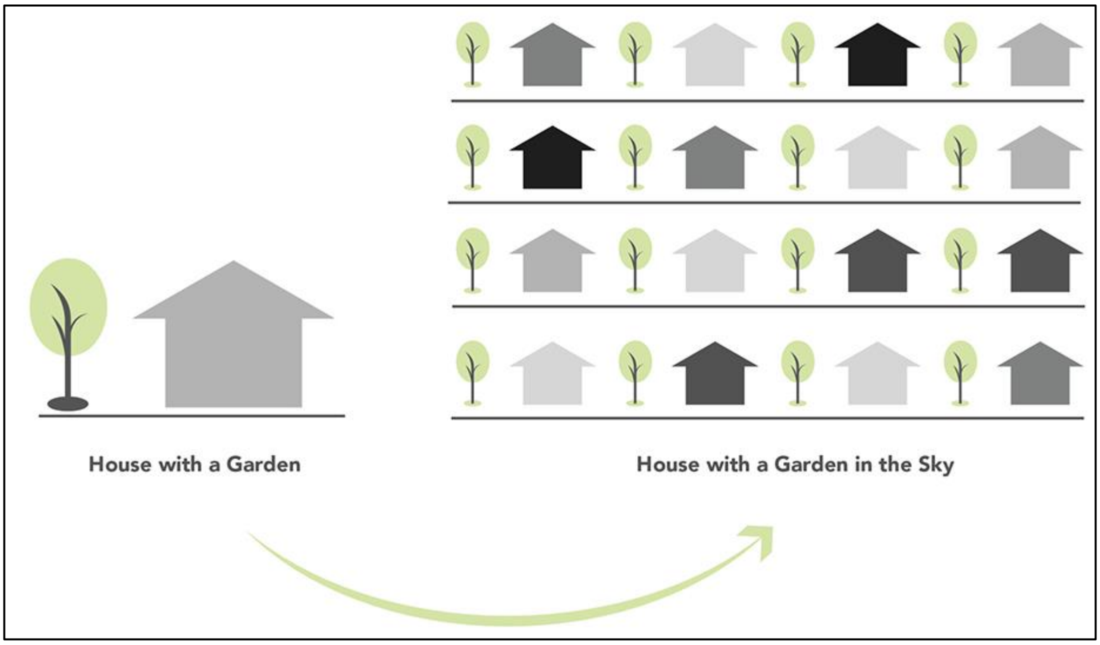



Figure 40 Concept of Incorporation of vegetation with residential units (Precht, 2016)

The orientation of the plan is in a way that it lets the incoming wind pass through the units through balconies incorporated with modular planter system. These planters can be filled with variety of plants according to the choice of occupants. The air purified through the vegetation than enters the residential unit to ventilate the spaces (Precht, 2016).

Figure 41 Balcony planters (Designboom, 2016).

annual energy saving of each residential unit in this building is expected (according to pre-construction estimation) to be 60% (Designboom, 2016).

### 4.2.9 Solaris

Solaris Tower is 79 meters tall (15-storey). It is an office building located in the central business district of Singapore built in 2011 (Al-Kodmany, 2018b). The building is composed of two towers which are connected to each other through a central atrium that is naturally ventilated. The ventilation system being used in this building is hybrid. Building is naturally ventilated through stack affect due to atrium, as well as cross ventilation due to terraces (A. Wood, Payam Bahrami, & Daniel Safarik, 2014).

Architectural features used in this building to reduce cooling load are Roof Gardens, Green ramps along the perimeter of the building, sky terraces which open extent the atrium at top floors, central atrium, solar shaft, climate responsive façade, corner sky terraces and louvers for shading (A. Wood, Payam Bahrami, et al., 2014).

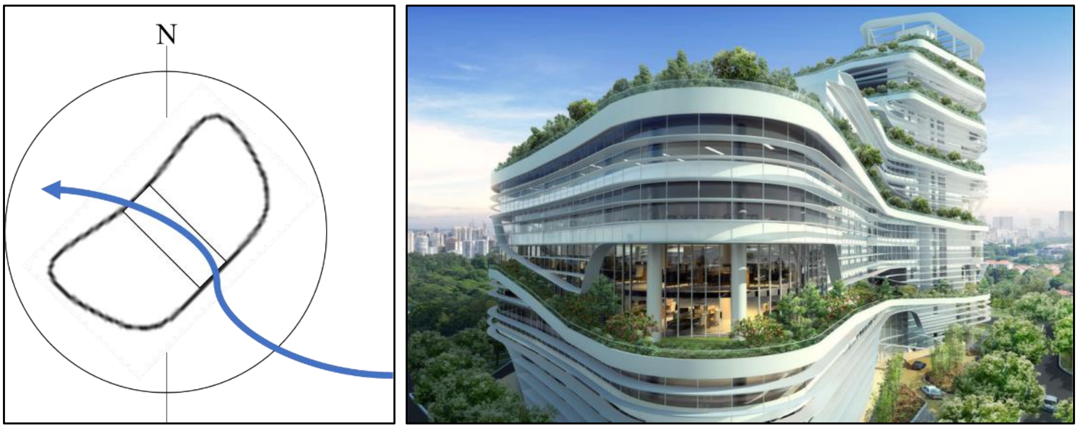



Figure 42 a) Plan shape and wind flow ; b) View of the building ("Solaris – Singapore | Esther Klausen," 2019)

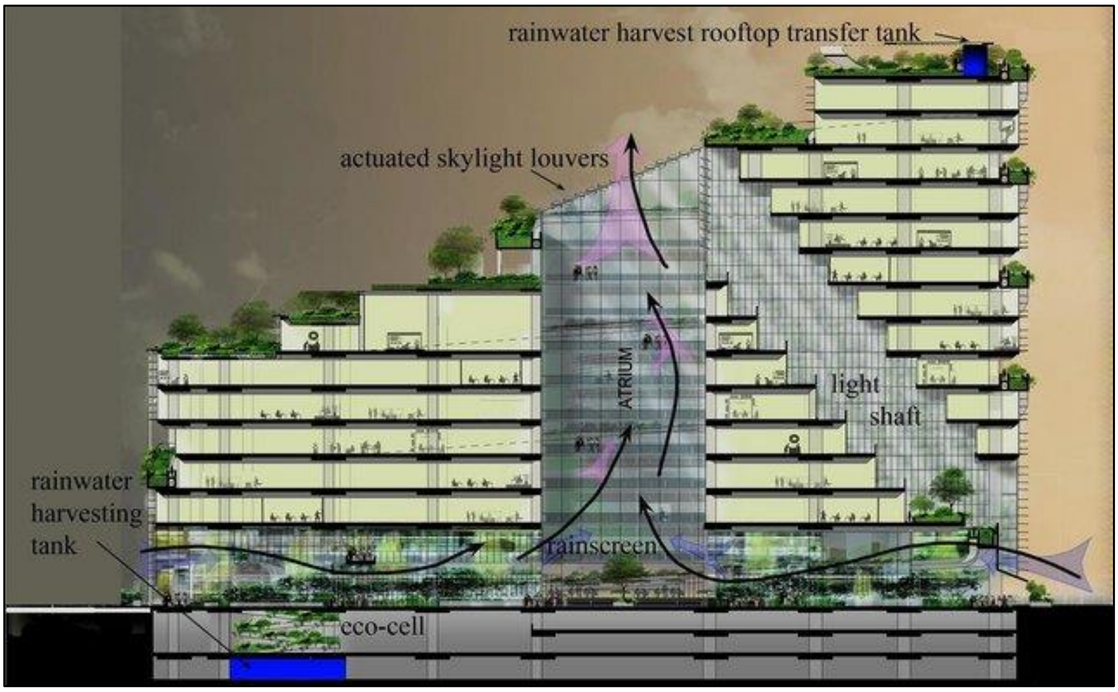



Figure 43 Different greening systems used in Solaris tower (Widera, 2014)

All the mentioned features contribute in annual energy saving of this building that is reported to be 2,828,470 kWh/yr (36%)  (BCA, 2010; A. Wood, Payam Bahrami, et al., 2014).

### 4.2.10 Parkroyal on Pickering

Parkroyal on Pickering Tower is 89 meters tall (15-storey). It is a hotel and office building located in the central district of Singapore built in 2012 (Al-Kodmany, 2018b; A. Wood, Bahrami, et al., 2014). Narrow plan depth (15 meters) with the open sided courtyard helps in enhancing the cross ventilation in the building ("Passive Strategies: Natural Ventilation," 2019).

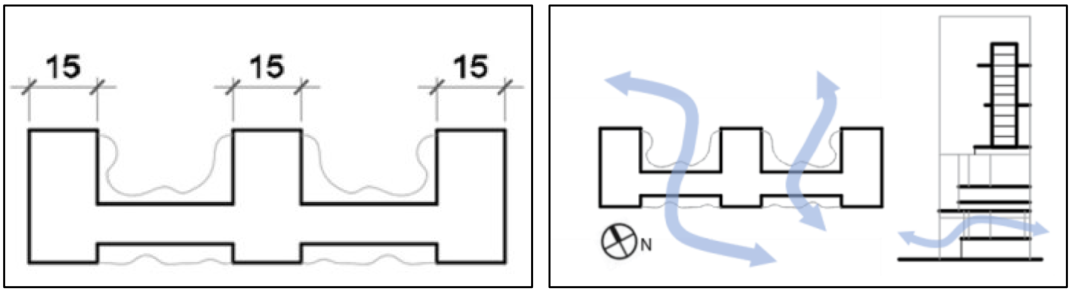



Figure 44 a) Plan depth b) Plan and section of the building showing the airflow path (Sharma, Bisen, Hongbo, & Yanming, 2018)

Prominent features of this building are the integrated vegetation systems i.e. balconies and terraces covered with plants, roof terrace, sky gardens and green facades (Safarik, 2016).

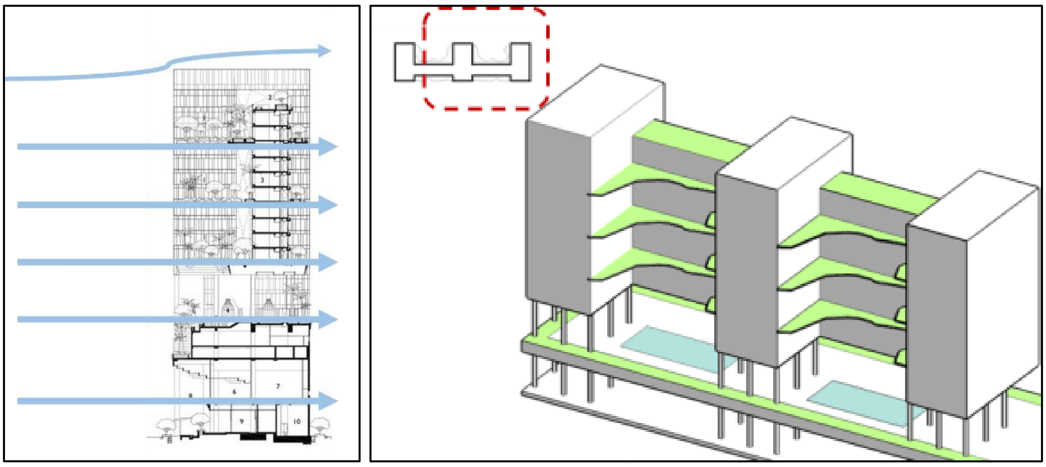


Figure 45 a) Ventilation process of Parkroyal on Pickering involving cross ventilation; b) Building Integrated vegetation (Sharma, Bisen, et al., 2018)

All the mentioned features contribute in annual energy saving of this building that is reported to be 30% (A. Wood, Bahrami, et al., 2014).

## 4.3 Comparison criteria

Literature has shown that the successful output of the implementation of NV and VG may be guaranteed through the adoption of some specific design concepts (i.e. incorporation of segmentation, incorporation of airshaft, overall building shape/form, plan depth, shape of floor plan, shape and location of airshaft in building, ceiling height of each story and night time ventilation), architectural elements (i.e. wing wall, wing roof, double skin façade, wind catcher, lobbies, operable windows and shading devices). The comparison of the case studies and their analysis is made on the basis of adopted design characteristics, architectural element (suitable for the affective implementation of NV and BIV systems in tall building in tropical climate) and corresponding percentage of annual energy saving and is shown in **Table 21**.

Table 21 Comparison Criteria of cases studies of tall buildings located in tropical climate(S. F. Alnusairat, 2018; Ismail, 2007; The Chartered Institution of Building Services Engineers (CIBSE), 2005)

| **Comparison Criteria** | **Parameters** |
|---|---|
| Applied design characteristics/ concepts | • Segmentation<br>• Location of air shaft<br>• Overall Building shape/form<br>• Plan depth<br>• Plan shape<br>• Shape of air shaft<br>• High ceiling height (to enhance stack effect)<br>• Night-time ventilation |
| Architectural elements | • Wing wall<br>• Wing Roof<br>• Double skin façade/Rain screen/Brise-soleil<br>• Wind Catcher<br>• Lobbies<br>• Operable window<br>• Shading devices |
| Annual energy saving (AES) | • Percentage savings for heating and cooling in comparison with a similar building using mechanical air conditioning system |

**Table** 22 contains floor plan shapes, wind direction and corresponding annual energy saving of the buildings that are in tropical climate region and selected for this study. The plan shapes are based on the arrangement and manipulation of basic geometrical shapes/form i.e. circle, triangle and rectangle. For instance, Menara Umno tower is based on rectangular shape with one curved façade. This concept is shown in the **Figure 46**.

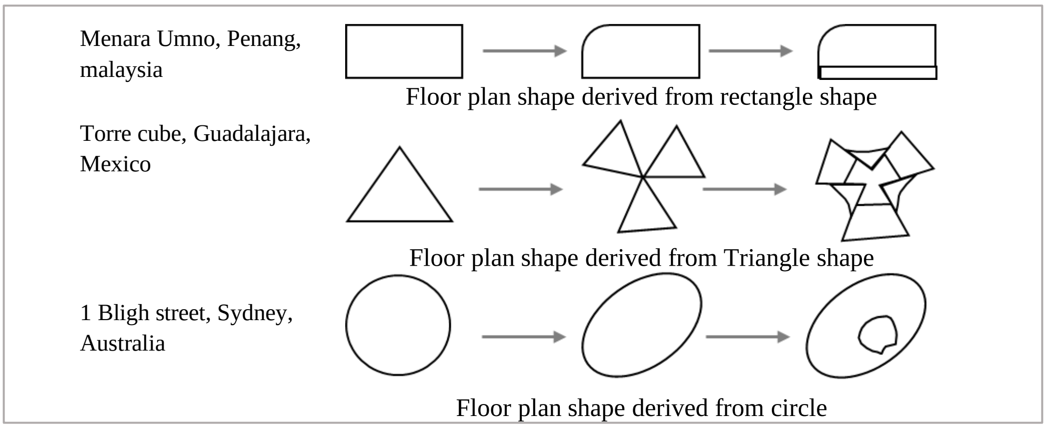
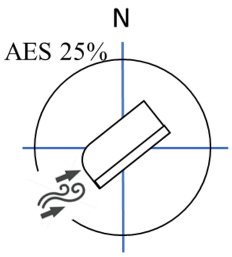
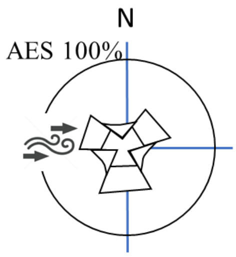
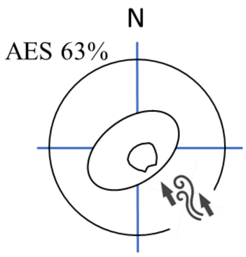
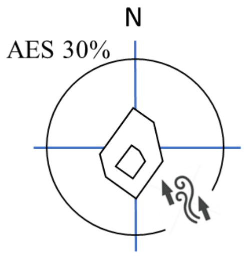
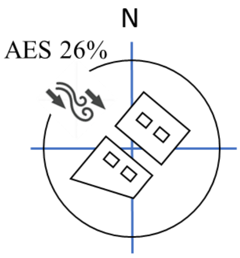
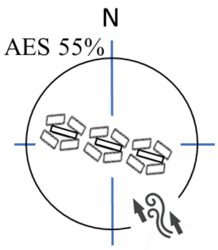
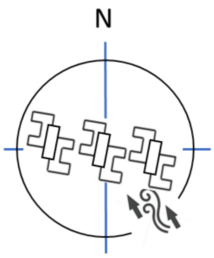
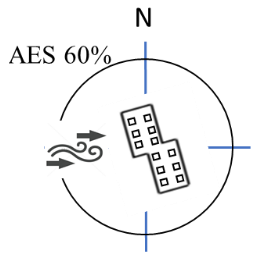
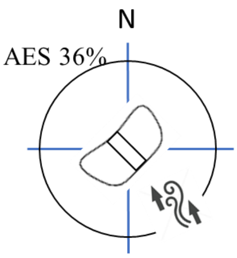
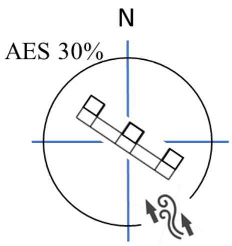



Figure 46 Examples of floor plan shapes of three buildings as derived from basic geometrical shape.

The floor plan shapes are defined based on wind direction and other climatic conditions. In tropical climate the aim is to avoid the summer sun and rainwater and invite the wind to ventilate the spaces for reducing the cooling load. It can be seen from the

**Table** *22* that buildings are oriented in a way that the building floor plan/shape offers least resistance to the incoming wind.

Table 22 Case study buildings, their orientation, wind direction and respective annual energ saving (AES) values in percentateg (Mughal & Beirão, 2019b)

| **1** | **2** | **3** | **4** |
|---|---|---|---|
| <br>Menara Umno, Penang, malaysia | <br>Torre cube, Guadalajara, Mexico | <br>1 Bligh street, Sydney, Australia | <br>Capitagreen, Singapore |
| **5** | **6** | **7** | **8** |
| <br>One Central Park, Sydney, Australia | <br>Skyville@Dawson, Singapore | <br>Skyterrace@Dawson, Singapore | <br>Magic Breeze Sky Villas, Hyderabad, India |
| **9** | **10** | | |
| <br>Solaris, Singapore | <br>parkroyal on pickering, singapore | | |

Taken together, these studies support the notion that shape, and orientation of building plays a significant role in annual energy performance, shown in **Figure 47**. However, one should consider that design of tall building is not an easy process, there are several other factors that may affect the energy performance.

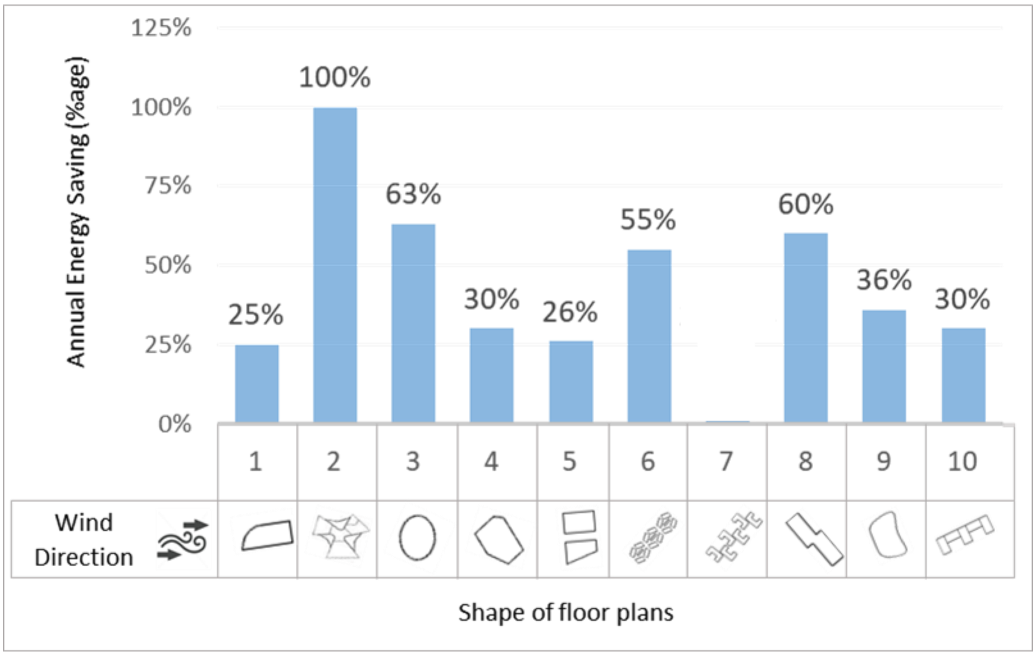



Figure 47 Energy savings associated with different floor plans in case study buildings

The evidence reviewed here seems to suggest a pertinent role for the service core/air shaft /atrium providing stack affect for NV process. In this regard the location and shape of the core is found to be affecting the ventilation phenomenon. The most common shape adopted for atrium is rectangular while the location is either along the façade or in the centre depending on the case and urban context together with the wind direction.

**Table 23** shows the location and shape of atrium in the buildings. Together, these studies indicate that there is strong relationship between the integration of SG, NV and Segmentation concept for maximum cooling energy saving i.e. Torre Cube Tower is based on natural ventilation and is incorporated with SG and segmentation concept, saving 100% cooling energy.

**Table 24** shows the energy saving by the buildings using the NV and different types of VG systems.

**Table 25** shows the adaptation of design characteristics/strategies and architectural elements for reducing cooling load by these buildings.

Table 23 Location of service core/atrium in buildings

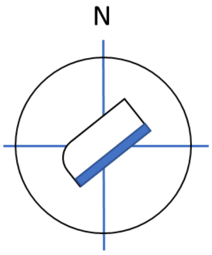
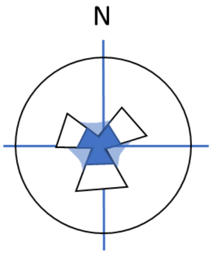
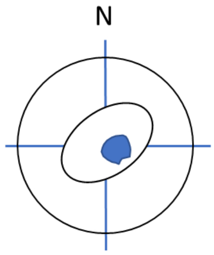
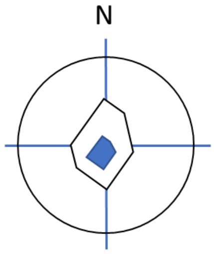
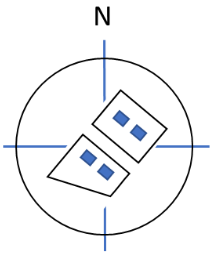
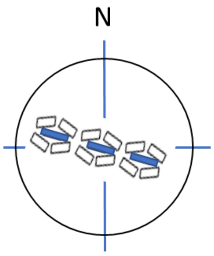
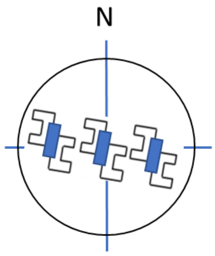
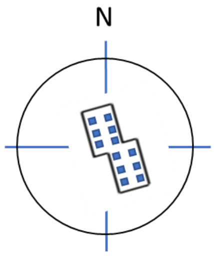
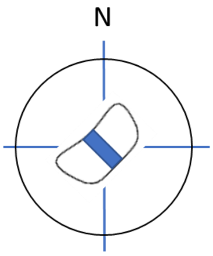
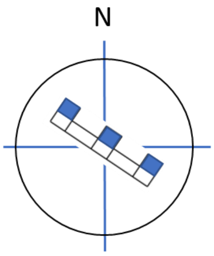
| 1 | 2 | 3 | 4 |
|---|---|---|---|
|  Menara Umno, Penang, malaysia |  Torre cube, Guadalajara, Mexico |  1 Bligh street, Sydney, Australia |  Capitagreen, Singapore |
| **5** | **6** | **7** | **8** |
|  One Central Park, Sydney, Australia |  Skyville@Dawson, Singapore |  Skyterrace@Dawson, Singapore |  Magic Breeze Sky Villas, Hyderabad, India |
| **9** | **10** | | |
|  Solaris, Singapore |  parkroyal on pickering, singapore | | |

Table 24 List of case studies with NV, VG and usage information

| Case No. | Usage | AES (%) | Segmentation | Ventilation type | Type of vegetation | | | | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Green Walls | Sky-Gardens | Vegetative Balconies | Roof Garden | |
| 1 | Off. | 25 | | MM | | | | | (Ismail, 2016) |
| 2 | Off. | 100 | ✓ | N | | ✓ | | | (McManus, 2018) |
| 3 | Off. | 63 | | MM | | | | | (Lochhead et al., 2017) |
| 4 | Off. | 30 | ✓ | M | | ✓ | ✓ | ✓ | (Parakh, 2016) |
| 5 | Mix | 26 | | MM | | | | ✓ | (A. Wood, Bahrami, et al., 2014) |
| 6 | Res. | 55 | ✓ | MM | | ✓ | | ✓ | (Samant & Menon, 2018) |
| 7 | Res. | N/A[16] | | MM | | | ✓ | ✓ | (CTBUH, 2019c) |
| 8 | Res. | 60 | | MM | | | ✓ | | (Designboom, 2016) |
| 9 | Off. | 36 | | MM | ✓ | | ✓ | ✓ | (Yeang, 1999) |
| 10 | Off. | 30 | ✓ | MM | ✓ | ✓ | ✓ | | (Frearson, 2103) |

*where Off: office use, Res: residential use; Mix: mixed usage (both office and residential use); AES= Annual energy saved; M=Mechanical; MM: mixed mode; N=natural mode

Table 25 Comparison of incorportion of suitable design characteristics/stretegies and architectural elemnts for reducing cooling load in tropical climate in 10 cases of tall buildings

| Strategies | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Narrow plan depth | ✓ | ✓ | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ | ✗ | ✓ |
| Increased ceiling height | ✓ | N/A | N/A | ✓ | N/A | N/A | N/A | N/A | N/A | N/A |
| Night-time ventilation | ✗ | ✗ | N/A | ✗ | N/A | N/A | N/A | ✗ | ✓ | N/A |
| Wing wall | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Wing roof | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Double skin façade | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Wind catcher | ✗ | ✗ | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Lobbies | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Operable windows | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Shading device | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**Figure 48** shows the relationship of overall building form and energy saving through NV. It has been found that the circular shape/ forms have the maximum capacity to reduce the energy

[16] The total energy saving per year for Skyterrace@Dawson was only found in kWh/yr (that is reported as 793,962 kWh/yr) (BCA, 2010).

consumption through NV provided the other architectural elements are supporting NV as well i.e. atrium, segmentation, wind scoop, wing wall etc. Polygonal shape is the second-best shapes for the effectiveness of NV as they provide less resistance to the incoming win das compared to the sharped edged building i.e. rectangular.

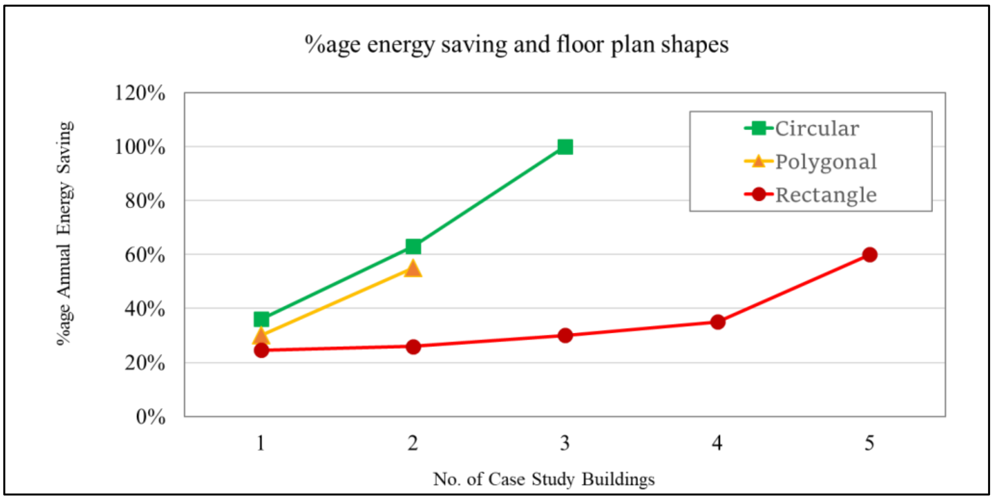



Figure 48 Energy saving by case builidng having different overall shapes/forms

Furthermore, potential of integrated VG system to enhance the effect of NV for reduced cooling load is found to be the most effective in case of the sky gardens. Green walls also help reducing the cooling load but the significance of GW to reduce cooling load is through insulation provided by the growing medium of the plant. SG on the other hand not only provide the insulation to the floors below but also channelize NV for the adjacent floors.

**Figure** 49 gives the reflection of this concept through the observation from the case studies.

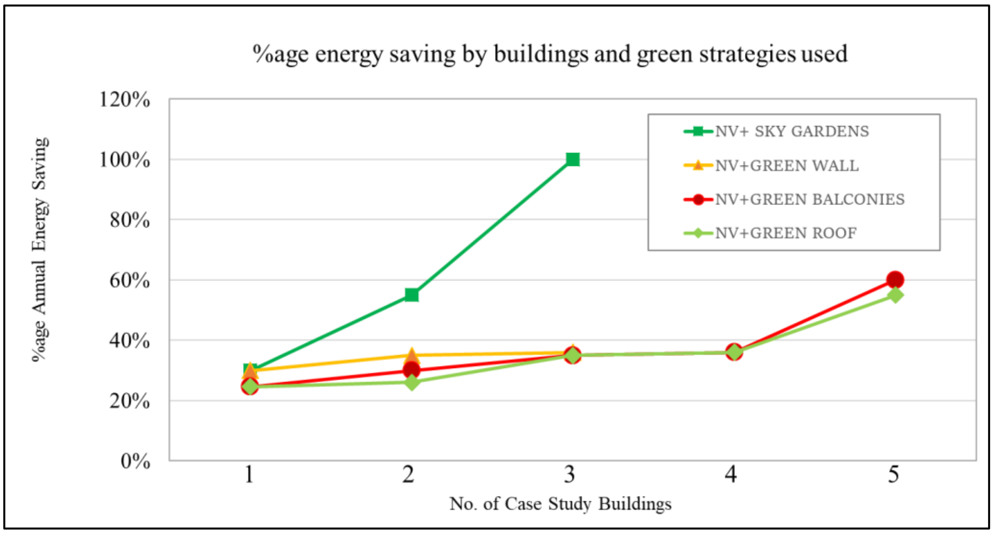



Figure 49 Green stretegies and their impact on energy saving in case studies

## 4.4 Observations

- Approximate percentage of the year, when NV can be utilized is 100% for the building with narrow plan depth e.g. Menara Umno, Torre Cube, skyville@Dawson, Skyterrace@Dawson and parkroyal on pickering.
- Shape of the service core or atrium is found to be rectangular/square for 7 out of 10 buildings i.e. Menara Umno, Torre Cube, Once Central Park, Skyville@Dawson, Skyterrace@Dawson, Magic Breez Sky Villas and Parkroyal on Pickering, usually located in the centre of the building plan.
- Usual Floor Plan shapes are found to be rectangular, circular or triangular.
- All the buildings have lobbies, operable windows, shading devices and air shafts which are necessary architectural elements for reduction of cooling load in tropical climate.
- Most of the buildings using the concept of segmentation have the advantage of using NV highest time of the year i.e. Torre Cube and 1 Bligh Street. Thanks to the characteristics of Tropical climate that makes the use of this strategy even efficient than using in any other climate.
- Highest annual energy saving is found in buildings using the combination of NV, SG and Segmentation.
- Highest annual energy saving is found in buildings with circular shapes or curved /trimmed corners of Plan shapes and the shape with least resistance to incoming wind (If the building is having narrow plan depth and is oriented in a way that the longer side is parallel to the wind direction than the wind patterns are going to suitable to channelize the natural ventilation across or along the building envelope).
- Sky/Gardens accelerate the wind speed causing efficient air flow across the buildings and provides better psychological situation for the users at top floors i.e. Torre Cube.
- Floor to ceiling height is ranging between 3.2 meters to 3.85 meters.
- Buildings using only NV for cooling have narrow plan depth i.e. 11 meters or 15 meters etc.

- Buildings using combination of NV and SG are saving almost 100% cooling load i.e. Torre Cube.

## 4.5 Findings of the Case studies

Since all buildings have different urban context, a real comparison cannot be made for identifying the absolute design strategies that can be implemented for the best design solution. However, the most obvious finding to emerge from this study is that the few characteristics must be applied to the design of tall building for the effectiveness of NV and SG as cooling strategies in tropical climate. These characteristics (also verified from the literature) include:

- Narrow plan depth (B. Raji et al., 2014)
- Increased ceiling height (The Chartered Institution of Building Services Engineers (CIBSE), 2014)
- Incorporation of segmentation (Liu et al., 2012)
- Floor plan shapes with less resistance to incoming wind i.e. circular edged (Zhao & He, 2017), and elongated (having the shorter width facing incoming wind) (Hadji, 2019).
- Rectangular shape of atrium located in the centre of floor plan (Aldawoud, 2013).

Together, this study indicates that double skin façade, operable windows and shading devices and central atrium/air shaft are the most favourable architectural elements for promoting NV to reduce cooling load (Elotefy et al., 2015).

# *Development*

*This part of the thesis is composed of chapter#5 and chapter#6. It gives a detailed description about the development process of optimization model, applicable for the design of nearly zero energy tall buildings for tropical climate. It encompasses the thorough explanation of the development of i) generative tool (GT), ii) an algorithm for the generation of random population of 3D-models of tall buildings, termed as random generator (RG), iii) an algorithm for the partial integration of RhinoCFD tool for simulation of the 3D models generated through GT iv) an algorithm for the fitness evaluation and ranking of simulated 3D-models v) an algorithm for the storage of database of all the results in excel. The concept of integration of Genetic Operation for finding the optimal solution has also been described.*

*A part of this chapter has been published in the eCAADe conference: Architecture in the Age of the 4th Industrial Revolution, under the title "A Workflow for the Performance Based Design of Naturally Ventilated Tall Buildings Using a Genetic Algorithm (GA)"* (Mughal & Beirão, 2019) *in which the proposed optimization model has been applied to a set of random 3D Models of tall buildings for finding the best solution.*

*This part is completed with conclusion and future recommendations.*

# 5 DEVELOPMENT OF GENERATIVE TOOL (GT)

Development of proposed GT is based on parametric generative design (GD), that is a process to generate numerous design solutions from a set of rules and constraints defined by a parametric system. The parametric design system is primarily based on algorithmic principles. El-Khaldi (2007) defined parametric DG as "Thinking in terms of algorithms" (El-Khaldi, 2007). While an algorithm is a mathematical description of a well-defined action that we want to perform. We can view them as a set of steps to follow in order to achieve a specific goal. It takes one or several input values, executes a sequence of computational steps to produce an output (DİNO, 2012). It may relate to the example of baking a cake, however proposed generative algorithm may relate to a situation where several cakes are being produced by varying the ingredient quantities. The process of making a cake requires i) ingredients ii) recipe. The ingredients may be termed as the input variables, the quantity of these ingredients may vary within the range of values of these variables that has got some constraints to have the better-quality cake, the recipe represents the set of rules to be followed or the algorithm and the cake is the final output. Changing the quantity of ingredients i.e. values within the range of values of input variables can help making variety of cake (Tedeschi, 2014). The process can be shown through the following figure.

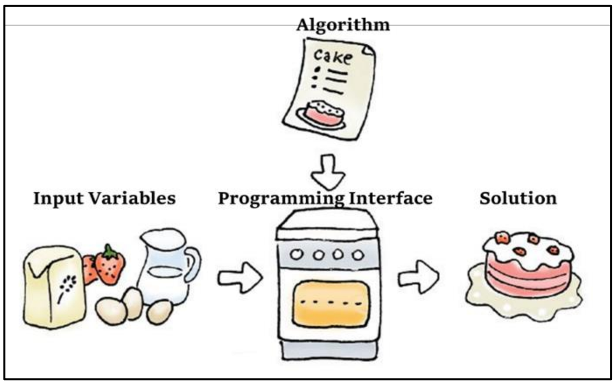



Figure 50 Parametric generative design

Algorithms cannot only computationally generate design solutions but also have the capability to manipulate them (DİNO, 2012) therefore they are viewed as extensions to the human brain and help to get to the unpredictable potential of design solutions (Menges & Ahlquist, 2011).

Thus, the proposed Generative Tool (GT) is composed of several input variables and a generative algorithm for the development of various solutions. The selection of input variables is based on scientific literature (i.e. already available research and already tested solutions). The developed algorithm is capable to produce multiple solutions by varying the range of these input variables. The workflow for this process is shown in **Figure 51**. It is composed of four steps: i) Review of the already available literature and cases for the scientific basis of the selection of input variables and constraints for the design rules ii) Decision of input variables and the range their values by Identifying the elementary design rules for tall building generation (based on the previous data) iii) Development of generative algorithm composed of; a)genetic code generation and b)Parametric 3D model generation code and iv) 3D model generation of tall buildings.

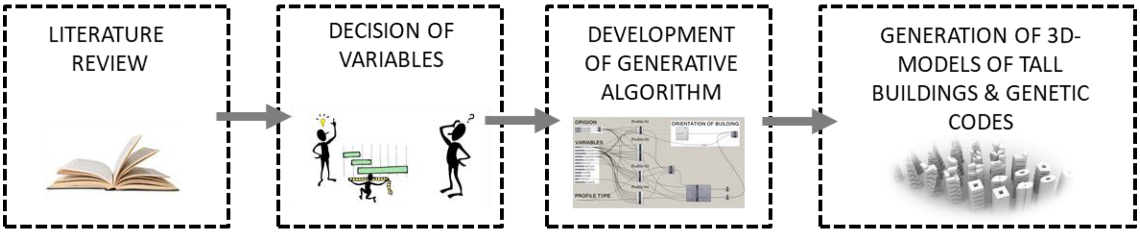



Figure 51 Workflow for the development of GT

## 5.1 Design rules and constraints

GT development process starts with the definition of the geometrical design features and constraints that are needed to be identified to generate various, in fact as much as possible, tall building morphotypes to promote natural ventilation in tropical climate. These features are summarized to be

- **Introduction of an inner ventilation shaft or chimney** to help buoyancy effect in tall buildings (Moghaddam, Amindeldar, & Besharatizadeh, 2011; Mughal & Corrao, n.d.; Oldfield et al., 2009); that can also aid the effectiveness of cross-ventilation when the spaces are facing a tall open space such as an atrium (A. Wood & Salib, 2012).

- **Introduction of the concept of segmentation**[17] with a set of green terraces called sky gardens (David & Brian, 2008; A. Wood & Salib, 2013; J. Yang et al., 2004)
  that not only enhance natural ventilation but also provide better thermal conditions as compared to green balconies (Taib, Abdullah, Fadzil, & Yeok, 2010) by cooling down the local temperature to a maximum of 3ºC decrease (Babak Raji et al., 2015). They also reduce congestion and provide better psychological impact in tall buildings (Oberndorfer et al., 2007) together with increasing the wind velocity and consequently improving the effectiveness of NV phenomenon by improving the permeability of building (Mohammadi & Calautit, 2019; Mughal & Corrao, n.d.; J. . Niu & Burnett, 2001; J. Yang et al., 2004).

[17] Segmentation refers to dividing the building in several parts along its vertical development separating parts by open spaces (Liu et al., 2012).

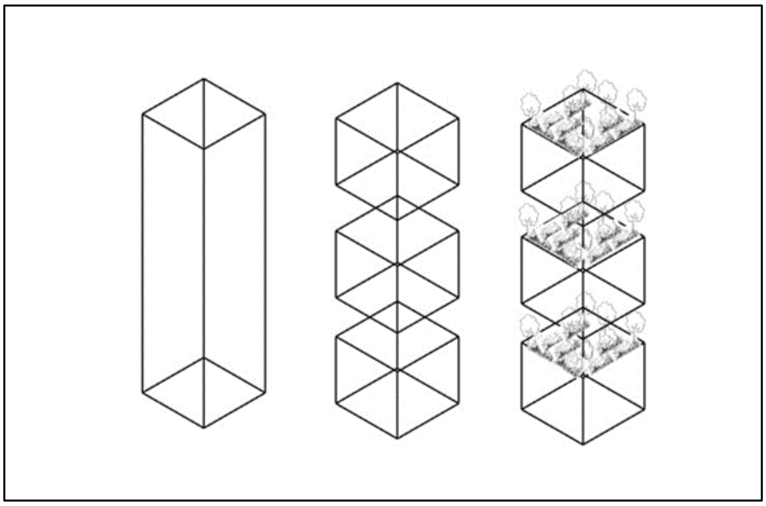


Figure 52 Concept of segmentation and incorporation of vegetation in the space between segmented floor sections i.e. sky gardens

- **Manipulation of external form of building** by rotation, stepping and scaling to develop the effective pressure differences for efficient natural airflow and to lessen the wind loads on the structure (Bing & Ali, 2015).

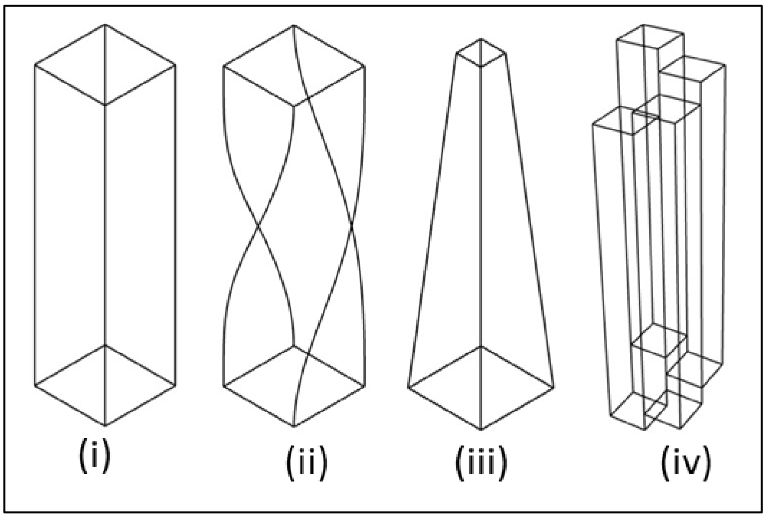



Figure 53 External forms (i) Straight extrusion, (ii) Twisting form, (iii) Scaled form, (iv) Stepped form

- **Shape of plan;** Polygon, square and circular shapes are chosen for the plan shape which can be further manipulated into rectangular, oval and any type of polygon with a central ventilation shaft for air flow. It has been found that the shape of corner affects the flow of air around the building and can either drag it or create vortex and filleted corners are found be more efficient for building aerodynamics (Asghari Mooneghi & Kargarmoakhar, 2016; Elshaer, Bitsuamlak, & El Damatty, 2017). Fewer edges have low drag coefficient values and lead to the most efficient aerodynamic shape (Asghari Mooneghi & Kargarmoakhar, 2016; Tanaka et al., 2013). So, the fillet radius has been provided to give round corner shapes even to the sharp corners of the floor plan geometry. The variable controlling the Floor width makes sure, that the width should be in a way that cross ventilation can be channelized efficiently, i.e., a minimum of 10m and maximum of 21 meter of floor width or plan depth from façade to central core can be ventilated through a natural wind flow process as cross-ventilation - the depth of the room must not exceed five times its height 3.5*5=17.5). However, the buoyancy effect can also aid the effectiveness of cross-ventilation when the spaces are facing a tall open space such as an atrium or a large ventilation shaft (A. Wood & Salib, 2012).

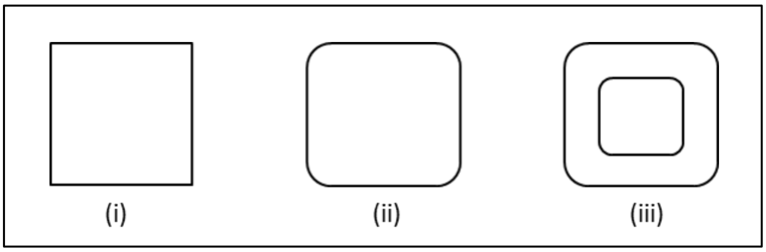



Figure 54 Rectangular Floor plan shape with (i) sharp corners, (ii) Rounded corners, (iii) rounded corners and central air shaft

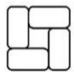
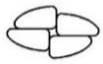
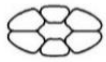
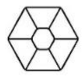
- **Plan depth;** A min of 10m and max of 21m of floor width/plan depth from central core can be ventilated through natural wind flow processes as for effective cross-ventilation, the depth of the room must not exceed five times its height 3.5*5=17.5. (Kubota & Ahmad, 2006) So this is a parametric variation of what can be considered a normal building depth, both in terms of cross-ventilation as well as access to natural light (The Chartered Institution of Building Services Engineers (CIBSE), 2005)

- **The shape of the central core or ventilation shaft;** an atrium has great importance in energy savings and reducing carbon footprints(Aldawoud, 2013; Bano & Sehgal, 2018; Liu et al., 2012; Sher, Kawai, Güleç, & Sadiq, 2019). Atrium geometry affects the total energy consumption of buildings. Narrow, elongated atrium shapes show poor results in all climates and square shapes are found to be the best among all (Aldawoud, 2013; Bano & Sehgal, 2018). Hence the shape of the central atrium is considered rectangular or polygonal.

## 5.2 Decision of input variables

Building morphotypes or profile type is one of the variables of generative model. This variable involves the selection of one of four available building types, that are categorized based on building plan shape and named as profile -01, profile -02…to profile -04. These morphotypes are selected on the base of previously made studies on tall buildings where the outcomes of the research on the energy performance of the case studies (existing buildings) demonstrated specific improvements in performance (Mughal & Beirão, 2019b). The architectural characteristics for these morphotypes for effective use of natural ventilation and BIV systems involves the possibility of dividing the floor slab into a number of parts introducing the concept of varying cross sections through stepping and scaling (**Figure 53**), possibility of manipulating the edges or corner of plan shapes[18], possibility of introducing segmentation[19] (**Figure 52**) and a ventilation shaft[20]. Even though the idea was to define an algorithm capable of generating as much variety as possible, the 4 morphotypes are not necessarily absolute in their capacity of generating a universal set of solutions. The system could have additional morphotypes, but this does not in fact alter the working concept. It only limits the solution space. However, the solution space due to parametrics is still wide enough to be unmanageable by the human mind.

Table 26 Basic floor plan shapes of four profiles

| **Morphotype** | **Profile-01** | **Profile -02** | **Profile -03** | **Profile -04** |
|---|---|---|---|---|
| **Basic Floor plan shape**[21] |  Square |  Circular/Oval |  Circular/Oval |  Polygon |

Other variables include parameters bringing a wide variety within the plan shapes of these morphotypes e.g.

1. Fillet Radius: this refers to floor plan shape corners.
2. Number of Floor Parts: this refers to a number of subdivisions of the plan shape which can be moved, rotated and scaled along the vertical axis of the building - applies to morphotypes 3 and 4; morphotypes 1 and 2 are by definition divided in 4 parts.
3. Floor surface width/ Side B (m): this refers to the width of the floor plan from outer façade till the inner air shaft.
4. Side X of Chimney: this refers to the width of the central ventilation shaft.
5. Side Y of Chimney: this refers to the length of the central ventilation shaft and applies to only to Morphotype “profile-04”.

The parameters affecting the overall building form through geometrical operations performed for various floor/space arrangements (i.e. rotation, scaling, etc.).

6. Scale Factor: that refers to the distortion of the plan according to the vertical axis
7. # of floors per Section: Number of floors between sky gardens
8. # floors per sky gardens: Number of floors devoted to sky gardens
9. Rotation: angle of rotation
10. Step # Floor per Section: Vertical shift per section given in number of floors (slides sections vertically generating height shifts between floor parts – also called ‘stepping’ due to the generation of step like shapes between building parts)
11. Number of Floors: Total number of floors
12. Ceiling Height: Average ceiling height of one story

[18] In order to have round shaped edges of the building the fillet radius is provided as an input variable.
[19] Introducing segmentation reduces the wind pressure on the building façade in vertical direction and give rise to the effectiveness of cross as well as stack effect in the presence of a central core/atrium/chimney.
[20] Introducing a central core/atrium/chimney here refers to the use of this area for stack effect.
[21] Basic Floor plan shape can be varied according to primary variables which define the dimensions of floor surface

The total set of building morphotypes was programmed using the parametric design interface, Grasshopper, a plug-in for the CAD software Rhinoceros, generating solutions from the combination of a reduced set of input parameters.

These input variables and their value ranges are given in **Table 27**. L and M values are fixed as design fixed constraints and not input as design variables (hence not part of the genetic code). The principle is that for a specific tall building design the number of floors will be probably fixed as well as the floor height (at least for the purpose of a preliminary study) and in principle these values are fixed either by regulations or contractual constraints and therefore not subject to optimization. However, these values are mentioned in the table and have provided the range of values as an input variable because the future work might involve them as variables.

Table 27 Variables and range of values

| No. | Genetic Code | Variables | Value Range |
|---|---|---|---|
| 1 | **A** | Morphotype | 1-4 |
| 2 | **B** | Fillet Radius(m) | 0.0-2.0 |
| 3 | **C** | Number of Floor Parts | 2-8 |
| 4 | **D** | Floor surface width/ Side B (m) | 10-21m |
| 5 | **E** | Side X of Chimney (m) | 10-50m |
| 6 | **F** | Side Y of Chimney (m) | 10-50m |
| 7 | **G** | Scale Factor | 0.2-1.2 |
| 8 | **H** | # of floors per Section | 3-10 |
| 9 | **I** | # floors per sky gardens | 1-4 |
| 10 | **J** | Rotation | 1.0-2.0 |
| 11 | **K** | Step # Floor per Section | 0-3 |
| 12 | **L** | Storey Height | 3-100 |
| 13 | **M** | Number of Floors | 3-3.5 |

## 5.3 Development of the algorithm for GT

The algorithm for proposed GT is based on mathematical description of set of actions to be taken to develop various form of tall building. This mathematical description is termed as scripting and the language used to write this script in this study is visual programming language using visual programming interface of Grasshopper that is a plugin for Rhino (Tedeschi, 2014).

The algorithm is composed of a network of six components and the workflow is shown in **Figure 55**.

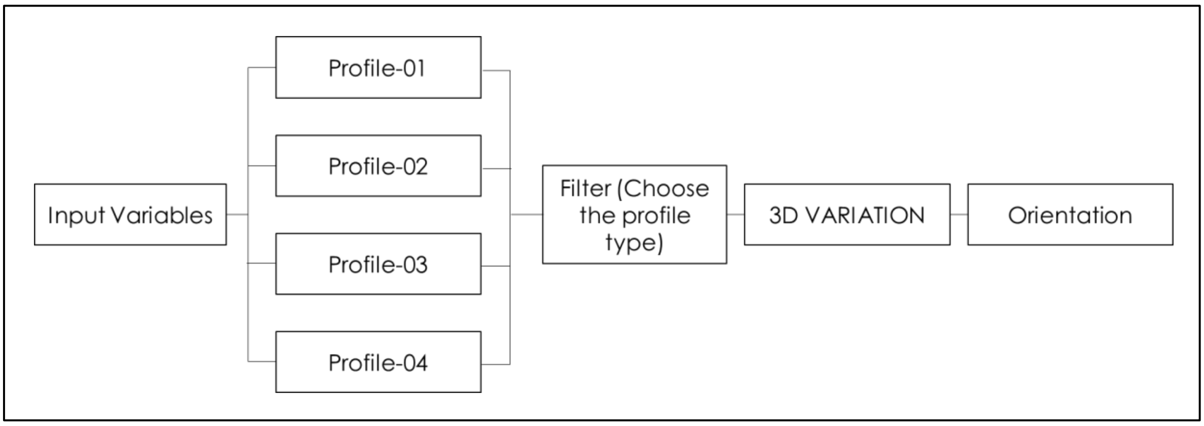



Figure 55 Workflow for generative algorithm

The architectural characteristics of parametric models are defined by the variables which serve as input for four grasshopper components of generative algorithm, generating the four morphotypes shown in **Table 26** as profile-01, profile-02, etc. Each of these four components develops a unique floor shape that is afterwards input to a 5th component named as "3D model Generation". This component defines the height of the building by extruding each floor and then rotating/scaling and 'stepping' the overall building form.

The output model is parametric, which means its architectural features can be changed according to the change in the values of the set of input variables within the ranges already defined. These sets of values are termed as chromosome. Each chromosome is composed of a string of 11 instructions. Each instruction represents a characteristic of 3D model and is termed as gene i.e. A, B, C… to K as given in **Table 27.** In this table L and M values are defined as fixed design constraints for and not input as design variables (hence not part of the genetic code). The principle is that for a specific tall building design the number of floors will probably be fixed by the client or some local regulation; and the floor height as well will be fixed (at least for the purpose of a preliminary study). So, L and M are still variables of GT but fixed for each optimization problem.

Sixth component is capable to change the orientation of the model. **Figure 56** shows the screenshot of Grasshopper interface having the Generative Algorithm for the generation of 3D-Models of tall buildings.

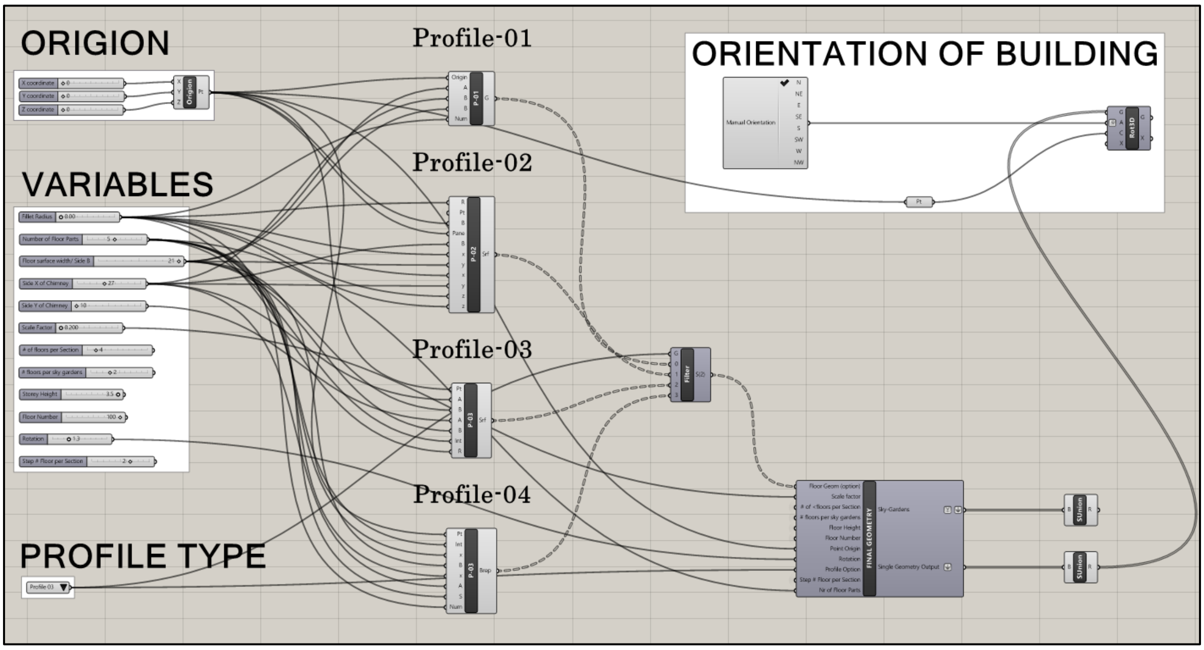



Figure 56 Generative algorithm for the generation of 3D-models of tall buildings.

So, the recipe for the development of 3D Model of tall buildings following this generative algorithm is: (1) the selection of floor plan shape through the components of four morphotypes that are termed as profile-01, profile-02, profile-03, and profile-04; (2) once this floor shape is defined and the profile type has been selected, other geometrical operations are performed through component "3D-Variation". These geometrical operations involve 'stepping', rotation, scaling, extrusion. After all this process the orientation of the building can be decided and set for the CFD analysis. As an example of 3D geometric variations, a 3D model for morphotype profile-01 is shown in **Figure 57** where the referred operations are applied in sequence. The detailed script of these six components is provide in appendices for the curious readers.

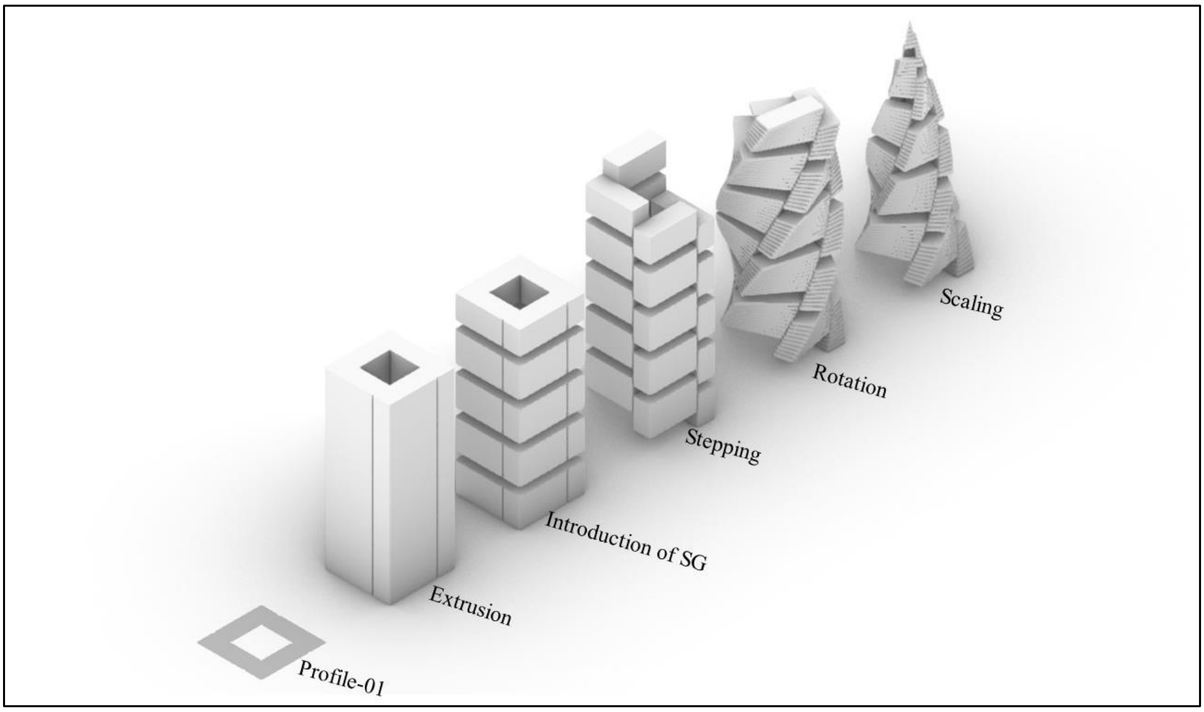



Figure 57 Effect of geometrical operations on the overall building form; An example of profile-01

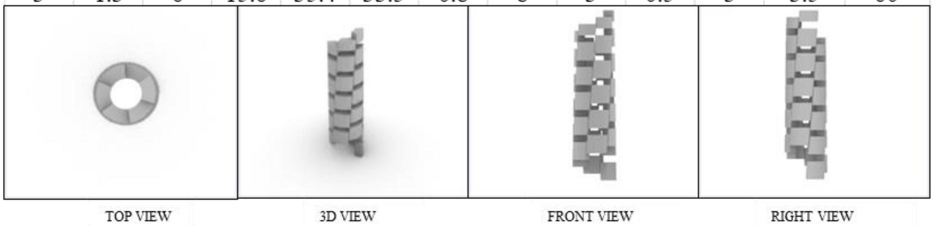
## 5.4 Output of GT

As discussed in an earlier section of the chapter, the output of this GT can provide a diversity of solutions through a set of input variables. If used solely for the purpose of tall buildings shapes/forms exploration, the values of input variables can be controlled and modified by the user to change the model parametrically. It may, thus, help architects and engineers to produce and explore multiple prototypes of tall buildings assuming different formal appearance.

This algorithm, however, is conceived to be connected to an optimization process to help designers find the most sustainable solutions for high-rise office buildings. when starting the optimization sequence the designer stops controlling the generative system because it is supposed to be generating solutions by the input of genetic codes which are randomly generated by the genetic code generator. There is also the possibility to develop 3D models for medium-rise or low-rise buildings. Some examples of the generation of tall building models & corresponding genetic codes are given in **Figure 58**.

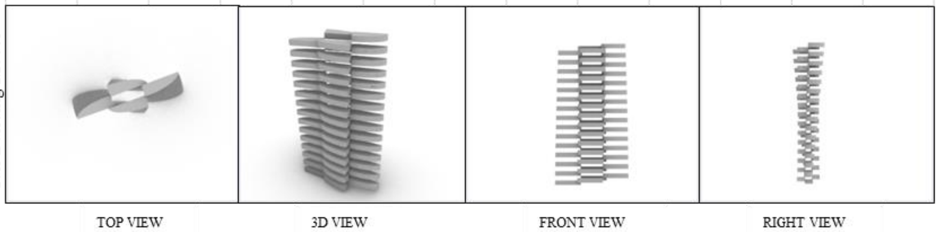
**Example 01**

| A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.3 | 6 | 15.6 | 35.4 | 33.5 | 0.8 | 8 | 3 | 0.5 | 3 | 3.5 | 60 |



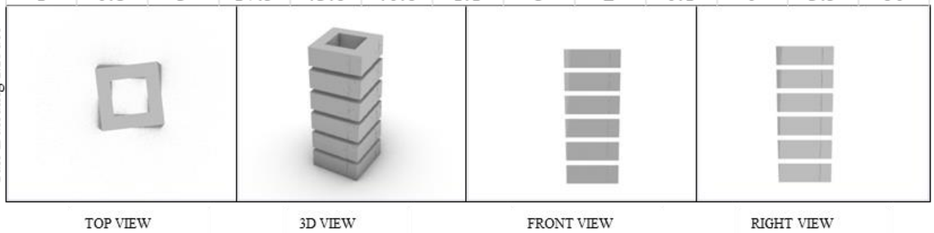

**Example 02** (G. Code / Tall Building Model)

| A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 0.8 | 2 | 10.3 | 33.1 | 30.1 | 1.2 | 2 | 2 | 0.3 | 1 | 3.5 | 60 |



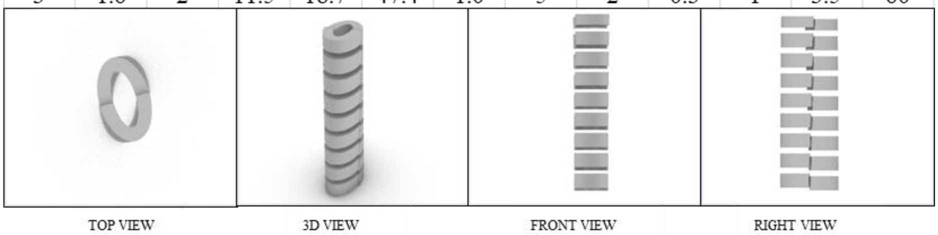

**Example 03** (G. Code / Tall Building Model)

| A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.8 | 3 | 17.5 | 43.6 | 40.6 | 1.1 | 8 | 2 | 0.1 | 0 | 3.5 | 60 |




**Example 04** (G. Code / Tall Building Model)

| A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 1.6 | 2 | 11.5 | 18.7 | 47.4 | 1.0 | 5 | 2 | 0.3 | 1 | 3.5 | 60 |




**Example 05** (G. Code / Tall Building Model)

| A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1.6 | 3 | 13.5 | 34.3 | 50.0 | 1.1 | 7 | 2 | 1.6 | 3 | 3.5 | 60 |

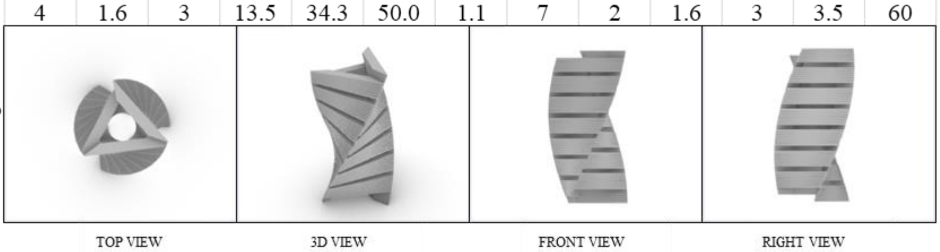



Figure 58 examples of 3D models of tall buildings generated by the described algorithm and their corresponding genetic codes

# 6 DEVELOPMENT OF OPTIMIZATION MODEL

## 6.1 Framework for optimization model (OM)

The optimization model (OM) is composed of a Generative tool defining a solution domain) through input variables (organized in genotype structure) and an evolutionary algorithm that evaluates solutions from the solution domain and selects the best fit according to a set of criteria as shown in **Figure 59**. This model scientifically supports building design in reducing energy consumption for cooling by exploiting the potential for NV in tropical climates.

A Genetic code generator is a function that generates a set of random numbers for generating a population of genes (which constitute the building genotypes) to produce individuals which are 3D Models of tall buildings by using the GT. This code is termed as "random generator (RG)". The range of the input variables is pre-set within architecturally meaningful values so that the code may only generate physically coherent buildings. Once defined the initial random population of the gene poll of tall buildings, the optimization procedure enters a loop involving a set of steps.

In the first step, the population is subjected to a multi-criteria evaluation procedure using a fitness function where the performance of developed individuals is assessed resorting to a computer fluid dynamics software that includes the information about the climate zone for which the building is being designed, informing designers about how their building's shape makes the best use of natural ventilation. From the CFD analysis, two values are considered:

- To reduce the temperature of ambient air that is to be introduced in the building
- To achieve optimum wind velocity; optimization of wind velocity is according to human comfort criteria that ranges between 0.25m/s to 1.0m/s) in indoors (Szokolay, 2008).

The other criterion is to maximize the accommodating capacity of the tall building.

The fitness function algorithm ranks the population according to the defined criteria/ objectives given above and selects the best ranked individuals to be the parents for the next generation of 3D models.

After the selection process, genetic operations i.e. pairing, crossover and mutation are performed to develop another set of phenotypes termed as new individuals, together with an additional set of randomly generated individuals which are submitted again to the fitness evaluation and ranked.

The whole process is repeated several times until the best ranked solutions show no meaningful improvements. This stage of the process gives the optimized outputs and a database of gene pools that may produce optimized solutions. The designer is therefore free to (designerly[22]) explore this information to further improve the design involving other aspects of the design problem that were not included before.

[22] Reference to the term coined by Nigel Cross's 'Designerly ways of knowing', 1982.

Proposed OM is developed through:

- Development of a Generative Algorithm for the generation of tall buildings
- Development of an algorithm for random generator (RG) for the generation of a random set of genotypes for the generation of a population of 3D-Models of tall buildings (the RG feeds inputs to the generative algorithm)
- Development of an algorithm for the fitness evaluation and solution ranking
- Development of an algorithm for integrating the CFD simulation software within the looped sequence of the evolutionary OM.
- Development of an algorithm for storing a database of genetic codes and corresponding fitness values

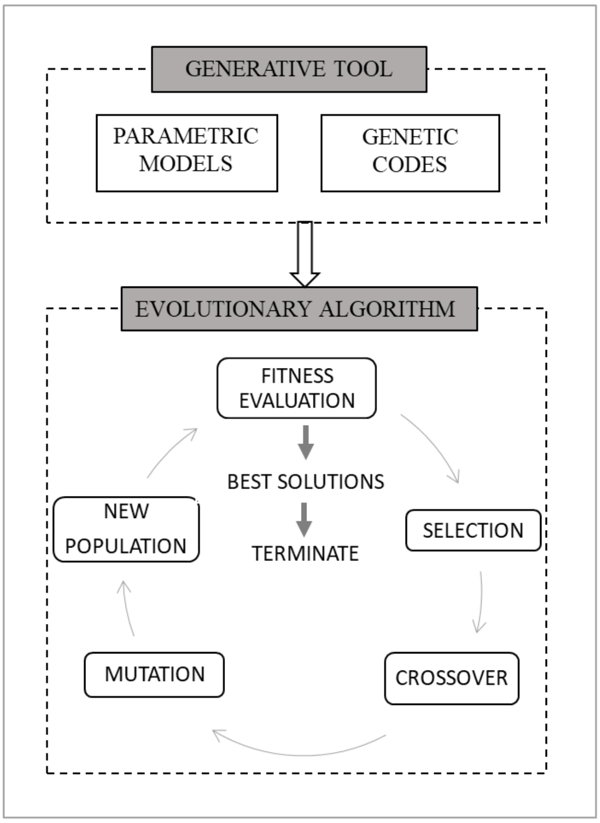



Figure 59 Optimization model

### 6.1.1 Random generator (RG)

The random generator (RG) is an algorithm capable of generating a set of random numbers for the input variables within a previously defined range, to produce a set of random genes defining a chromosome for a 3D Model of a tall building resorting to the generative algorithm. These output models are generated one at a time until a specific number of models are ready for the optimization procedures. The RG algorithm has been developed as a component in Grasshopper using Python script. The script contains 13 loop functions, one per random number/gene. A screenshot of the grasshopper component is shown in **Figure 60** and corresponding python script is shown in **Figure 61**. While the complete code is available in appendices.

The component allows the user to change the decimals and range of numbers together with the quantity of random numbers.

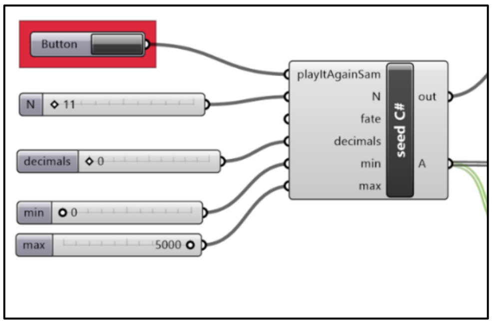



Figure 60 Grasshopper component for the random generation of numbers

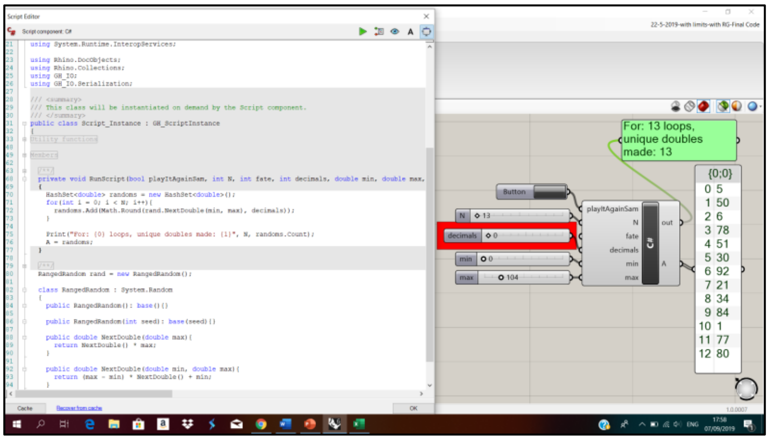


Figure 61 A screenshot of random generator component and corresponding python code

## 6.1.2 Development of evaluation model

This model is comprised of fitness function and CFD simulation for the selection of best solution.

### *6.1.2.1 Development of algorithm for fitness function (FF)*

The fitness value for the tall building model generated through proposed GT is a function of the following three criteria:

$$X = f\,(T_{reduced},\ V_{wind},\ \text{Building Capacity})\text{----------(Eq. 1)}$$

Where X is fitness value or ranking value.

This function ranks each solution on a scale of 0-10 representing worst to the best options. Each of three criteria have been normalized and produce a specific value within a predefined normalization range i.e. 0 to 100. Then the fitness function sums up the weightage of three ranks to get the total performance rank.

The weightage given to the reduction of air temperature, optimum velocity and for optimized building capacity is 30%, is 30% and 40% respectively. The screenshot of the algorithm developed for fitness value on Grasshopper is shown in **Figure 62**.

**#1 *Temperature reduction of indoor air:*** very few studies have been done on the cooling effect of sky gardens in indoor environment and one of the recent studies indicates that the sky gardens help reducing indoor air temperature by 0.52°C mean to 2.0°C max (Mohammadi & Calautit, 2019).

This criterion is evaluated using a scale ranging from 0 to 10 representing minimum to maximum values of reduction in air temperature (compared to ambient temperature) inside the ventilation shaft and sky gardens, obtained through CFD simulation using RhinoCFD tool. The higher value on the scale, the better is the solution. Decrease in the air temperature of indoor air is calculated and the domain of this value is between 0 to 2 degrees. So, the value was remapped for a domain 0 to 10 and given weightage and added to the other values of fitness criteria.

**#2 *Wind velocity of indoor air:*** Wind velocity should be in the comfortable range as given by Szokolay (0.25-1.0m/s) in indoors (Szokolay, 2008). However, a wind speed ranging between 8 to 10 m/s is considered to be effective for channelizing the optimum flow of air in ventilation shaft and sky garden zones (Stathopoulos & Dean, 2009). Sky gardens can generate high wind velocity up to 10 m/s in high-rise buildings, however, additions of trees or some other architectural features like space distribution and arrangement of floor plates can reduce it up to 50% to 80% and also reduce the temperature (Mohammadi & Calautit, 2019).

This criterion is evaluated using a scale ranging from 0 to 10 representing minimum to maximum values of increase in wind velocity (compared to outdoor air velocity) inside the ventilation shaft and sky gardens, obtained through CFD simulation using RhinoCFD tool. Increase in the indoor air velocity is calculated while the domain of this value is between minimum to maximum velocity wind in the sky gardens and central atrium. So, the value was remapped for a domain 0 to 10 and given weightage and added to the other values of fitness criteria.

**#3 *Building configuration:*** It considers the principle that an investor will demand the best possible floor surface use considering the legal constraints of the plot, and therefore that investor will be wanting the maximum possible area while keeping the other evaluation criteria also at good performance levels. So, in this case, more area means better building configuration.

This criterion is evaluated using a scale ranging from 0 to 10 representing minimum to maximum values of increase in Gross floor area (compared to first random solution).

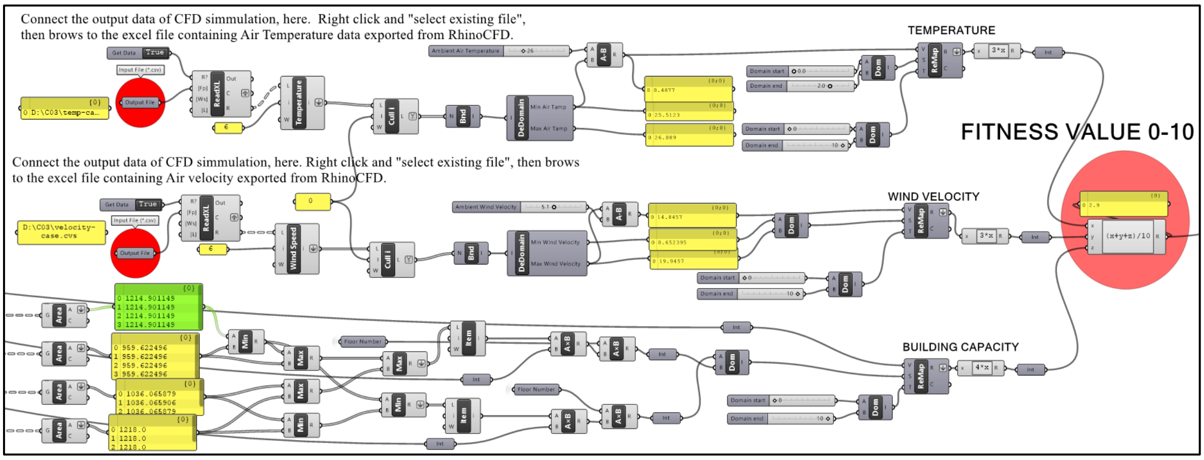



Figure 62 A screenshot of Grasshopper interface with the algorithm finding the fitness values of the 3D-model ranging between 0-10 representing worst to the best solution

#### *6.1.2.2 Integration of CFD simulation tool (RhinoCFD) with Grasshopper*

RhinoCFD is a computation fluid dynamics (CFD) plugin, built directly into the Rhino environment. It allows users to investigate the interaction of their designed model with the surrounding fluid. This allows the optimization and testing of the fluid dynamics of the building designs without requiring the familiarity of the Rhino environment (A et al., 2017; A. Chronis et al., 2017). However, the commercial version of this tool, that has full features for detailed analysis, is not free. Hence, the version selected for the optimization purpose is RhinoCFD Lite, that is free. It contains all the physical models and capabilities of the full version of the software but is limited in the number of cells used for a simulation i.e. 40x40x40 cells in one domain. This version allows the user to get an idea for how it works and ensure it's the right software before committing to buying a license. While in reality the number of cells available in RhinoCFD Lite version are enough for using it for the proposed OM. If the number of cells is increased, the process becomes extremely slow and even though it can give more accurate results, the optimization process will no more be useable on a normal laptop due to its processing capacity. Best of all, one can use RhinoCFD Lite for as long as he/she wants. Furthermore, there is the possibility to evaluate the cooling effect of vegetation in this tool (A. Chronis et al., 2018).

As the algorithms regarding optimization processes have been developed on Grasshopper, it is necessary to integrate this tool in Grasshopper interface so the optimization of whole system can be done without compatibility issues. Nine .gh components have been developed for this purpose, written in python (shown in **Figure 64**) and each component is capable for calling each command of RhinoCFD Lite as shown in **Figure 63**.

CFD simulation using the developed components for RhinoCFD, is a step by step process and so one must follow all the steps in order to get the required results. The result data of the simulation can be obtained in visual or in descriptive (i.e. Excel) form. For the proposed optimization process the extracted of excel files with the numerical values of temperature and velocity are more important than visualisation of the results. This plugin is compatible with both Rhino3D version 5 and 6. Once the CFD plugin is installed, the .gh components are ready to be used for the simulation process (Cham, 2019). However, this is a partial integration that makes does not allow the direct connection of this simulation process with the geometry developed by GT.

The steps to carry out CFD simulation using RhinoCFD commands integrated on Grasshopper interface are shown in **Figure 63**.

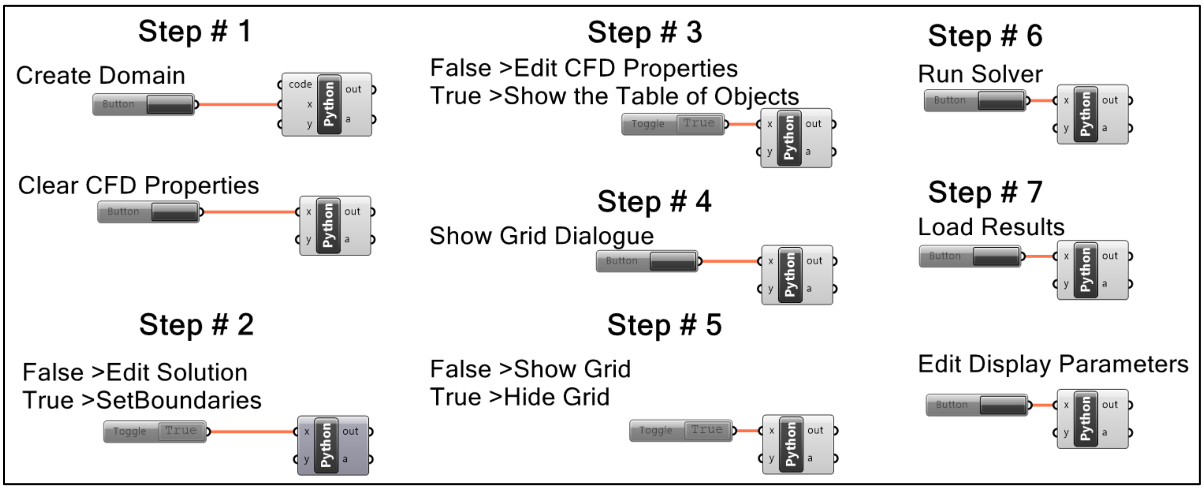



Figure 63 CFD Components on Grasshopper for RhinoCFD Lite commands

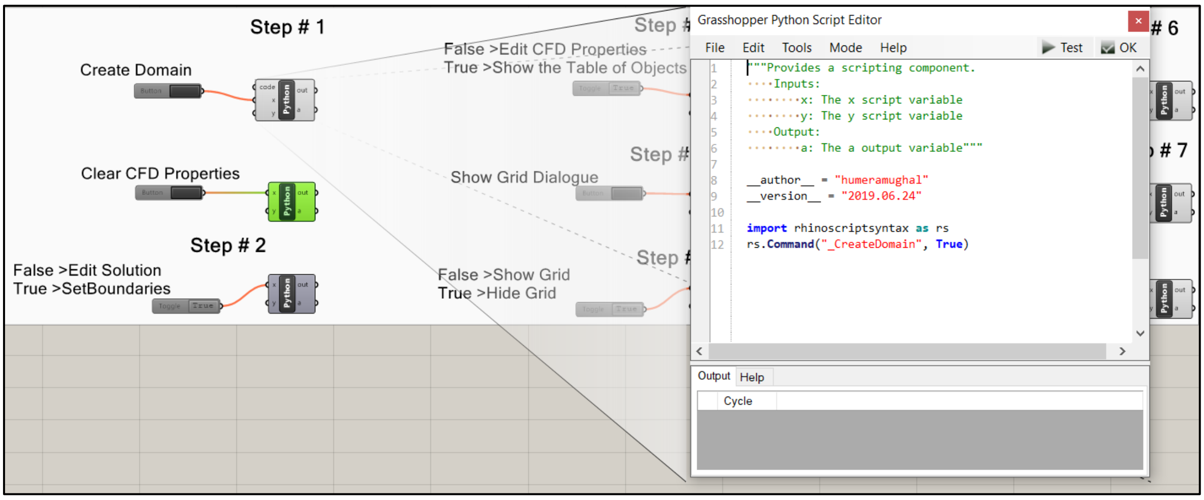



Figure 64 A screenshot showing the python script for one of the components

**Step#1** is to create the domain around the Building to be simulated. A file location dialogue box appears that creates working directory for case to be simulated and the results of the simulation and all the details of simulation will be saved in this directory. Other option for this step is to choose the version of RhinoCFD. Currently available versions are core[23] and flair[24] and the designer in this case should choose flair.

[23] The general multi-purpose PHOENICS CFD solver, designed to be used for a wide variety of uses.
[24] It is a specialised version of PHOENICS for use by architects and building services engineers. FLAIR provides designers with a powerful and easy-to-use tool which can be used for the prediction of airflow patterns, temperature distributions, and smoke movement in buildings and other enclosed spaces, and wind flows around buildings (A et al., 2017).

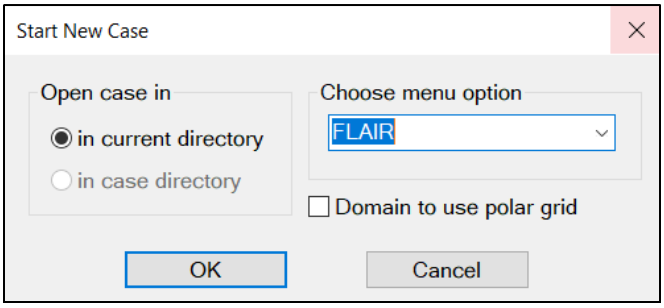



Figure 65 Menu Option: creating working directory

**Step#2** opens the dialogue box for main CFD settings. The most important part of this step is to create wind object[25]. Weather data files can be used to set wind profiles across an inlet of a wind object to match specific conditions from a specific region.

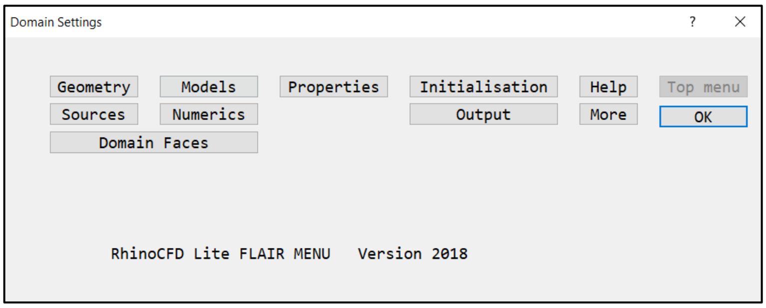



Figure 66 Domain setting dialogue box

**Step#3** opens the dialogue box for Editing the CFD properties

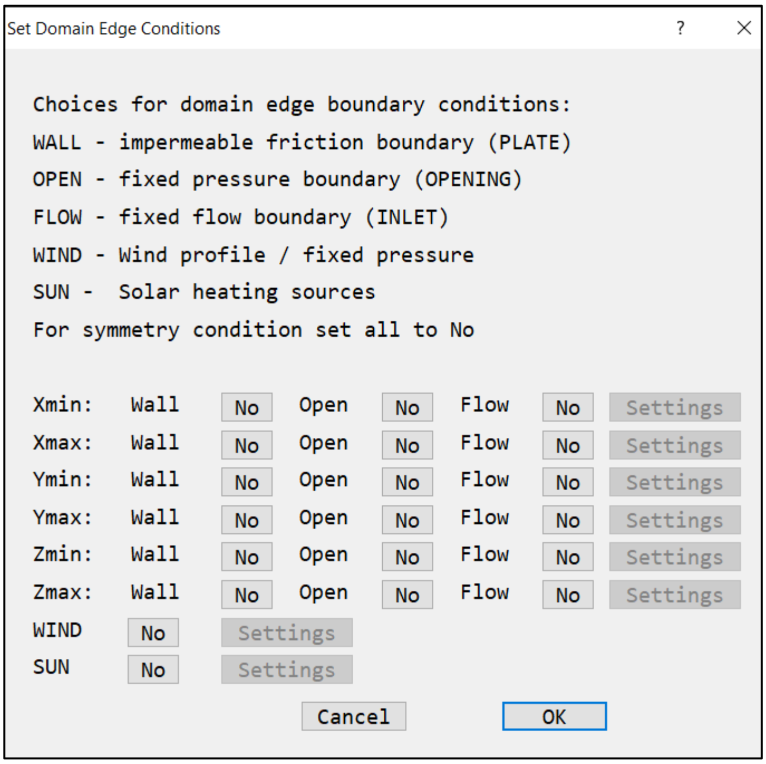



Figure 67 Domain face dialogue

[25] Attributing the properties to the wind surrounding the building.

**Step#4** opens the dialogue box for setting grid Properties. It is to ensure if the mesh is adequate to resolve the flow near the building of interest.

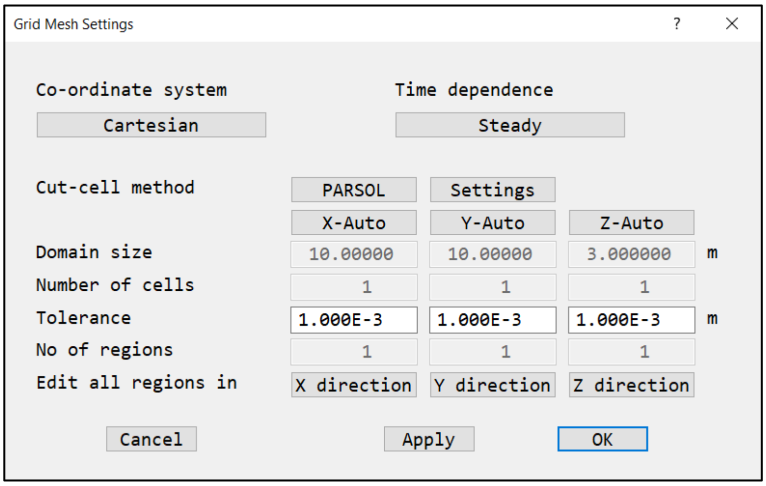



Figure 68 Dialogue box for setting grid properties

**Step#5** shows or hide the grid that is only for checking purpose.

**Step#6** Clicking on this button will command the tool to start the simulation according to the given input settings.

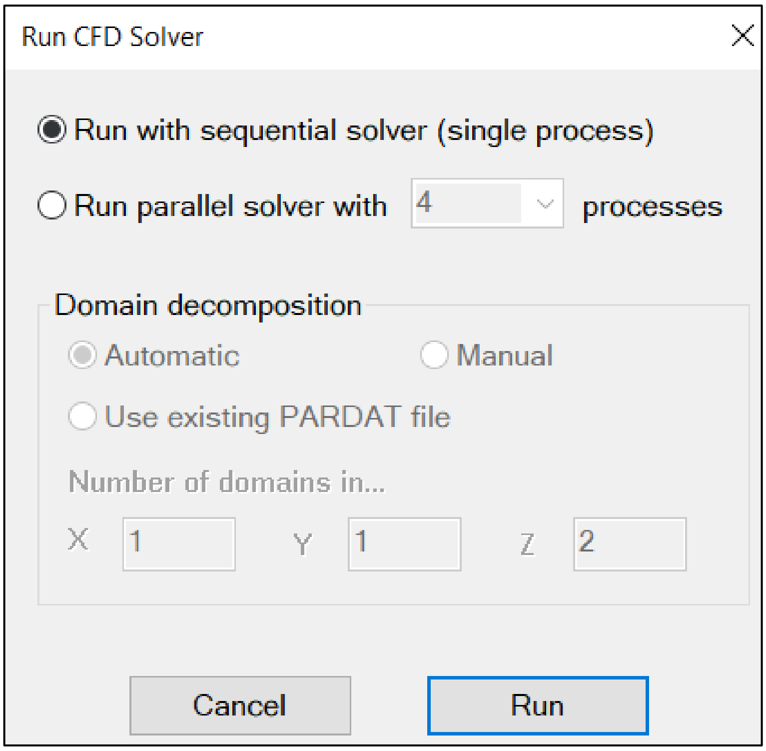



Figure 69 Dialogue box for runing CFD solver

**Step#7** opens the dialogue box for the display of parameters i.e. wind Velocity, pressure, Temperature. From here excel file can be exported to the working directory. That excel file and be imported into the Grasshopper algorithm of fitness function that is programmed to rank 3D models on the basis of results available in the imported excel file.

1. Choose considered parameters i.e. temperature, velocity etc.
2. Set minimum and maximum value of the scale to display the results attributed with different color ranges according the values of parameters on the scale.
3. Type of plane i.e. filled with colors, arrows etc. showing the direction or intensity of parameter
4. Export the excel file of results regarding considered parameter to the working directory

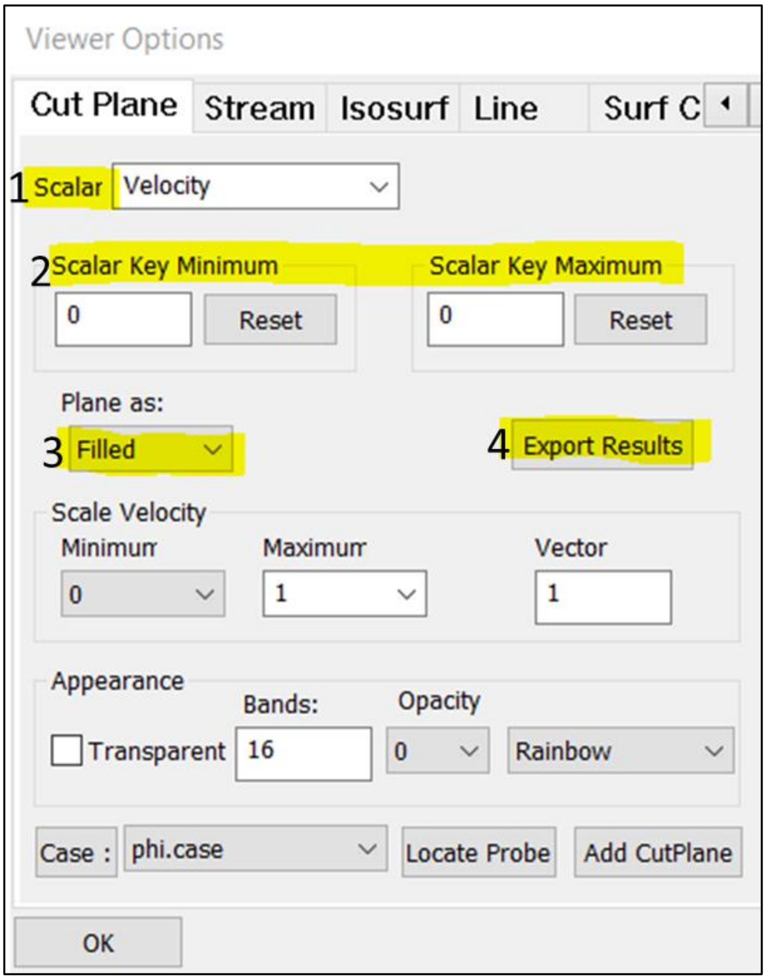



Figure 70 View and export result options menu

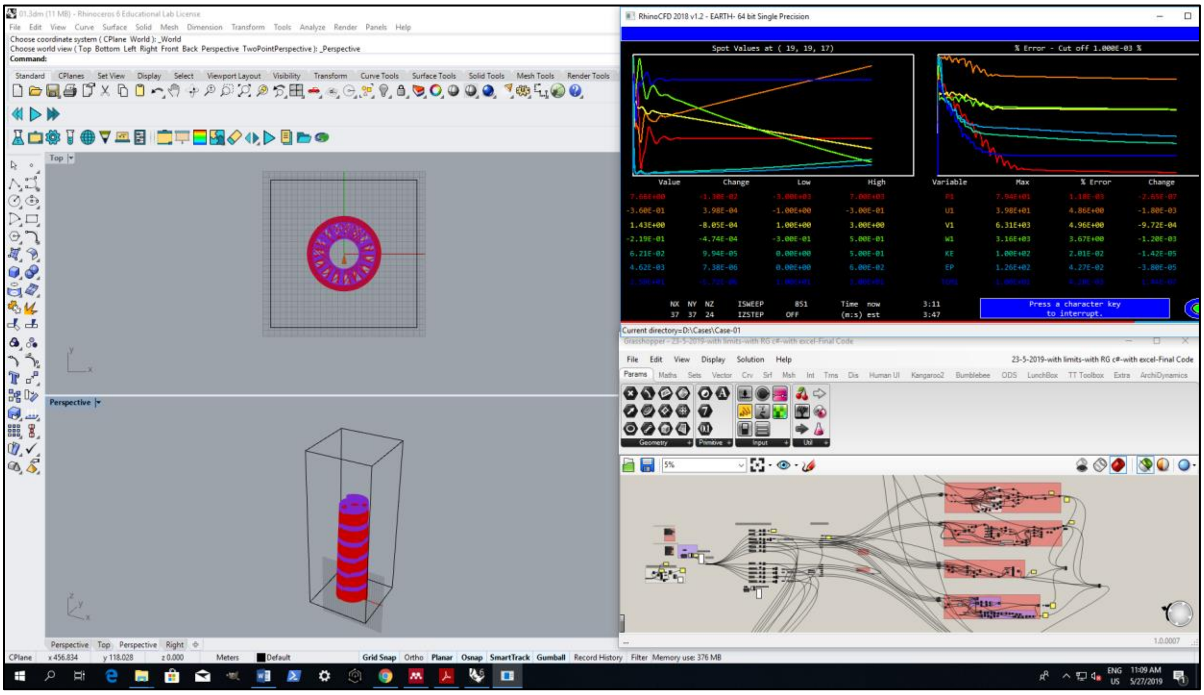


Figure 71 A screentshot of the CFD simulation of an output generated by GT through RhinoCFD Lite

### 6.1.3 Algorithm for database generation

A plugin for grasshopper named as "TT Toolbox" is used to export the genetic code and fitness values of corresponding phenotypes. The component that generates the excel file is "WriteXL". Screenshot of this algorithm is shown in **Figure 72**.

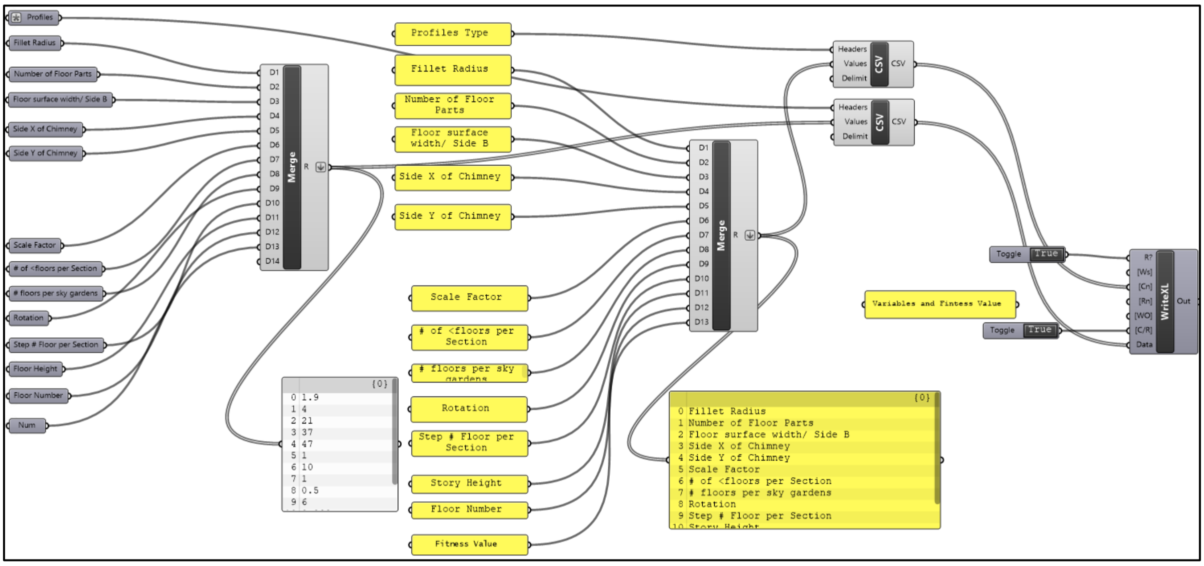



Figure 72 Algorithms for the database generation

### 6.1.4 Evolutionary model

Evolutionary model could not be followed for the development of evolutionary algorithm suitable for the suggested framework of optimization model, however the framework of evolutionary model has been provided and explained through the implementation of optimization model on an initial random population of eight individual/models of tall buildings.

## 6.2 Algorithm of the developed optimization model

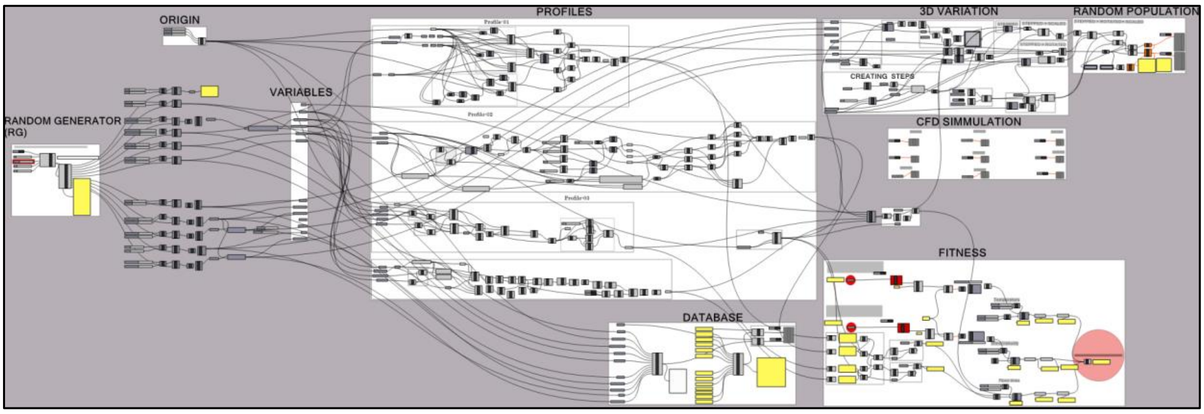



Figure 73 Optimization algorithm

## 6.3 Application of OM

This part of the thesis gives a foretaste for how to implement proposed OM for the optimization of a tall building for the best use of NV and SG.

For this purpose, process of optimization of a tall building located in tropical climate region is described, with the assumption[26] that the client wants the height of the building limited to 60 floors and ceiling height to 3.5 meters that in turn fixes the total height of the building. So, L and M chromosome are no longer part of genetic code. The input variables are A, B, C, ..., K. The weather data file of Singapore is taken to be used for simulation purpose. And the building is considered to be located in an isolated place i.e. not surrounded by any other building. Although there is possibility to optimize the tall building design with this OM considering any kind of urban context by simply adding an algorithm for the 3D model of urban context, however the logic of not considering any type of urban context is to carefully evaluate the effect of input Variables on the NV performance of building. The design of tall building with and without any urban context must be very different as the urban wind patterns are already affected due to the presence of surrounding buildings.

OM presented in **Figure 73** has been applied to the tall building design for best use of NV and SG and the first iteration of this process involves a random population of eight models of tall buildings just to give an idea the process is implemented on eight models and is shown in **Figure 82**.

The proposed evolutionary model uses two best fit parents for multi-point crossover, one best fit for bit-flip mutation and hence 3 children of next generation are born through genetic operations. Two best fit models/individuals are selected from previous generation and three models/individuals/children are randomly generated again through generative tool. So, the second population is comprised of eight individuals which are tested for their fitness again and

[26] Assumption is taken on the basis that researchers agree that a tall building can be represented through the use of 60 floors or more (CTBUH, 2019b; Valente, 2012; A. Wood & Salib, 2013).

this loop continues until no improvement is shown. W.-Y. Lin et. al. (2003) in his research suggested that crossover and mutation rates are adapted in response to the evaluation results of the respective offspring in the next generation. According to him, the optimum rate varies for different problem and even for different stages of genetic operation. So it is basically a hit and trial method (W.-Y. Lin, Hong, Lin, Lee, & Hong, 2003).

### 6.3.1 Generation of random population

An initial population of eight models of tall buildings is given as follows:

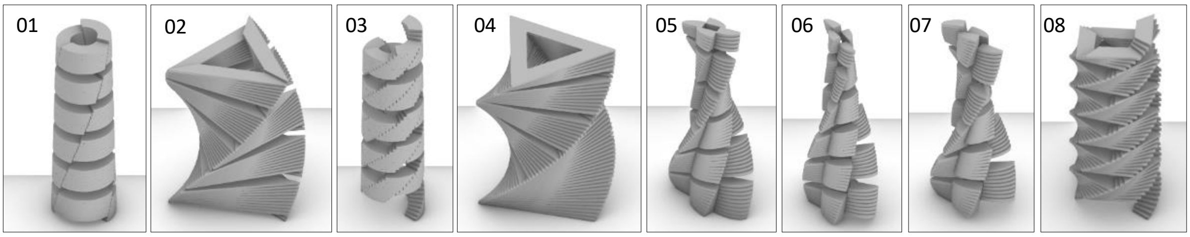



Figure 74 A random population of 3D-models of tall buildings

The genetic code of these models is given as follows.

Table 28 Genetic code of initial population

| Individuals | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| **2** | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| **3** | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| **4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| **5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |
| **6** | 2 | 0.55 | 4 | 13.01 | 20.95 | 20.95 | 0.47 | 8 | 3 | 2.74 | 1 |
| **7** | 2 | 0.69 | 4 | 13.78 | 23.73 | 23.73 | 0.54 | 9 | 3 | 3.43 | 2 |
| **8** | 4 | 1.90 | 5 | 20.47 | 48.09 | 48.09 | 1.15 | 10 | 4 | 6.16 | 3 |

### 6.3.2 Application of evaluation model

CFD simulation process of this random population of eight models for the first iteration is described using the example of one model. **Figure 75** shows different views of Case with sky gardens space (in green colour) whose CFD results are being presented in **Figure 76** and **Figure 77**.

| Code | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Value | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |

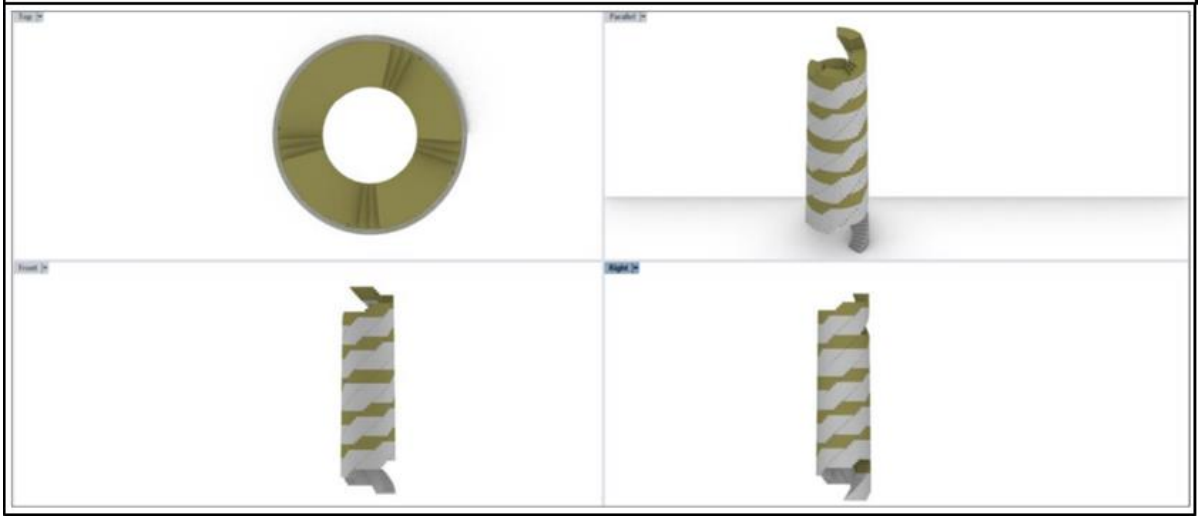


Figure 75 3D-model based on the 3rd list of genetic code

The total computational domain has 60x60x40 (L × W × H) cells in FLAIR for a simulation. Domain was characterized by the wind and solar data taken from weather data of Singapore. The data was taken on August 01 and time 1 pm When;

Wind velocity= 5.1 m/s

Wind Direction=170 degrees from y-axis

Ambient Temperature= 26℃

The turbulence model used is Chen-kim KE (Monson, Seegmiller, Mcconnaughey, & Chen, 1990). In order to evaluate temperature reduction due to foliage (vegetation present in sky gardens), the energy source is switched to Fixed Heat Flux for foliage for a negative value of 300 W/m3 as cooling effect due to vegetation (Timmermans et al., 2014). The 3D Model is analysed as an isolated building with the terrain type considered as open flat terrain with few grasses and few isolated obstacles. Relaxation factor for convergence control is taken as 0.001 which is global convergence criteria. The total number of iterations is 1000.

**Figure 76a** shows the effect of vegetation on temperature reduction. From the results, it was found that the minimum temperature is recorded at 25.3℃. Also, this lowest temperature of air is attained after it passed through the vegetation. Hence a reduction of 0.1-2℃ in indoor air temperature has been attained due to vegetation in sky gardens. Blue arrow shows the direction of wind.

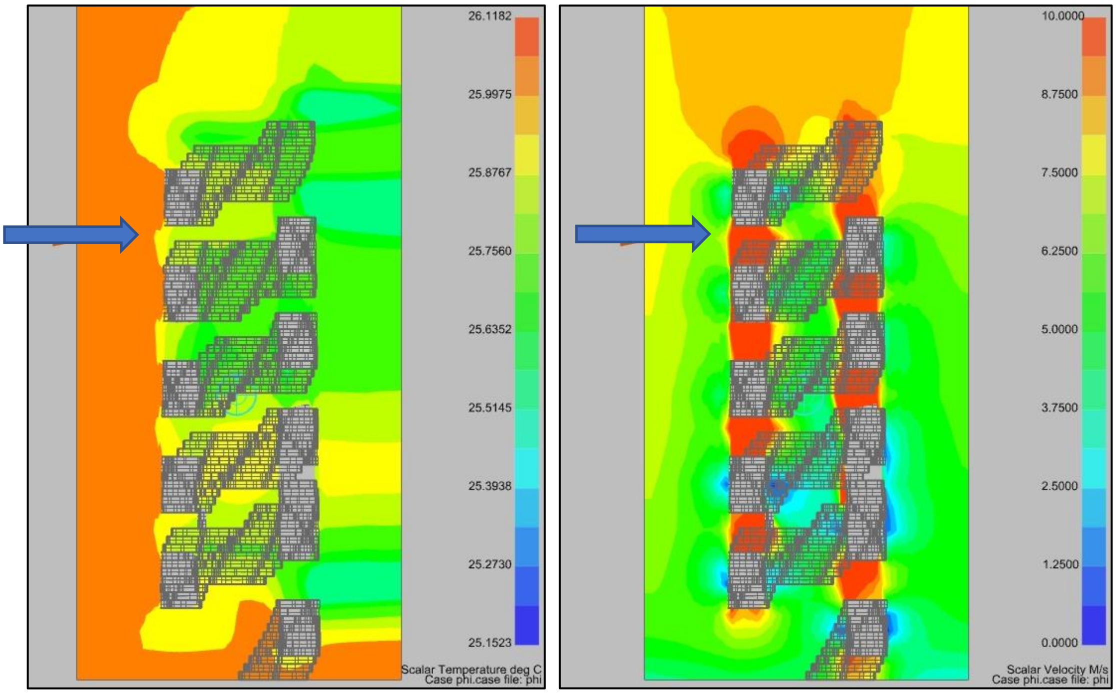



Figure 76 a)Air temperature on a cut-plane passing through the center of building and parallel to the wind direction, b) Wind Velocity on a cut-plane passing through the center of building and parallel to the wind direction

**Figure 76b** shows the behaviour of wind velocity while passing through the building. The wind velocity has been increased after passing through the vegetation. The wind comes towards windward façade and it slows down near the building surface and changes its direction to the sides of building where it gains more speed. While the vortex is generated on the leeward façade due to negative pressure. The configuration of the building is in a way that inlet and outlet are at different heights, so the stack effect is basically occurring in small steps and enters from one floor and exists from the floors above. This phenomenon can be seen clearly in **Figure 77**.

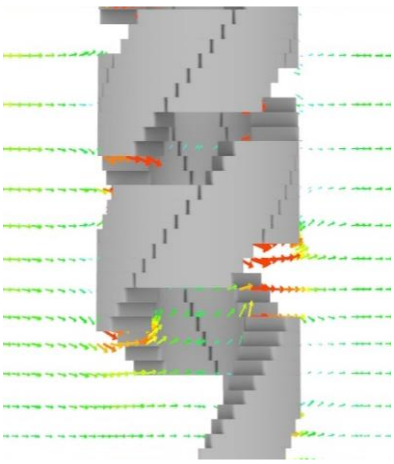


Figure 77 Close up of the simulation results near ground floor

For this case, the maximum velocity of the wind passing through the sky gardens is recorded as 10.7m/s. Similar results have been driven by (Mohammadi & Calautit, 2019).

### 6.3.3 Application of evolutionary model

According to this model the selected chromosomes of initial population are taken into consideration for the generation of new population that should have better genes than the previous one. As described earlier, this part of work is not fully developed in this thesis hence a description of the use of this model is explained here through this example explaining the need of automatization of and generation of algorithm for this model. It involves selection of best fit models according to fitness value, application of genetic operations and Loop the whole process for the next iteration.

### 6.3.4 Selection

The genetic code of 8 models and their fitness value according to the CFD simulation results are analysed for the selection of best fit solution to become the parents of the second generation.

**Table 29** shows the selection of the better solutions according to their fitness values. According to the given data all models are found to be fit according to fitness criteria accept model 6 and 7 as they have got the least fitness value.

Table 29 Genetic Code and fitness value of the random population of 3D-models of tall buildings

| Individuals | A | B | C | D | E | F | G | H | I | J | K | Fitness Ranking | Selection |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 | 9 | ✓ |
| **2** | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 | 8 | ✓ |
| **3** | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 | 7 | ✓ |
| **4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 | 8 | ✓ |
| **5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 | 9 | ✓ |
| **6** | 2 | 0.55 | 4 | 13.01 | 20.95 | 20.95 | 0.47 | 8 | 3 | 2.74 | 1 | 4 | ✗ |
| **7** | 2 | 0.69 | 4 | 13.78 | 23.73 | 23.73 | 0.54 | 9 | 3 | 3.43 | 2 | 3 | ✗ |
| **8** | 4 | 1.90 | 5 | 20.47 | 48.09 | 48.09 | 1.15 | 10 | 4 | 6.16 | 3 | 7 | ✓ |

Hence the selected models (**Table 30**) are 1,2,3,4,5 and 8, whose chromosomes will be used for the genetic operation used through evolutionary model.

Table 30 Parents selection for the second generation

| Parent | A | B | C | D | E | F | G | H | I | J | K | Fitness Ranking | Selection |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 | 9 | ✓ |
| **2** | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 | 8 | ✓ |
| **3** | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 | 7 | ✓ |
| **4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 | 8 | ✓ |
| **5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 | 9 | ✓ |
| **8** | 4 | 1.90 | 5 | 20.47 | 48.09 | 48.09 | 1.15 | 10 | 4 | 6.16 | 3 | 7 | ✓ |

### 6.3.5 Genetic operations

Parent 1 and parent 2 are selected for multipoint crossover operation (**Figure 78**), parent 3 is selected to bit-flip mutation operation (**Figure 79**) and the phenotypes for parents 4 and 5 are taken as they are for the next generation. Three more child individuals are generated randomly (**Table 31**) from GT. Thus, a second population of genes, comprising of eight children is created.

***Children generation due to crossover:***

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parent 1** | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| **Parent 2** | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| **Child 1** | 4 | 1.99 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.03 | 1 |
| **Child 2** | 3 | 1.07 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.45 | 1 |

Figure 78 Crossover operation to generate child 1 and 2

***Children generation due to mutation:***

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parent 3** | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| **Child 3** | 3 | 1.34 | 6 | 17.38 | 17.38 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |

Figure 79 Mutation operation to generate child 3

Child 4 and 5 are selected by taking the same chromosomes of parent 4 and 5 without any sort of alteration in the genes (**Figure 80**).

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Child 4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| **Child 5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |

Figure 80 Child 4 and 5

***Randomly generated children:*** individuals 6,7 and 8 are generated randomly.

Table 31 Randomly generated individuals

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Child 6** | 1 | 1.9 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 4 | 2.03 | 3 |
| **Child 7** | 3 | 1.34 | 6 | 17.38 | 31.41 | 49.88 | 0.74 | 7 | 3 | 2.45 | 1 |
| **Child 8** | 2 | 1.07 | 3 | 15.89 | 36.82 | 36.82 | 0.87 | 10 | 5 | 2.03 | 3 |

The chromosomes of a new generation for second population together with their phenotypes are given in **Table 32** and **Figure 81** respectively.

Table 32 Population of new generation

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Crossover** | Child 1 | 4 | 1.99 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.03 | 1 |
| | Child 2 | 3 | 1.07 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.45 | 1 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mutated** | Child 3 | 3 | 1.34 | 6 | 17.38 | 17.38 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| **Old Generation** | Child 4 | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| | Child 5 | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |
| **Randomly Generated** | Child 6 | 1 | 1.9 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 4 | 2.03 | 3 |
| | Child 7 | 3 | 1.34 | 6 | 17.38 | 31.41 | 49.88 | 0.74 | 7 | 3 | 2.45 | 1 |
| | Child 8 | 3 | 1.07 | 3 | 15.89 | 49.88 | 49.88 | 1.2 | 10 | 5 | 6.71 | 3 |

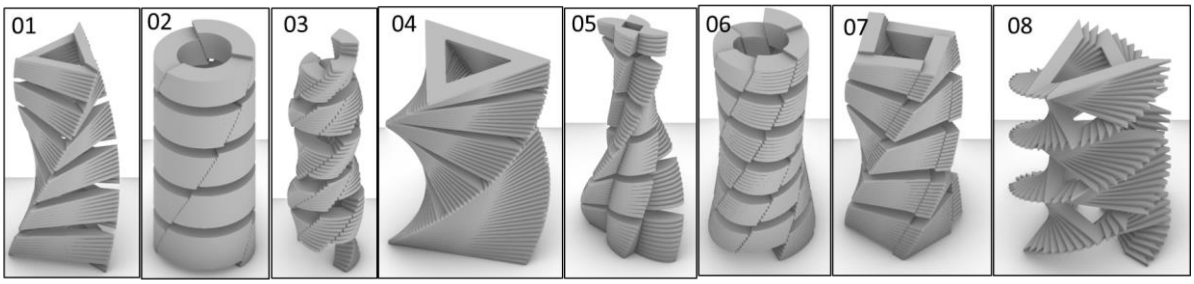


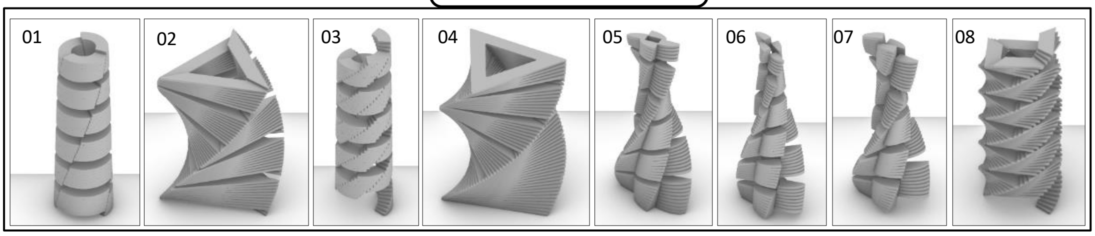

Figure 81 Phenotypes of second generation

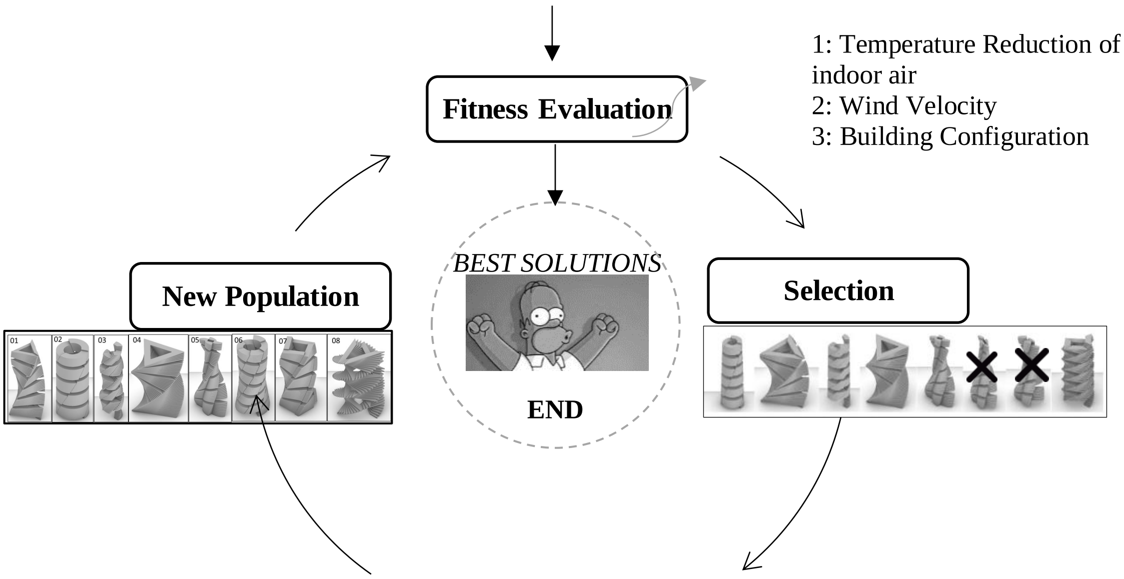
The whole process applied to this set of eight models is only one iteration (**Figure 82**). In order to apply the optimization model properly, the process is followed for several iterations until the best fit solution are obtained and the process shows no more improvement.

**Genetic Code**

| Individuals | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 3 | 1.07 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.45 | 1 |
| **2** | 4 | 1.99 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.03 | 1 |
| **3** | 3 | 1.34 | 6 | 17.38 | 36.82 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| **4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| **5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |
| **6** | 2 | 0.55 | 4 | 13.01 | 20.95 | 20.95 | 0.47 | 8 | 3 | 2.74 | 1 |
| **7** | 2 | 0.69 | 4 | 13.78 | 23.73 | 23.73 | 0.54 | 9 | 3 | 3.43 | 2 |
| **8** | 4 | 1.90 | 5 | 20.47 | 48.09 | 48.09 | 1.15 | 10 | 4 | 6.16 | 3 |

**Population I**




**Genetic Operation**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Crossover** | **Child 1** | 4 | 1.99 | 3 | 15.89 | 31.41 | 31.41 | 0.74 | 7 | 3 | 2.03 | 1 |
| | **Child 2** | 3 | 1.07 | 3 | 20.97 | 49.88 | 49.88 | 1.20 | 10 | 3 | 2.45 | 1 |
| **Mutated** | **Child 3** | 3 | 1.34 | 6 | 17.38 | 17.38 | 36.82 | 0.87 | 10 | 5 | 6.71 | 3 |
| **Old Generation** | **Child 4** | 4 | 1.78 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 2 | 2.81 | 0 |
| | **Child 5** | 2 | 0.68 | 3 | 13.75 | 23.63 | 23.63 | 0.54 | 9 | 2 | 3.41 | 0 |
| **Randomly Generated** | **Child 6** | 1 | 1.9 | 2 | 19.81 | 45.66 | 45.66 | 1.09 | 9 | 4 | 2.03 | 3 |
| | **Child 7** | 3 | 1.34 | 6 | 17.38 | 31.41 | 49.88 | 0.74 | 7 | 3 | 2.45 | 1 |
| | **Child 8** | 3 | 1.07 | 3 | 15.89 | 49.88 | 49.88 | 1.2 | 10 | 5 | 6.71 | 3 |

Figure 82 Application of optimization model 01 on a random population of tall buildings

# 7 CONCLUSION

To conclude we may point that the presented system interface does have the potential to inform designers about the building morphotypes that best respond to the fitness function, but although this may be considered to be a step towards building sustainability, we should also pinpoint the insufficiency of this as the single aspects to manipulate in the design of tall buildings, even if looking just at natural ventilation. Future work, will require the combination of more factors involved in the design of the building, addressing the many additional aspects referred in this discussion.

- Overall results show that the temperature reduction is not very significant. But the fact that in all eight samples results are consistent just proves that sky gardens reduce temperature. As there was no real optimization yet, these results only support the assumption that after a substantial number of optimization cycles involving hundreds of solutions, the results might reach higher temperature reductions.

- The same assumption applies for wind velocity with the additional difficulty that it is harder to say what is the desired wind speed. Although the optimum indoor air velocity for the human comfort is already defined to be 2 to 5 m/s (Szokolay, 2008), the results achieved regarding this measure only informs that the wind might become uncomfortable in the sky gardens. The important information that we need, is to know where wind speed (within a given comfortable range) coexists with the maximum temperature reduction, and once finding such information, investigating how such outside wind characteristics may be passed through the inner spaces of the building (without increasing velocity to uncomfortable values) while taken advantage of the temperature reduction. This means giving admittance to air with reduced temperature while expelling to the outside the inner hotter temperatures. This also means that in future development of the work, the façade design should take this information into account in order to define the better façade details that may take advantage of the positive aspects gained from the natural ventilation strategies. This is itself a whole research project.

- For the fitness, the range normalization, depending on how it is mathematically obtained may provide an absolute rank or a relative rank. The absolute rank should be a value that could express an absolute expression relative to a maximum known value. This is in most situations impossible to know in advance and therefore it might be impossible to produce fitness absolute values. Relative values can easily be produced but they express nothing regarding the ‘goodness’ of the design. They only express ‘I am better than the others’, but in absolute terms we might still be talking about poor performance. This study has been developed with a relative fitness ranking system.

- This study provides a GT generating four tall building morphotypes, where a great diversity of solutions can be obtained from a small set of input variables. It will help architects and engineers to produce and explore multiple prototypes of tall buildings. This algorithm is conceived to be connected to an optimization process to help designers find the most sustainable solutions for high-rise office buildings regarding their performance in terms of natural ventilation. There is also the possibility to develop 3D models for medium rise or low-rise buildings. Although the generative algorithm is designed to feed a genetic evolutionary algorithm for optimizing the building's natural ventilation performance. However, it can also work well with different optimization questions i.e., this approach scientifically supports building design which reduces energy consumption by exploiting the potential for natural ventilation in tropical and subtropical climates, but, a variety of building typologies, could also be subject to optimization within different climate zones considering different fitness adequate to the other region's climate. An example of using GT with other developed simulation and optimization algorithms is shown in **APPENDIX 12.2** and **12.3.**

- The insulation effect provided by SG to the floors below may help reducing the energy load and may be one of the fitness criteria if the OM is further advanced for the optimized energy efficient solution for tall buildings.
- The process of selection of CFD tool has been challenging since most of CFD solvers that are integrated with the CAAD environments do not have the capability to be used to optimize the geometrical characteristics e.g. ANSYS Fluent (A. Chronis et al., 2017, 2018). Open Foam is the only CFD solver, that has limited shape optimization capability and has addon Butterfly on Rhino (A. Chronis et al., 2017, 2018). Some CFD solvers have no optimization capabilities at all e.g. RhinoCFD (A. Chronis et al., 2017, 2018). Currently last two options are the most validated ones. The second option has been used in various studies already for shape optimization and thus RhinoCFD was chosen in this study. This solver was partially integrated into the optimization process since a complete integration was beyond the scope of the work due to time constraints.

# 8 FUTURE RECOMMENDATIONS

Following aspects regarding this study can be explored for future development.

- The input variable rotation usually has some influence (positive or negative) in the wind behaviour (with reference to the NV performance) as it affects the wind pressure on the façade. That is the reason why this is one of the input variables of generative tool (GT). However, it may also cause structural difficulties. Hence the decision of the range of this variable requires more plausible and convincing structural engineering base. The model does not have anything controlling this aspect. There are however two ways of controlling this: (1) restricting a lot more the values for rotation to a lower range, or (2) introducing a factor giving preference to low values so that even though the system still tries high rotation values, at least a large percentage are kept under smaller values expected to be less troublesome. In any case, the fitness function does not reflect structural performance at all and so this topic is out of the scope of this research; however, future work may (and certainly should) integrate this aspect.

- Optimization model (OM) is still in the form of a combination of processes and each process is performed with the help of one specific algorithm at a time. The whole system is still envisioned to be fully automatized and might become an efficient plugin for Grasshopper in near future.

- There is no consideration of a specific urban context for this study, because the idea was to conceive a general-purpose tool for hot climate. In order to make it specific to a specific location and urban environment, an algorithm may be developed to include different urban contexts that can be connected to the generative model.  Just like urban context, the climatic conditions may also vary, as the CFD simulation process requires climatic data or a weather data file to be uploaded. Further studies, which take these variables into account, will need to be undertake.

- OM provides the results assuming a fixed capacity of sky gardens of inducing a specific cooling effect. The design of the sky garden is not discussed nor explored in all its variables. It is simply taken as a cooling device with a specific cooling effect. If the design variables of a sky garden are also taken into consideration, it could be possible to induce higher energy saving in both hot and cold climates. Such exploration should be done according to specific types of climates to evaluate the types of design producing the most effective energy performance behaviour. For example, in hot humid climates it could be useful to explore the use of materials that capture moisture and are simultaneously used to pass the air through to induce the cooling effect while in cold climate it is more important that the sky gardens act as a barrier/buffer (by using dense leaves)to the incoming wind and provide insulation affect to the adjacent floors. This is can be an important and interesting issue for the future research.

- Different greenery systems provide different levels of cooling effect as reported in **Table 11.** The highest temperature reduction is found to be 14°C in hot and dry climate and 10°C in case of hot and humid climate of the surface air temperature (Morakinyo, Dahanayake, Ng, & Chow, 2017b). The reduction in air temperature due to vegetation depends on many factors e.g. climate, leaf area index, evapotranspiration, location of installation of vegetation etc. It is possible to hypothesise that a proper design of sky gardens can help in achieving a temperature reduction up to 10°C. Furthermore, Different types of vegetation may provide different types of sky garden response increasing humidity if needed or decreasing humidity if species collecting humidity from the air are use in the sky garden. A study on the investigation of all these factors to optimize the detailed design of sky gardens in tall buildings in hot and humid climate is, therefore, suggested.

The construction materials of the sky gardens may complement the effects of the vegetation especially in relation to the possibility of capturing air humidity (useful in humid climates) and using the water/humidity thus collected to further cool the air. This aspect can be explored in future.

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# *10 LIST OF FIGURES*

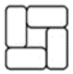
# *11 LIST OF TABLES*

## 12.1 Appendix A

This part of appendices corresponds to chapter#5 regarding the development of generative tool (GT). As, discussed in the chapter, the proposed tool is comprising of generative algorithm that is programmed on Grasshopper. The algorithm is structured in a way to produce various 3D-models of tall buildings based on four types of basic floor plan shapes. These floor plan shape correspond to algorithms termed as profile-01, profile-02, profile-03 and profile-04. These profiles are connected to another algorithm that is capable to create variation in overall building shape and is termed as 3D-Variation. These algorithms are given as follows.

### 12.1.1 Profile-01

This algorithm is based on rectangular floor plan shape. First of all four rectangular shapes are generated and arranged in a way to produce a space for the atrium in the centre. The size of these rectangles and atrium can be varied however the arrangement of these rectangle shapes is constraint. After the definition of size of shapes (corresponding to the area of floor and atrium), the algorithm is capable to generate the surface of the floor.



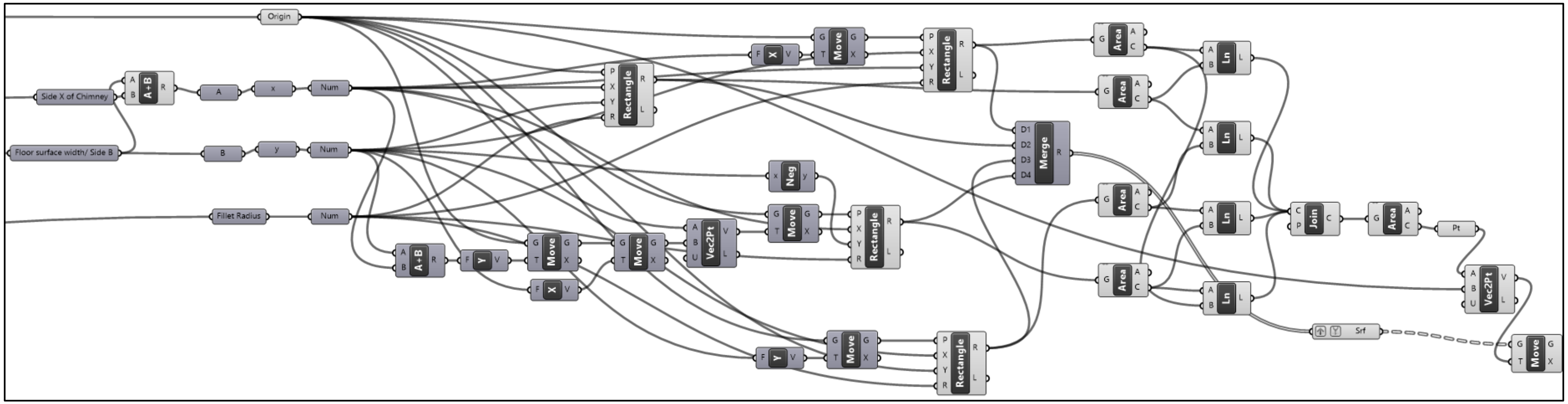



Figure 83 Algorithm of profile-01

### 12.1.2 Profile-02

This algorithm is based on elliptical floor plan shape. First of all one ellipse is generated and then divided into four parts. These four parts are arranged in a way to produce a space for the atrium in the centre. The size of the floor parts and atrium can be varied by varying the size of ellipse, but the arrangement of these floor parts remain constraint. After the definition of size of shapes (corresponding to the area of floor and atrium), the algorithm is capable to generate the surface of the floor.

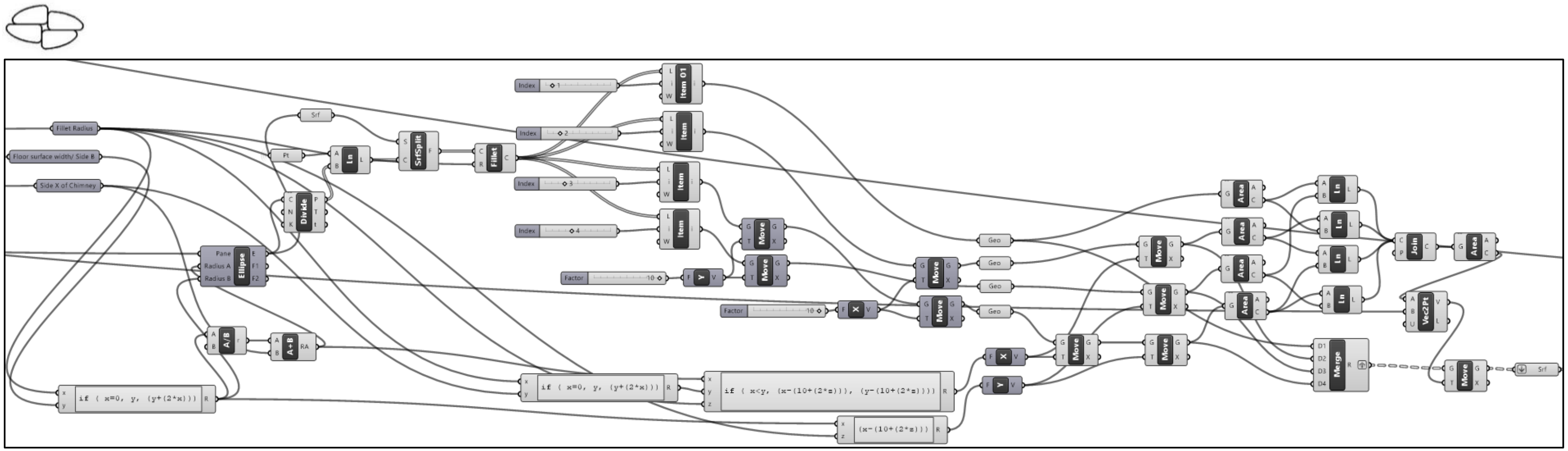



Figure 84 Algorithm of profile-02

### 12.1.3 Profile-03

This algorithm is based on elliptical floor plan shape. First of all two ellipse are generated. One represents perimeter of overall floor plan shape and the other is in the centre of first ellipse, representing central atrium. The floor shape can be divided into several parts. The size of the floor parts and atrium can be varied by varying the size of the two ellipses. After the definition of size of shapes (corresponding to the area of floor and atrium), the algorithm is capable to generate the surface of the floor.

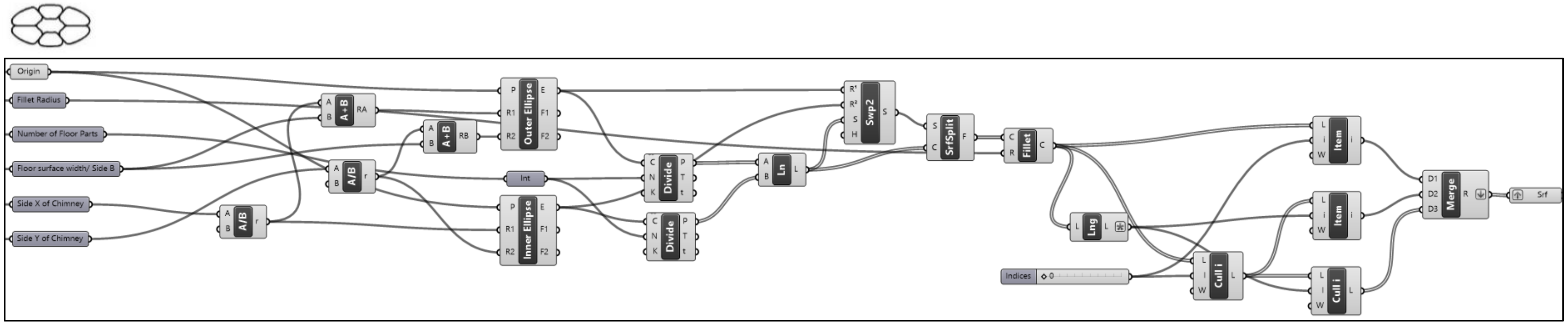



Figure 85 Algorithm of profile-03

### 12.1.4 Profile-04

This algorithm follows the same pattern for the development of floor plan shape as that of profile-03, with the only difference that it is based on polygonal shape. Thus, giving the opportunity to create variety of floor plan shapes i.e. triangle, square, pentagon, hexagon etc. with the incorporation of central atrium. First of all two polygonal are generated. One corresponds to the perimeter of overall floor plan shape and the other represents central atrium. The floor shape can be divided into several parts. The size of the floor parts and atrium can be varied by varying the size of the two ellipses. After the definition of size of shapes (corresponding to the area of floor and atrium), the algorithm is capable to generate the surface of the floor.

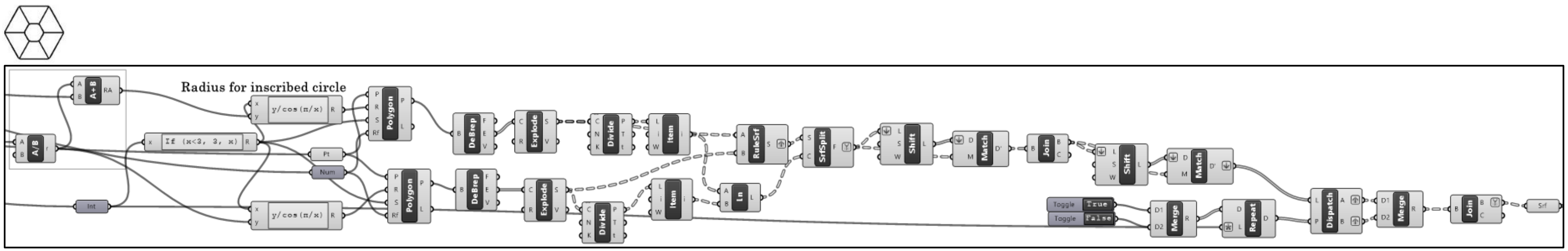



Figure 86 Algorithm of profile-04

## 12.1.5 3D-Variation

This algorithm is capable to create variety within the overall shape and form of building. The variation involves several mathematical operations for extruding, stepping, scaling and twisting the shape of the building. Other features that can be varied through this algorithm are introduction of sky gardens, number of floors, height of building etc. The algorithm and an example of variation in shape is given in the following figure.

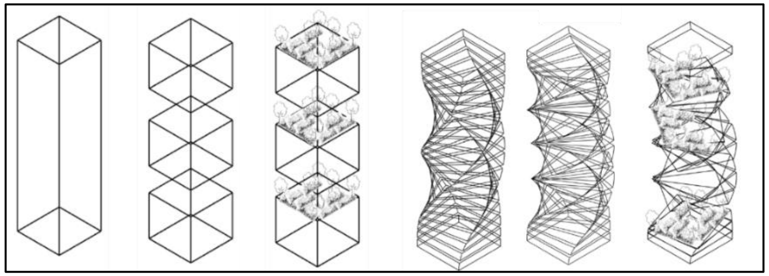


Figure 87 An example of possible variation in overall building shape/form through “3D-Variation” algorithm

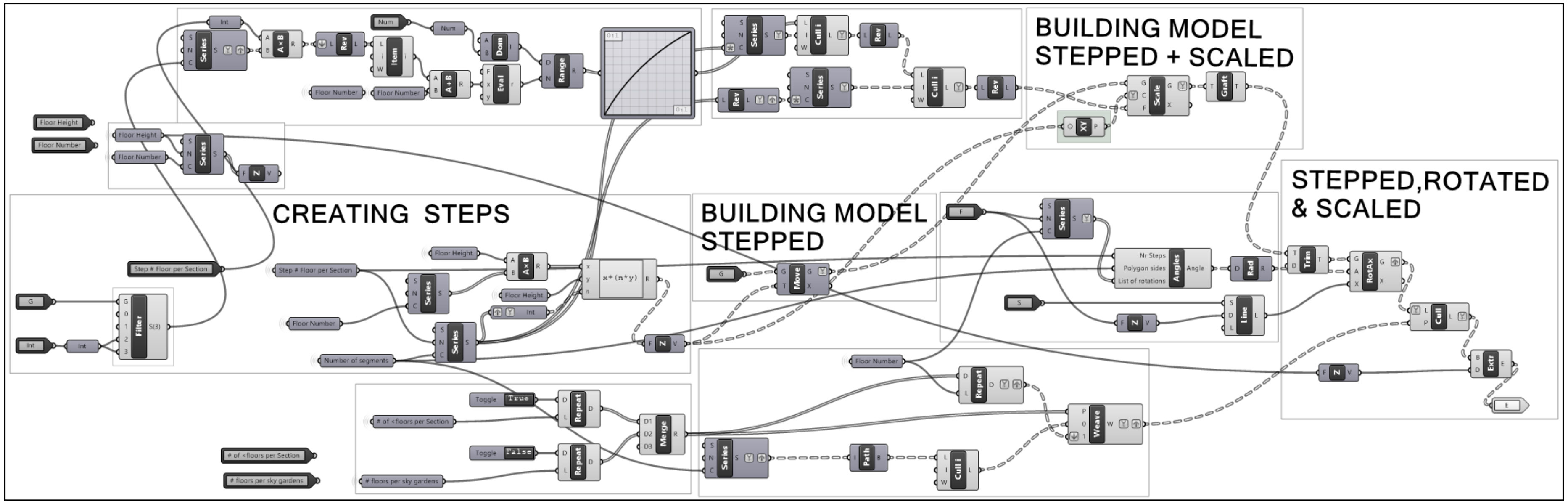



Figure 88 Algorithm of 3D-Variation

### 12.1.6 Fitness function

This algorithm is programmed in three parts First part corresponds to temperature reduction of the indoor air. CFD simulation results are saved in excel file in a working directory. The excel file containing the temperature values of all the points in a specific location (that is, in this case, a plane passing through the centre of building in vertical direction), is uploaded in the first part of algorithm. This part reads all the values and finds the value of temperature reduced due to the design strategies adopted. Second part calculates the optimization of wind velocity that should be between 2-5m/seconds. Third part of the algorithm calculated the gross floor area of the building and ranks it by comparing it with the gross floor area of other profiles with the same design. All these criteria are given weightage and the solution is ranked on a scale of 0-10 (corresponding to worst to best solution).

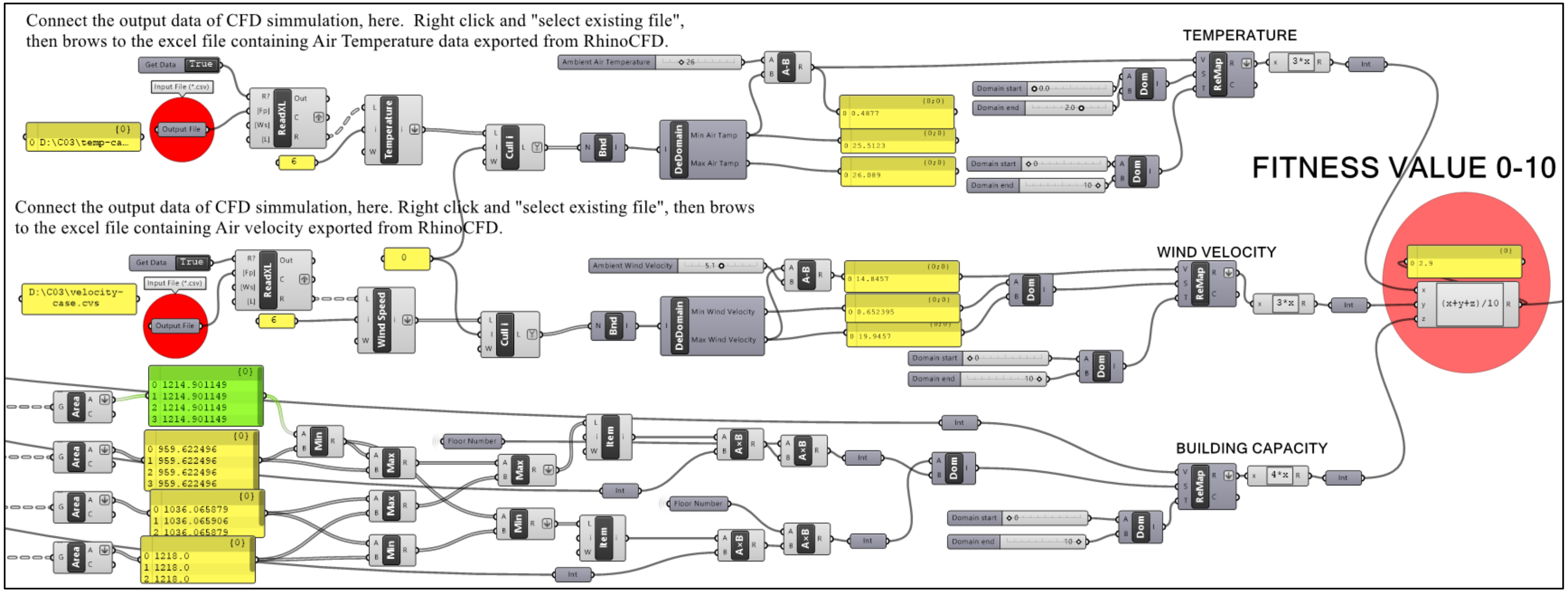



Figure 89 Algorithm for fitness function

## 12.2 Appendix B

### 12.2.1 OM-01 by integrating Opossum

In case of complete integration (that is partial now) of RhinoCFD, the proposed optimization model can be used by integrating Opossum for optimization. This algorithm for this OM id gives in following snapshot.

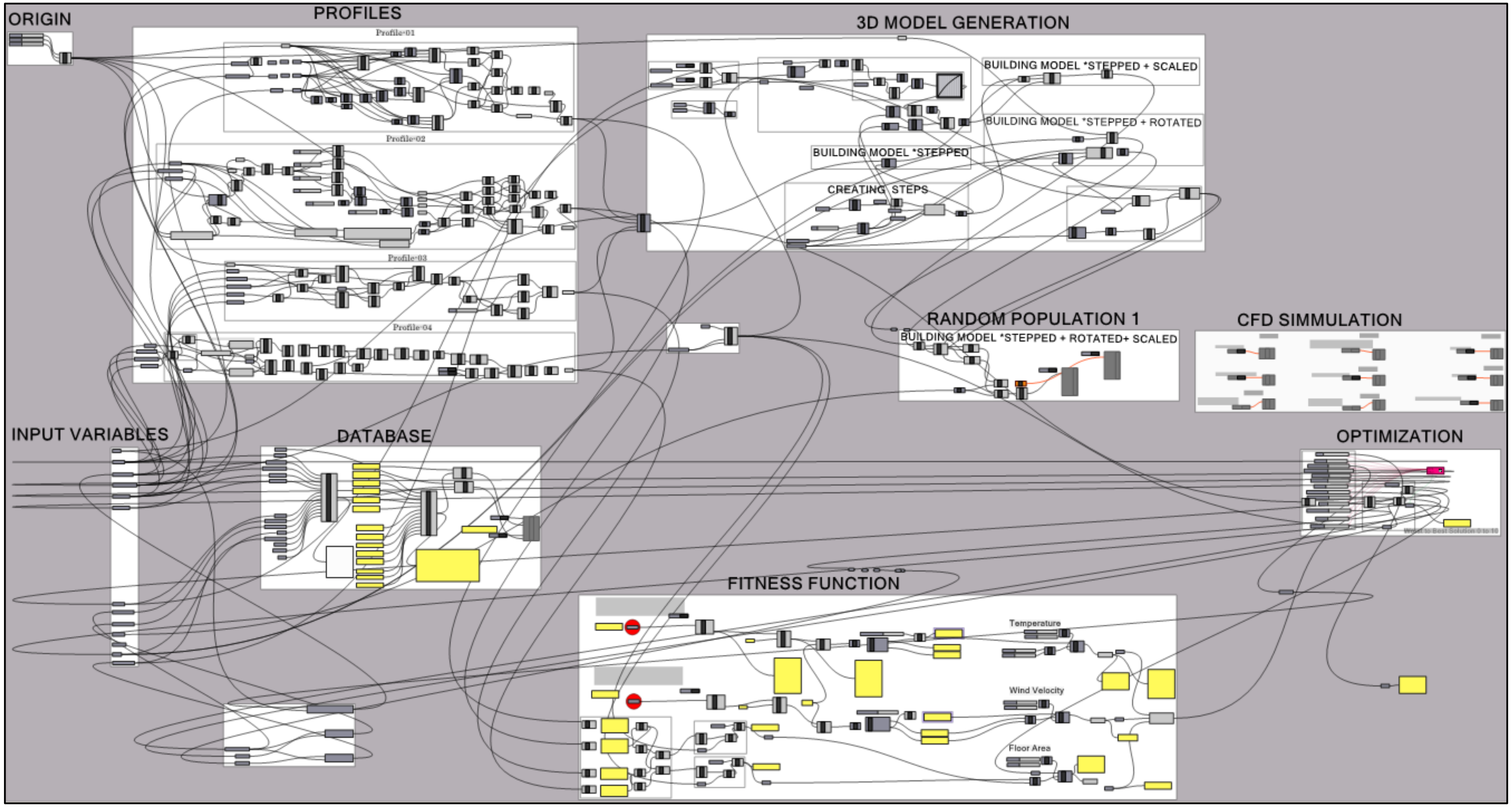



Figure 90 Algorithm of proposed optimization model using Opossum for optimization

## 12.3 Appendix C

### 12.3.1 OM-02 by integrating Opossum and Butterfly

This model (given in the following figure) suggests the integration of algorithms of generative tool (GT) and fitness function (FF) developed in this study with Butterfly (CFD simulation algorithm) and opossum (optimization plugin).

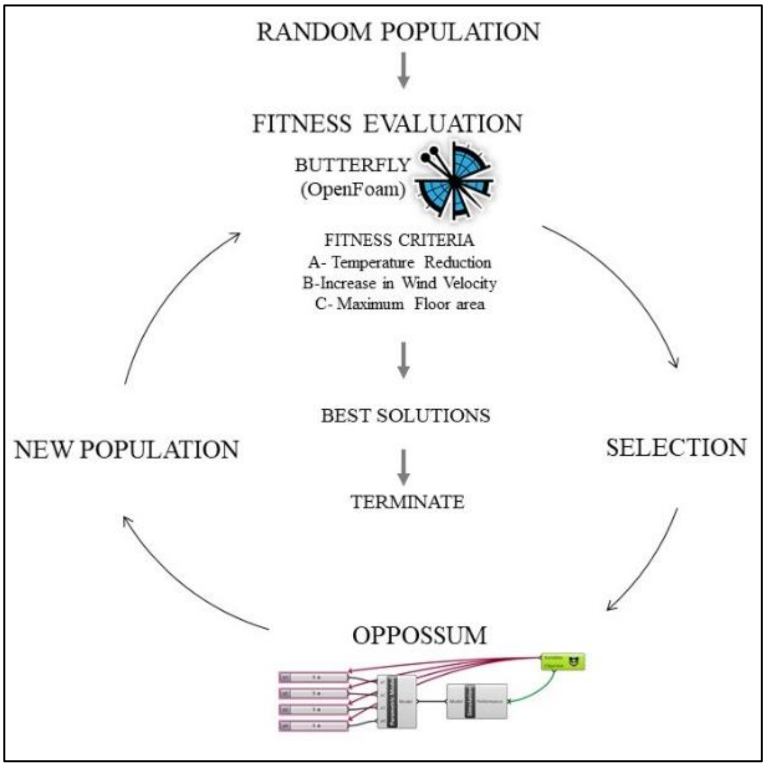



Figure 91 Optimization model using Butterfly and Opossum

- **Integration of Butterfly with generative model for CFD Simulation**

Butterfly is a Grasshopper/Dynamo plugin and object-oriented python library that runs computational fluid dynamics (CFD) simulations through OpenFOAM. Nowadays, OpenFOAM is a validated open source CFD engine that can run several advanced simulations and turbulence models (from simple to complex). Butterfly exports the geometry to OpenFOAM for various airflow simulations i.e. outdoor simulation for urban wind pattern and indoor bouyancy-driven simulations for finding the effectiveness of NV etc. (G. Theodore, 2019).

- **Fitness evaluation**

The fitness function remains the same for OM-02 as in the case of OM-01. Butterfly features for calculating wind pressure and wind velocity. The pressure values can be converted to the temperature by applying a conversion equation into the fitness evaluating algorithm. However, it is difficult to set up a model for the evaluation of wind flow through vegetation using butterfly algorithm. It is one of the deficiencies of the tool for the optimization of the models that are being studied in this research.

- **Opossum**

Opossum is a model-based optimization tool for Grasshopper based on black-box optimization (also known as derivative-free optimization). It utilizes sophisticated machine learning techniques to find optimum solutions with a small number of iterations. Latest version of Opossum includes single-objective model-based optimization algorithms as well as the multi-objective evolutionary algorithms.

The process to use Opossum is same as that of Galapagos. It provides a results table, through which all optimization results can be revisited by double-clicking entries in the table (Wortmann, 2017).

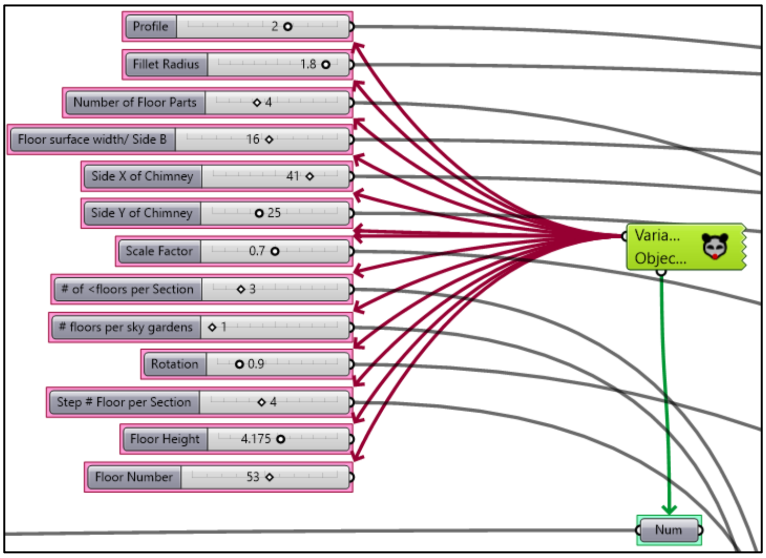



Figure 92 Optimization with Opossum; applied to the proposed generative model

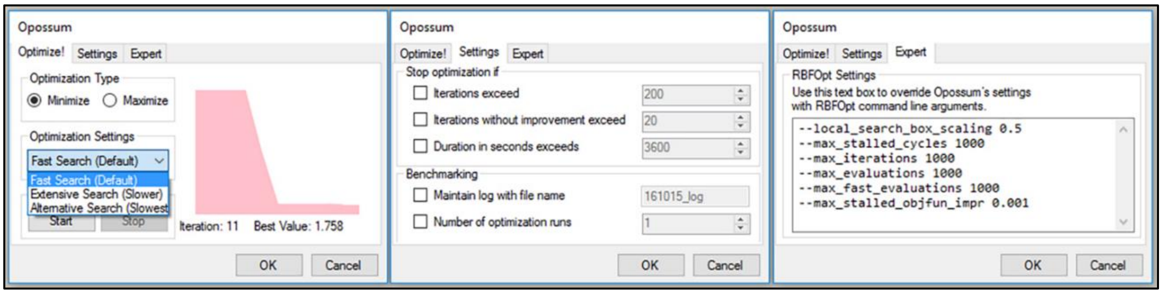



Figure 93The three tabs of Opossum's GUI, from left to right (Wortmann, 2017).

The algorithm developed for the OM-02 is given in the following snapshot.

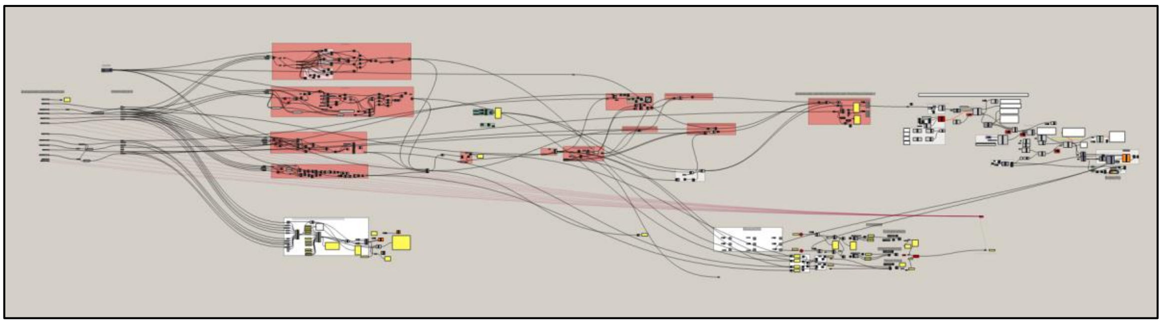


Figure 94 Integration of optimization model 02 to the generative model

## 12.4 Appendix D

### 12.4.1 Graphical data for checking convergence during CFD simulation of eight cases

A CFD simulation process involves solving highly non-linear equations recursively for variable i.e. momentum, energy, and mass etc. During this process, the solutions should be converged. Convergence of a solution means the tendency of the variables to reach a limit and errors in equations be minimized. Thus, the process should provide a solution in which all the equations are solved with negligible error after some iterations.

During the CFD simulation process with RhinoCFD, a probe is located downstream from the inlet and away from the building geometry. When the simulation is being proceeded, a dialogue box is appeared showing a graph of "spot values" on the left and of "% Error" on the right side. The all the (variable) lines in the left graph become horizontal, it means the solution is being converged. The graph of "% Error" is logarithmic and shows irregularities in general but should show a steady fall. This fall in "% error" plot and stabilization of the "spot values" lines represents the convergence of solution, that means the CFD simulation is being run well (Ahmed et al., 2019).

If the solution is not being converged on RhinoCFD, the simulation will be terminated by itself. If the % Error values fall below 1% for all variables, convergence may generally be deemed acceptable (Ahmed et al., 2019). chapter#6 involves the implementation of proposed OM on eight 3D-models of tall buildings, that requires CFD simulation. Convergence plot of these simulations are shown from **Figure 95** to **Figure 102.** All these plots show that the solutions have been converged and so the simulation went well. The results of velocity and temperature were extracted in excel file in working directory from where the data was imported in Grasshopper for evaluation it through fitness function.

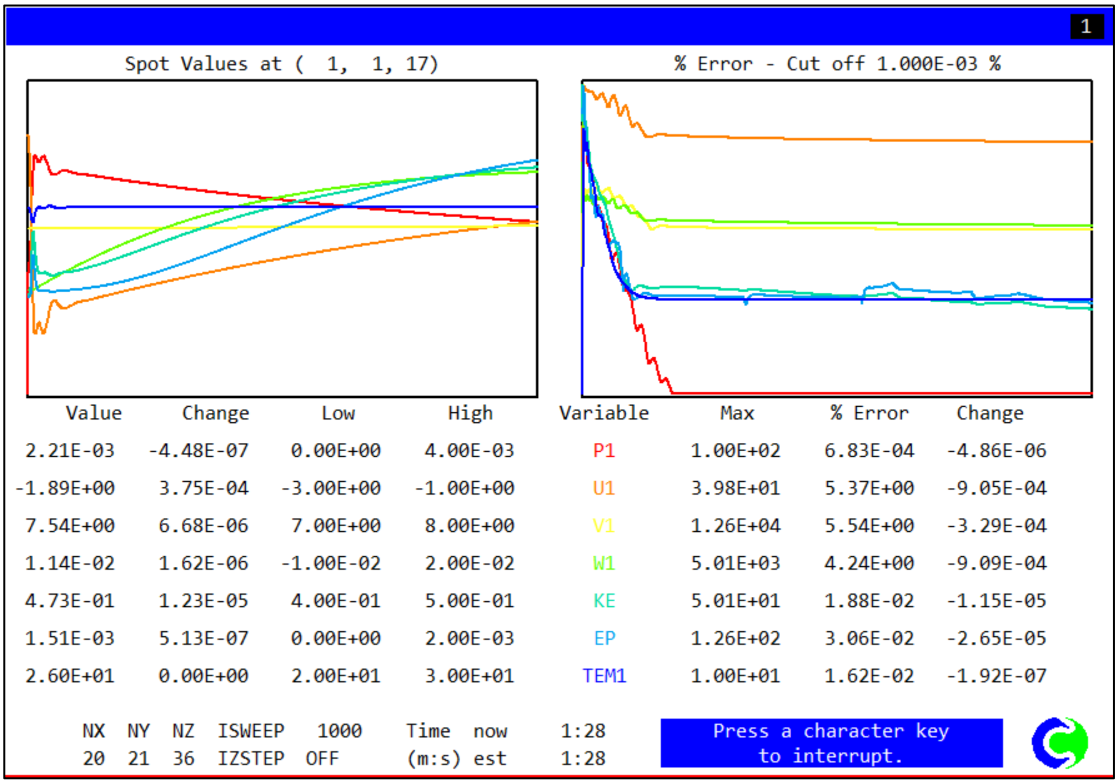



Figure 95 Convergence plot of building-01

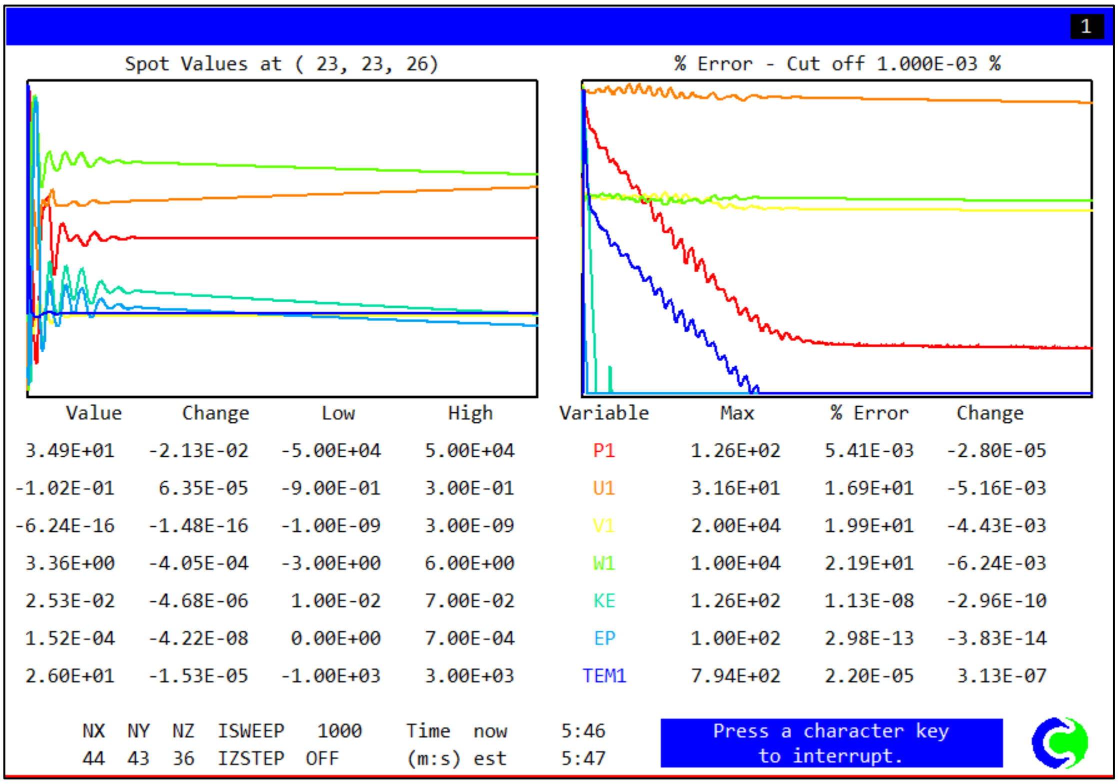



Figure 96 Convergence plot of building-02

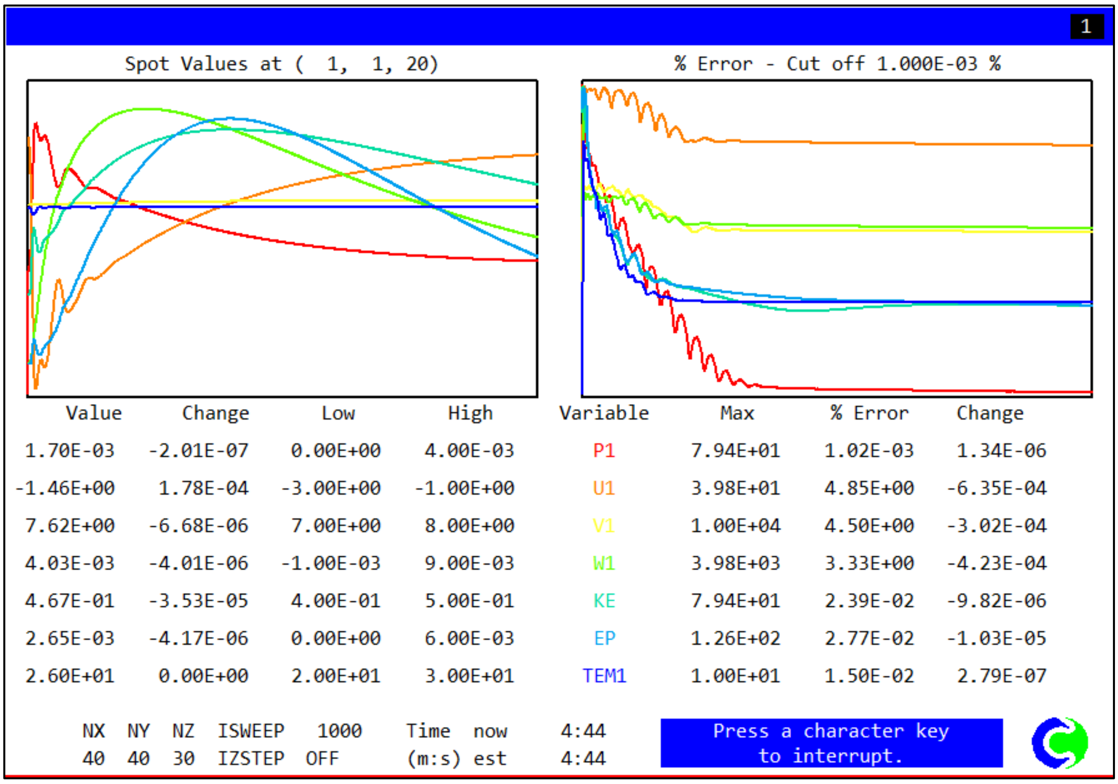



Figure 97 Convergence plot of building-03

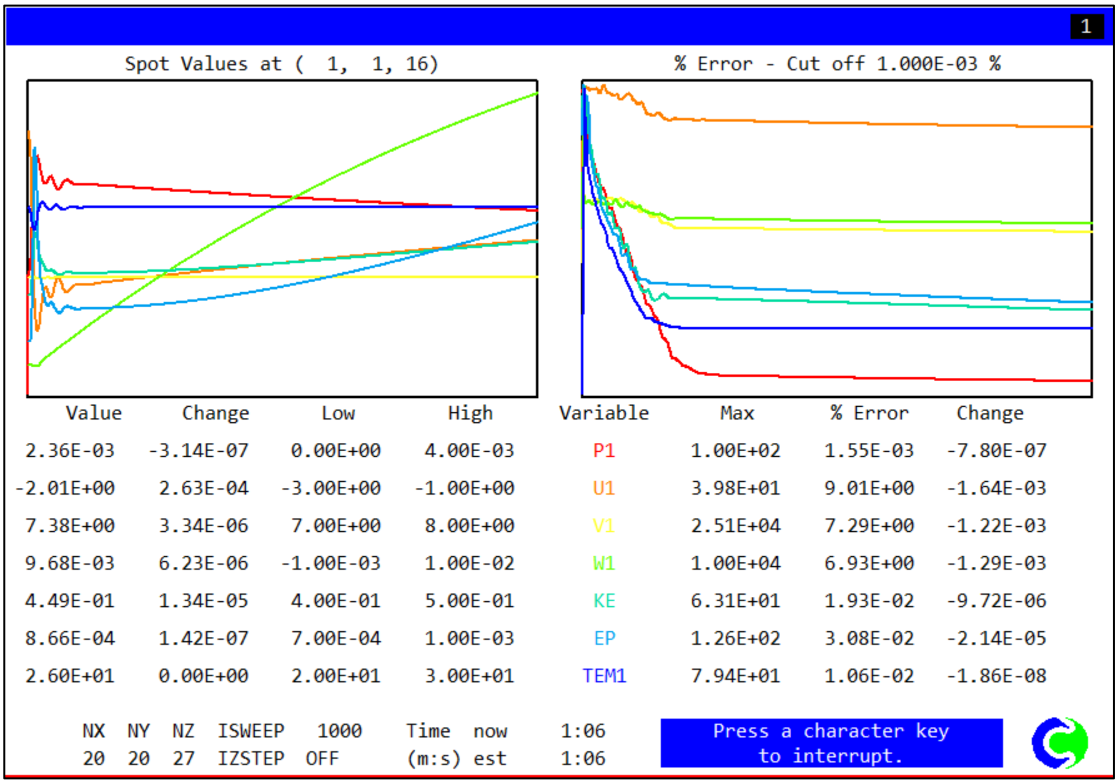



Figure 98 Convergence plot of building-04

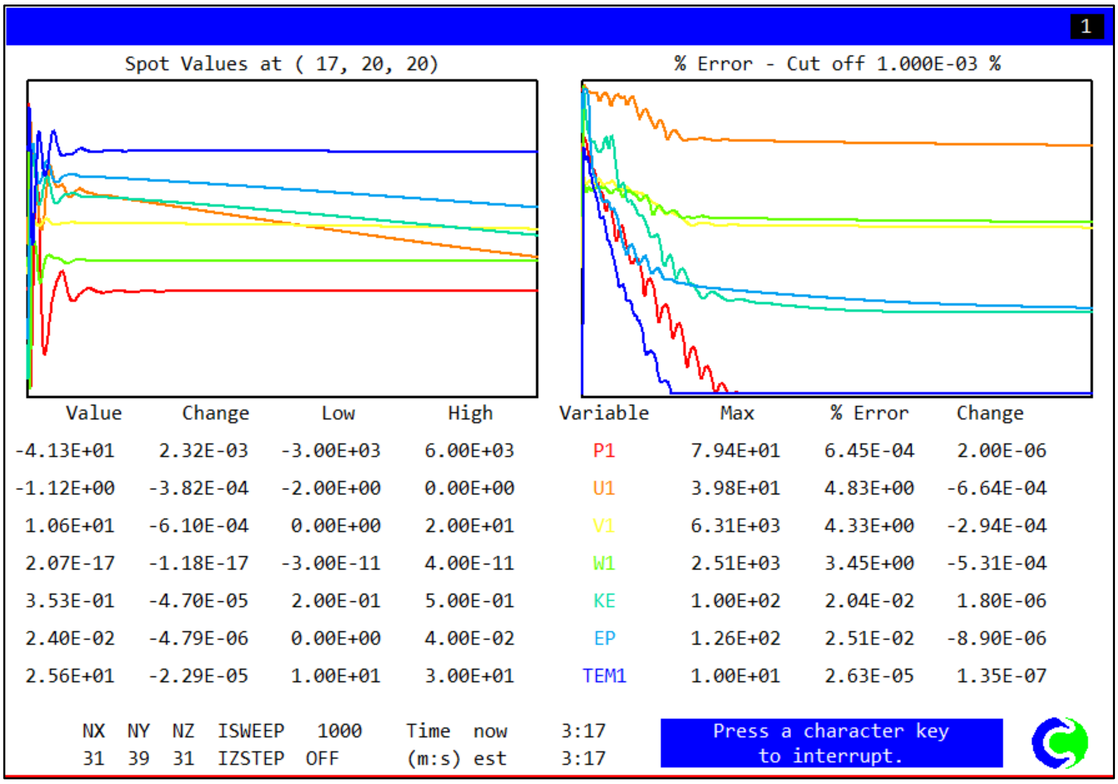



Figure 99 Convergence plot of building-05

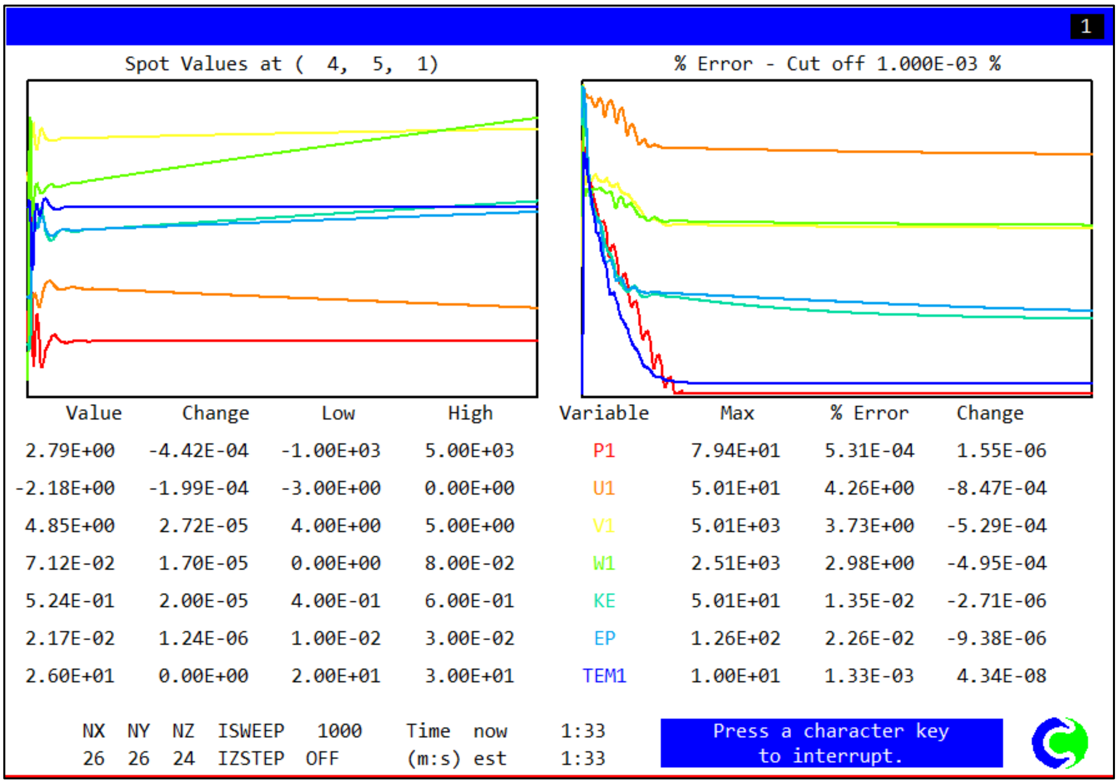



Figure 100 Convergence plot of building-06

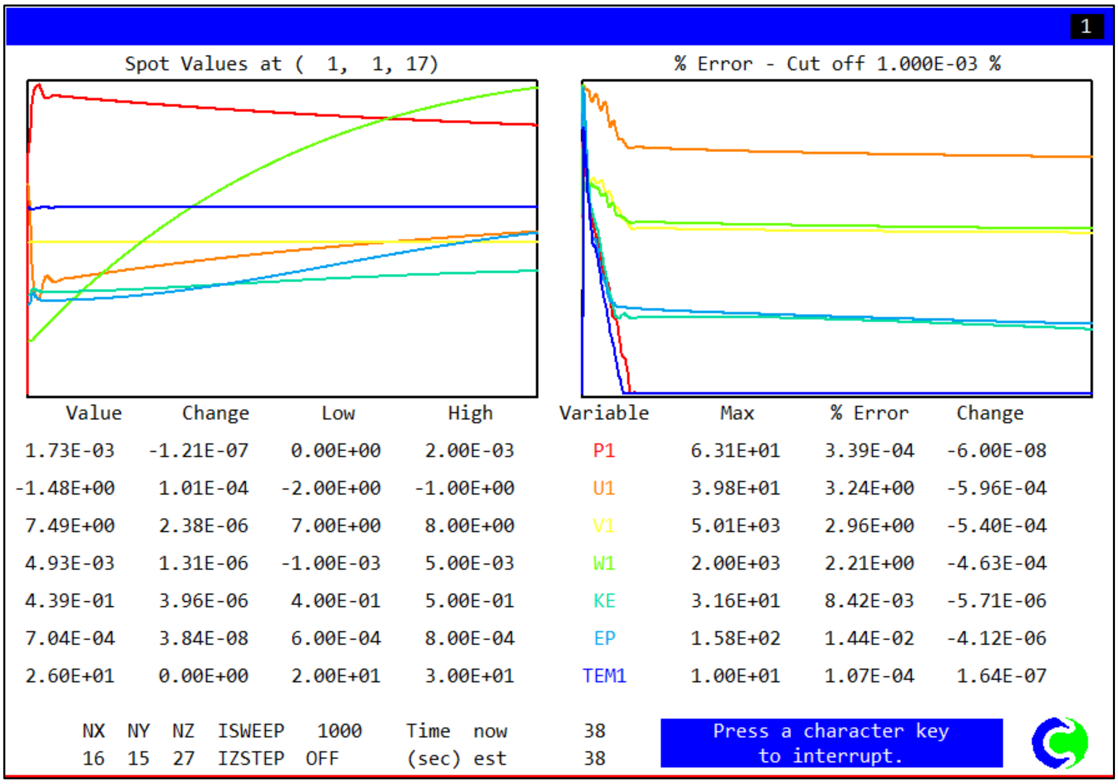



Figure 101 Convergence plot of building-07

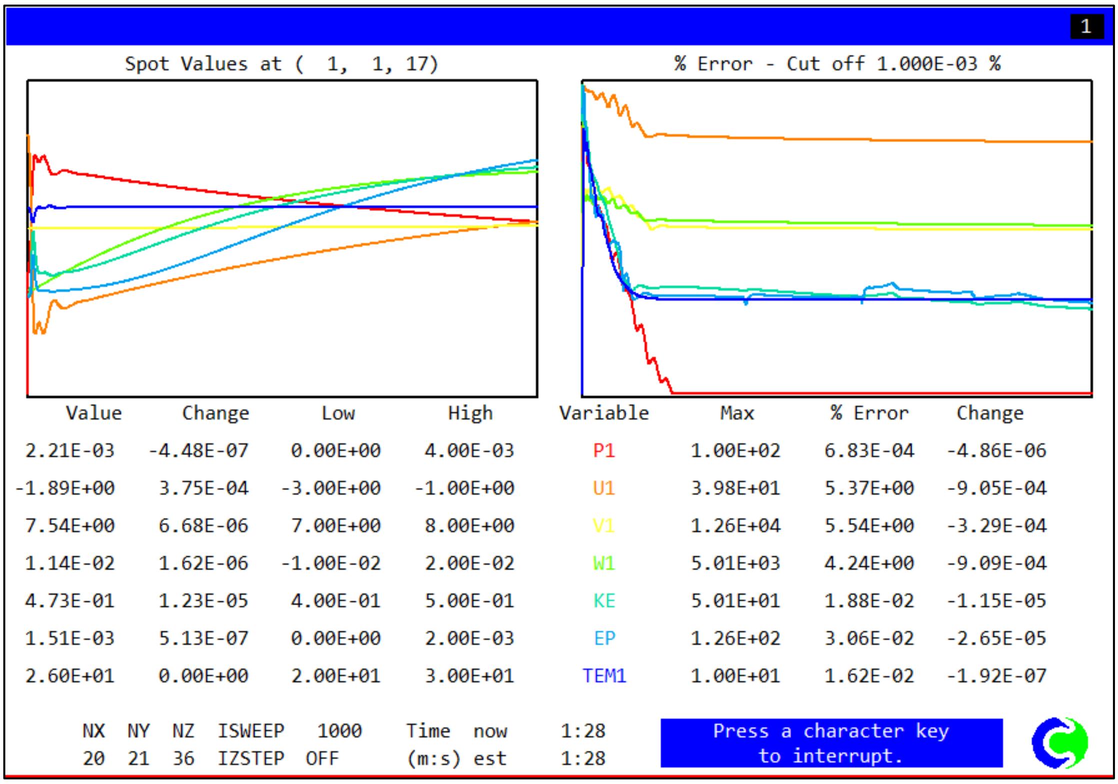



Figure 102 Convergence plot of building-08

## 12.5 Appendix E

### 12.5.1 Datasheets of case studies

Following are the datasheets that correspond to the case study of ten tall buildings discussed in chapter # 4.

| MENARA UMNO | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Penang, Malaysia | Architect/Design Team | T.R. Hamzah & Yeang |
| Completion year | 1998 | Site Context | Shopping district |
| Building type/s | Office | Site Typology | Flat land |
| Building height (m) | 94 | Climate Type | Tropical rainforest /Af |
| No. of floors | 21 | Orientation | NE- SW |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 5° 18' N, Long. 100°16' W | |
| Prevailing wind direction | | S-SW | |
| Average wind speed (m/sec) | | 2.6 | |
| Mean annual temperature (°C) | | 27.5 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 | |
| | Coldest months (Dec., Jan., Feb.) | 32 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 8 | |
| | Coldest months (Dec., Jan., Feb.) | - | |
| Mean annual precipitation (mm) | | 2398 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | N/A | |
| Location on the building | | N/A | |
| Surface area of green coverage ($m^2$) | | N/A | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Cross ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | 0-100 | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 25 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Not present | |

| | |
|---|---|
| Location of air shaft | On north facade |
| Overall building shape/form | Compact rectangular |
| Plan depth | Narrow |
| Plan shape | Rectangular with a curved wall |
| Shape of air shaft | Rectangular |
| High ceiling height (to enhance stack effect) (m) | 3.85 m |
| Night-time ventilation | Not present |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✓ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] Ismail, L. H. (2007). An evaluation of bioclimatic high-rise office buildings in a tropical climate: energy consumption and users' satisfaction in selected office buildings in Malaysia. University of Liverpool.<br>[2] Liu, P.-C. (2012). A modelling study of segmentation of naturally ventilated tall office buildings in a hot and humid climate Department of Architecture and Built Environment.<br>[3] Wood, A., & Salib, R. (2013). Natural ventilation in high-rise office buildings. | |

| TORRE CUBE | | | |
| --- | --- | --- | --- |
| **BUILDING INFORMATION** | | | |
| Building location | Guadalajara, Mexico | Architect/Design Team | Estudio Carme Pinós |
| Completion year | 2005 | Site Context | Dense office district |
| Building type/s | Office | Site Typology | Flat land |
| Building height (m) | 60 | Climate Type | Humid subtropical/Cwa |
| No. of floors | 17 | Orientation | No particular (symmetrical plan) |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 20° 41' N, Long. 103° 20' W | |
| Prevailing wind direction | | W | |
| Average wind speed (m/sec) | | 2 | |
| Mean annual temperature | | | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 20 | |
| | Coldest months (Dec., Jan., Feb.) | 24 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 16 | |
| | Coldest months (Dec., Jan., Feb.) | 19 | |
| Mean annual precipitation (mm) | | 972 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Sky gardens | |
| Location on the building | | 3-4 storey sky garden located on the segmented height of building | |
| Surface area of green coverage ($m^2$) | | N/A | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Natural ventilation | |
| Natural ventilation principle | | Cross & Stack Ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | 100 | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 100 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Present | |
| Location of air shaft | | Three atriums positioned around the periphery and one in the centre | |
| Overall building shape/form | | Circular | |
| Plan depth | | Narrow | |

| | |
|---|---|
| Plan shape | Triangular shaped three wings connected through central atrium |
| Shape of air shaft | Triangle |
| High ceiling height (to enhance stack effect) (m) | N/A |
| Night-time ventilation | Not present |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✓ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |

[1] Liu, P.-C. (2012). A modelling study of segmentation of naturally ventilated tall office buildings in a hot and humid climate Department of Architecture and Built Environment.
[2] Wood, A., & Salib, R. (2013). Natural ventilation in high-rise office buildings.
[3] Raji, B., Tenpierik, M. J., Bokel, R., & van den Dobbelsteen, A. (2019). Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. International Journal of Ventilation.

**1 BLIGH STREET**

**BUILDING INFORMATION**

| | | | |
|---|---|---|---|
| Building location | Sydney, Australia | Architect/Design Team | Architectus & Ingenhoven Architects |
| Completion year | 2011 | Site Context | Central business district |
| Building type/s | Office | Site Typology | Flat land |
| Building height (m) | 139 | Climate Type | Humid subtropical /Cfa |
| No. of floors | 30 | Orientation | NE-SW |

**CLIMATIC DATA**

| | | |
|---|---|---|
| Geographical position | | Lat.34° 0' S, Long. 151° 0' E |
| Prevailing wind direction | | N-NE |
| Average wind speed (m/sec) | | 3.8 |
| Mean annual temperature (°C) | | 18 |
| Average day time temperature (°C) | Hottest months (June, July, August) | 26 |
| | Coldest months (Dec., Jan., Feb.) | 17 |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 7 |
| | Coldest months (Dec., Jan., Feb.) | - |
| Mean annual precipitation (mm) | | 1222 |

**BUILDING INTEGRATED VEGETATION (BIV) SYSTEM**

| | |
|---|---|
| Type of BIV system | N/A |
| Location on the building | N/A |
| Surface area of green coverage ($m^2$) | N/A |

**VENTILATION SYSTEM**

| | |
|---|---|
| Ventilation type | Mixed mode |
| Natural ventilation principle | Cross & stack ventilation |
| Approximate percentage of the year natural ventilation can be utilized (%) | 100 |

**ENERGY PERFORMANCE OF BUILDING**

| | | |
|---|---|---|
| Annual energy saving | Heating and Cooling (%) | 63 |
| | Lighting & Electricity (%) | N/A |

**DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS**

| | |
|---|---|
| Segmentation | Present |
| Location of air shaft | Near Periphery of ES Façade |
| Overall building shape/form | Compact Oval |
| Plan depth | Wide |
| Plan shape | Oval |
| Shape of air shaft | Triangular with chamfered edges |
| High ceiling height (to enhance stack effect) (m) | N/A |

| | |
|---|---|
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✓ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] A. Wood and R. Salib, Natural ventilation in high-rise office buildings. New York: Routledge, 2013.<br>[2] Lochhead, H., Oldfield, P., & Lochhead, D. H. D. (2017). The Role of Design Competitions In Shaping Sydney's Public Realm Architecture/Design. CTBUH Journal 2017, (4). Retrieved from www.be.unsw.edu.au<br>[3] Raji, B., Tenpierik, M. J., Bokel, R., & van den Dobbelsteen, A. (2019). Natural summer ventilation strategies for energy-saving in high-rise buildings: a case study in the Netherlands. International Journal of Ventilation. | |

| CAPITAGREEN/MARKET STREET TOWER | | | |
|---|---|---|---|
|  | | | |
| **BUILDING INFORMATION** | | | |
| Building location | Singapore | Architect/Design Team | Toyo Ito |
| Completion year | 2014 | Site Context | Central business district |
| Building type/s | Office | Site Typology | Flat land |
| Building height (m) | 242 | Climate Type | Tropical rainforest / Af |
| No. of floors | 43 | Orientation | NE-SW |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 1.3° N, Long. 103.8° E | |
| Prevailing wind direction | | N | |
| Average wind speed (m/sec) | | 4.4 | |
| Mean annual temperature (°C) | | 27.5 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 | |
| | Coldest months (Dec., Jan., Feb.) | 26.6 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 82% | |
| | Coldest months (Dec., Jan., Feb.) | 86% | |
| Mean annual precipitation (mm) | | 201 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green roof, sky gardens, green balconies | |
| Location on the building | | Perimeter of building and on the roof, sky gardens on three levels | |
| Surface area of green coverage ($m^2$) | | 10443 (55 % of the perimeter of its façade) | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mechanical | |
| Natural ventilation principle | | N/A | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 30 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Present | |
| Location of air shaft | | Centre | |
| Overall building shape/form | | Triangular shape with chamfered edges | |
| Plan depth | | Wide | |

| | |
|---|---|
| Plan shape | Triangular shape with chamfered edges |
| Shape of air shaft | Rectangle with chamfered edge |
| High ceiling height (to enhance stack effect) (m) | 3.2 |
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✓ |
| Wind catcher | ✓ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] Parakh, J. (2016). The Space Between: Urban Spaces Surrounding Tall Buildings. CTBUH, 184–191. | |

| ONE CENTRAL PARK | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Sydney, Australia | Architect/Design Team | Jean Nouvel |
| Completion year | 2013 | Site Context | Central business district |
| Building type/s | Mixed-Use | Site Typology | Flat land |
| Building height (m) | 117 | Climate Type | Subtropical climate/Cfa |
| No. of floors | 34 | Orientation | NW-SE |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 34° 0' S, Long. 151° 0' E | |
| Prevailing wind direction | | N-NE | |
| Average wind speed (m/sec) | | 3.8 | |
| Mean annual temperature (°C) | | 18 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 26 | |
| | Coldest months (Dec., Jan., Feb.) | 26 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 17 | |
| | Coldest months (Dec., Jan., Feb.) | 7 | |
| Mean annual precipitation (mm) | | 1222 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green walls, green roof & bio filter walls | |
| Location on the building | | 2700 linear planter boxes to balcony and loggia areas (all façades from level 2 to level 33) | |
| Surface area of green coverage ($m^2$) | | 7 linear kilometres of greenery | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Cross ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 26 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Not Present | |
| Location of air shaft | | Centre | |
| Overall building shape/form | | Rectangular | |
| Plan depth | | Wide | |

| | |
|---|---|
| Plan shape | Rectangular |
| Shape of air shaft | Rectangular |
| High ceiling height (to enhance stack effect) (m) | N/A |
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] Nouvel, J., & Beissel, B. (2104). Case Study: One Central Park, Sydney. CTBUH Journal, (4).<br>[2] Golasz-Szolomicka, H., & Szolomicki, J. (2019). Vertical Gardens in High-Rise Buildings – Modern Form of Green Building Technology. IOP Conference Series: Materials Science and Engineering, 603, 022067.<br>[3] Wood, A., & Salib, R. (2013). Natural ventilation in high-rise office buildings. | |

| SKYVILLE@DAWSON | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Singapore | Architect/Design Team | WOHA Architects |
| Completion year | 2015 | Site Context | Metropolis's downtown |
| Building type/s | Residential | Site Typology | Flat land |
| Building height (m) | 152 | Climate Type | Tropical rainforest / Af |
| No. of floors | 48 | Orientation | EW |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 1.3° N, Long. 103.8° E | |
| Prevailing wind direction | | N | |
| Average wind speed (m/sec) | | 4.4 | |
| Mean annual temperature (°C) | | 27.5 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 | |
| | Coldest months (Dec., Jan., Feb.) | 26.6 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 82% | |
| | Coldest months (Dec., Jan., Feb.) | 86% | |
| Mean annual precipitation (mm) | | 201 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green roof & sky gardens | |
| Location on the building | | Sky terrace at every 12 floors, and a public garden on roof | |
| Surface area of green coverage ($m^2$) | | Green plot ratio is 110% | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Cross & stack ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 55 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Present | |
| Location of air shaft | | Centre | |
| Overall building shape/form | | Rectangular | |
| Plan depth | | Narrow | |
| Plan shape | | Rectangular | |
| Shape of air shaft | | Triangular | |
| High ceiling height (to enhance stack effect) (m) | | N/A | |

| | |
|---|---|
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] Wong, M. S., Hassell, R., & Yeo, A. (2016). Garden City, Megacity: Rethinking Cities for the Age of Global Warming. CTBUH Journal, pp. 46–51.<br>[2] Samant, S., & Menon, S. (2018). Exploring New Paradigms in High-Density Vertical Hybrids High-Rise Buildings Exploring New. [3] Paradigms in High-Density Vertical Hybrids. International Journal of High-Rise Buildings, 7(2), 111–125.<br>[4] Samant, S., & Hsi-En, N. (2017). A Tale of Two Singapore Sky gardens. CTBUH, (3). | |

| SKYTERRACE@DAWSON | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Singapore | Architect/Design Team | SCDA Architects Pte Ltd. |
| Completion year | 2015 | Site Context | Metropolis's downtown |
| Building type/s | Residential | Site Typology | Flat land |
| Building height (m) | 142.3 | Climate Type | Tropical rainforest / Af |
| No. of floors | 44 | Orientation | EW |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 1.3° N, Long. 103.8° E | |
| Prevailing wind direction | | N | |
| Average wind speed (m/sec) | | 4.4 | |
| Mean annual temperature (°C) | | 27.5 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 | |
| | Coldest months (Dec., Jan., Feb.) | 26.6 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | 82% | |
| | Coldest months (Dec., Jan., Feb.) | 86% | |
| Mean annual precipitation (mm) | | 201 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green roof & green terraces | |
| Location on the building | | N/a | |
| Surface area of green coverage ($m^2$) | | N/a | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Cross & stack ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | N/A | |
| | Lighting & Electricity (%) | 24.6 | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Present | |
| Location of air shaft | | Along the façade | |
| Overall building shape/form | | Rectangular | |
| Plan depth | | Narrow | |
| Plan shape | | Rectangular | |

| | |
|---|---|
| Shape of air shaft | Rectangular |
| High ceiling height (to enhance stack effect) (m) | N/A |
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] "Dawson state BTO projects", The Institution of Engineers, Singapore, 2001.<br>[2] "SkyTerrace @ Dawson, Singapore", Ctbuh.org, 2016. [Online]. Available: http://ctbuh.org/TallBuildings/FeaturedTallBuildings/FeaturedTallBuildingArchive2015/SkyTerraceDawsonSingapore/tabid/7096/language/en-US/Default.aspx. [Accessed: 30- Nov- 2017].<br>[3] "SkyTerrace & Skyville - FuturArc", Futurarc.com, 2013. [Online]. Available: http://www.futurarc.com/index.cfm/projects-2013/2013-jan-feb-skyterrace-skyville/. [Accessed: 30- Nov- 2017]. | |

| MAGIC BREEZE SKY VILLAS | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Hyderabad, India | Architect/Design Team | Penda |
| Completion year | Start year; 2017 | Site Context | City Centre |
| Building type/s | Residential | Site Typology | Flat land |
| Building height (m) | NA | Climate Type | Tropical climate / Aw |
| No. of floors | NA | Orientation | NW-SE |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 17.38°N, Long. 78.46°E | |
| Prevailing wind direction | | S (Feb to may); W (May to Sep); E (October to Feb) | |
| Average wind speed (m/sec) | | 1.7 | |
| Mean annual temperature (°C) | | 26.6 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 37 | |
| | Coldest months (Dec., Jan., Feb.) | 21.5 | |
| Difference between Day/Night temperature (°C) | Hottest months (June, July, August) | - | |
| | Coldest months (Dec., Jan., Feb.) | - | |
| Mean annual precipitation (mm) | | 766 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green terraces | |
| Location on the building | | On terrace of each apartment | |
| Surface area of green coverage ($m^2$) | | 8000 | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Cross ventilation | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving | Heating and Cooling (%) | 60 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Not Present | |
| Location of air shaft | | Along the façade | |
| Overall building shape/form | | Stepped rectangular | |
| Plan depth | | Wide | |
| Plan shape | | Rectangular | |
| Shape of air shaft | | Rectangular | |
| High ceiling height (to enhance stack effect) (m) | | N/A | |

| | |
|---|---|
| Night-time ventilation | Present |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1]"Magic Breeze Landscape \| Tag \| ArchDaily", Archdaily.com, 2016. [Online]. Available: http://www.archdaily.com/tag/magic-breeze-landscape. [Accessed: 15- Oct-2017]. | |

| SOLARIS | | | |
|---|---|---|---|
| **BUILDING INFORMATION** | | | |
| Building location | Singapore | Architect/Design Team | TR Hamzah & Yeang |
| Completion year | 2011 | Site Context | Dense Urban Business district |
| Building type/s | Office | Site Typology | Flat Land |
| Building height (m) | 79 | Climate Type | Tropical rainforest / Af |
| No. of floors | 15 | Orientation | NE-SW |

| **CLIMATIC DATA** | | |
|---|---|---|
| Geographical position | | Lat. 1.3° N, Long. 103.8° E |
| Prevailing wind direction | | North |
| Average wind speed (m/sec) | | 4.4 |
| Mean annual temperature | | 27.5 |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 |
| | Coldest months (Dec., Jan., Feb.) | 26.6 |
| Difference between Day/Night temperature (%) | Hottest months (June, July, August) | 82 |
| | Coldest months (Dec., Jan., Feb.) | 86 |
| Mean annual precipitation (mm) | | 201 |

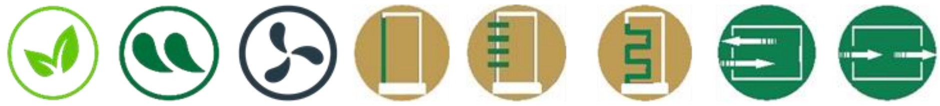
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | |
|---|---|
| Type of BIV system | Green walls, sky gardens & Green Terraces |
| Location on the building | All four facades and every four-floor level |
| Surface area of green coverage ($m^2$) | 4872 |

| **VENTILATION SYSTEM** | |
|---|---|
| Ventilation type | Mixed mode |
| Natural ventilation principle | Cross & stack ventilation |
| Approximate percentage of the year natural ventilation can be utilized (%) | N/A |

| **ENERGY PERFORMANCE OF BUILDING** | | |
|---|---|---|
| Annual energy saving for (%) | Heating and Cooling (%) | 36 |
| | Lighting & Electricity (%) | N/A |

| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
|---|---|
| Segmentation | Not present |
| Location of air shaft | Centre |
| Overall building shape/form | Curved and stepped |

| | |
|---|---|
| Plan depth | Wide |
| Plan shape | Rectangular with curved balconies on all sides |
| Shape of air shaft | Triangular with chamfered edges |
| High ceiling height (to enhance stack effect) | N/A |
| Night-time ventilation | Present |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✓ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |
| **SOURCE** | |
| [1] A. Wood, P. Bahrami and D. Safarik, Green walls in high-rise buildings. Chicago: Images Publishing Group, 2015, pp. 134-141. | |

| PARKROYAL on PICKERING | | | |
|---|---|---|---|
|  | | | |
| **BUILDING INFORMATION** | | | |
| Building location | Singapore | Architect/Design Team | WOHA |
| Completion year | 2012 | Site Context | Dense Urban Business district |
| Building type/s | Hotel & Office | Site Typology | Flat Land |
| Building height (m) | 89 | Climate Type | Tropical rainforest / Af (Köppen) |
| No. of floors | 15 | Orientation | NW-SE |
| **CLIMATIC DATA** | | | |
| Geographical position | | Lat. 1.3° N, Long. 103.8° E | |
| Prevailing wind direction | | North | |
| Average wind speed (m/sec) | | 4.4 | |
| Mean annual temperature | | 27.5 | |
| Average day time temperature (°C) | Hottest months (June, July, August) | 28.3 | |
| | Coldest months (Dec., Jan., Feb.) | 26.6 | |
| Difference between Day/Night temperature (%) | Hottest months (June, July, August) | 82 | |
| | Coldest months (Dec., Jan., Feb.) | 86 | |
| Mean annual precipitation (mm) | | 201 | |
| **BUILDING INTEGRATED VEGETATION (BIV) SYSTEM** | | | |
| Type of BIV system | | Green walls, sky gardens & green terraces | |
| Location on the building | | All four facades and every four-floor level | |
| Surface area of green coverage ($m^2$) | | 4872 | |
| **VENTILATION SYSTEM** | | | |
| Ventilation type | | Mixed mode | |
| Natural ventilation principle | | Single-sided & cross | |
| Approximate percentage of the year natural ventilation can be utilized (%) | | N/A | |
| **ENERGY PERFORMANCE OF BUILDING** | | | |
| Annual energy saving for (%) | Heating and Cooling (%) | 30 | |
| | Lighting & Electricity (%) | N/A | |
| **DESIGN STRATEGIES FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | | | |
| Segmentation | | Present | |
| Location of air shaft | | Along the façade and centre | |
| Overall building shape/form | | Rectangular | |
| Plan depth | | Narrow | |

| | |
|---|---|
| Plan shape | Rectangular |
| Shape of air shaft | Rectangular |
| High ceiling height (to enhance stack effect) | N/A |
| Night-time ventilation | N/A |
| **ARCHITECTURAL ELEMENTS FOR THE EFFECTIVENESS OF NV & BIV SYSTEMS** | |
| Wing wall | ✗ |
| Wing roof | ✗ |
| Double skin façade/Rain screen/Brise-soleil | ✗ |
| Wind catcher | ✗ |
| Lobbies | ✓ |
| Operable window | ✓ |
| Shading devices | ✓ |

**SOURCE**

[1] A. Wood, P. Bahrami and D. Safarik, Green walls in high-rise buildings. Chicago: Images Publishing Group, 2015, pp. 148-155.
[2] Frearson, A. (2103). PARKROYAL on Pickering by WOHA. Retrieved February 4, 2019, from DE-ZEEN website: https://www.dezeen.com/2013/10/10/parkroyal-on-pickering-by-woha/
[3] Hudson, C. (2014). Green Consumption: The Global Rise of Eco-Chic.