WIND BOY: AN EXPLORATORY DESIGN OF A WIND DRIVEN MODULAR FACADE

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By

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PREFACE

For centuries, men have been using the wind, which is a healthy and renewable resource, to improve the thermal comfort inside their structures. This traditional cooling system that have been providing relief from daytime heat are usually based on the presence of chimneys (cooling towers), courtyards, water sprays or associated with natural air movement. However, these strategies are usually dependent on building design and can sometimes be difficult to transport from one application to another. This study is an exploratory design of a new and innovative method for cooling buildings by a simple wind induced façade, which I called the *Wind Boy*. The term "*Wind Boy*" is my homage to a young African boy who, after a terrible drought struck his village, was able to provide electricity to his Malawian village by harnessing the power of the wind. A wind driven ventilation façade system that utilize wind as a natural energy to provide improved air quality inside the buildings is thus been explored in this paper. Subsequently, numerical analysis using computational fluid dynamics (CFD) was also employed to investigate internal flows inside a space using the proposed *Wind Boy*. Finally, the model will be analysed to determine if the façade configuration will provide better thermal comfort. The resulting study will benefit in the formulation of guidelines for the design of a sustainable building façade in the future.

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ABSTRACT

In this paper, a new concept to effectively collect the incoming wind into the building façade is proposed. The façade system acts as a secondary building skin and uses the well-established established Bernoulli's Principle to increase wind velocity. The proposed system, called the *Wind Boy*, is a modular façade system that theoretically increases wind speed to a sufficient level, thus improving the ventilation inside the building. Natural ventilation is an energy saving system for the building to ensure occupant's physical and thermal comfort. In order to determine optimal system of the *Wind Boy*, a CFD analysis was then applied using a hypothetical room to investigate the physical mechanism of air movement. The standard RANS *k–epsilon* model was chosen to simulate cross-sided ventilation. The results are presented in the form of the mean velocity vectors, the magnitude of velocity, the pressure distribution and the effect of incoming wind velocity inside and outside the room. During the CFD analysis, it was demonstrated that the prototype with the specially designed modular block can accelerate the wind speed. The façade system configuration including the distance between the building envelopes showed significant velocity distribution inside the room. The proposed system is a promising solution for improving the ventilation inside the building if combined with other applications (e.g. cooling pads, mini wind turbines, etc.) while also providing groundwork for future studies. Other potential areas of development and application of this new innovative concept are also being discussed.

Keywords:, Natural Ventilation, Wind Velocity, Building Skin, Active Facade , Bernoulli's Principle

Chapter 1. INTRODUCTION

1.1 Background of the Study

Numerous studies have shown that the current building sectors consumed approximately 47.6% (Fig. 1) of the global energy (Dixit et al., 2010), (Geller & Attali, 2005). This figure consisted of HVAC (Heating, Ventilation and Air Conditioning) systems which corresponds to about 65% of the energy used (Chua et al., 2013), (Pérez-Lombard et al., 2008).

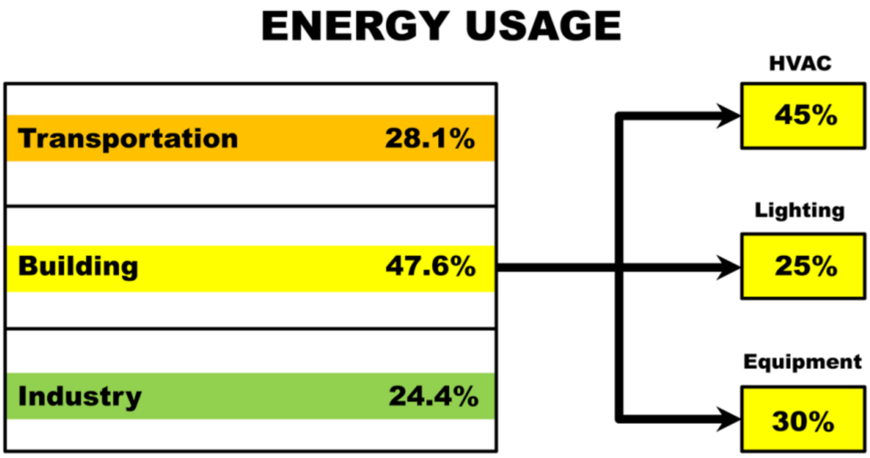


Figure 1. The current building sectors consumed approximately 47.6% of the global energy.

Before the advent of mechanical cooling, our ancestors have achieved thermal comfort in their dwellings by natural (passive) means for centuries (Asimakopoulos, 2013), (Serghides, 2010). For instance, the use louvered windows, curtains or interior blinds can provide adequate ventilation inside the building. Passive cooling uses free, renewable sources of energy such as the sun and wind to provide lighting, ventilation and cooling. Usually, the energy cost of a naturally ventilated building is 40% less than that of a building that uses mechanical energy systems (Allocca & Glicksman, 2003). Because of this, interest in passive design have grown recently in the past decade as part of the move towards sustainable architecture (Taleb, 2014) while considerable research has also been done into technologies at reducing the solar heat gain of buildings.

Some of the strategies have found increased use due to their effectiveness in reducing building energy cost. A practice that has recently been used by architects in the last two decades to reduce energy consumption for buildings is the use of the Double Skin façade (DSF) systems (Sanchez et al., 2016), (Barbosa & Ip, 2014), (Zöllner, 2002). However, very few buildings are constructed with the double skin facade because of high construction cost, increased weight, additional maintenance and operational cost (Azarbayjani, 2014), (Oesterle, 2001). Furthermore, if double skin facades are not properly designed it is possible that the temperature of the air in the cavity can increase, thereby overheating the interior space (Zhou & Chen, 2010), especially for countries with high solar gains (Lieb, 2001). A double skin facade is therefore, highly depend on the outdoor conditions (i.e. temperature, solar radiation, humidity, location, etc.) since they allow outdoor conditions to influence indoor comfort (Sadineni et al., 2011). Still, there are various attempts by architects and designers to emulate adaptive or bio-mimicry characteristics into the building facade to improve indoor conditions, however, there have been very few buildings that have been realized because there has been little experience in their behaviour (Zalewski et al., 2002). Recent designs for a sustainable smart façade have the ability to reduce interior thermal gains; however some of these designs require complicated mechanical systems or energy to operate.

In the end, it will be the shape of the building couples with orientation that can increase occupant comfort. For architects and designers, properly the application of passive design principles can greatly reduce building energy requirements before we even consider mechanical systems. Although the goal of achieving the ultimate passive design on every building may sometimes not be 100% fully achieved, instigating the passive design approach will ultimately lower building energy use.

1.1.1 Building Ventilation

According to ANSI/ASHRAE Standard 62.1-2004, ventilation is defined as the concept of exhaust and supply with the purpose of regulating air contaminant levels, humidity or temperature within the space of interest (ANSI/ASHRAE Standard, 2004). A number of researches have shown that increased airflow through natural ventilation can significantly enhance the functionality of buildings (Levermore, 2013). Thus, natural ventilation can help maintain comfort for the occupants, reduce energy usage, reduce cooling equipment size and increase indoor air quality (Haase & Amato, 2009). Proper ventilation improves the worker's productivity as well as avoiding the sick building syndrome (Burge, 2004), (Cardinale et al., 2003). Furthermore, the various benefits of natural ventilation have been stated in a report by Dr. Donald Atiken of the Renewable Energy Policy Project. Dr. Atiken indicated how increased productivity of the occupants is reason enough to consider better building technologies such as natural ventilation. In addition, the report asserts that natural ventilation can decrease employee absenteeism, increase retail cost and increase the performance of students in schools. Therefore, natural ventilation can be economically viable technology when considering these benefits. Therefore, good natural ventilation is significant in maintaining a healthy environment and can be economically viable technology when considering these benefits (Ghiaus & Allard, 2012). The circulation of the air within an enclosed space is essential to ensure that the temperature and humidity be maintained within a range that allows adequate evaporation of perspiration from the skin (Lien & Ahmed, 2011). Inadequate ventilation inside a building can result in problems with unpleasant smell, lack of oxygen, moisture, and the culmination of poisonous gases such as carbon dioxide that can cause serious medical conditions for the users (Pasquay, 2004). In spite of this, the number of studies on façade designs in improving the indoor climate, especially for naturally ventilated buildings are very limited (Liping & Hien, 2007).

1.1.2 Theory: Learning from nature

Architects and designers have been inspired by nature's ability for adaptation. The human body can perfectly respond and adapt to internal and external thermal changes through its different parts to maintain comfort levels. When the body temperature is elevated, the hypothalamus is stimulated to increase blood flow to the skin and therefore produces sweat to eliminate excess body heat. The human skin is the foremost separator between the body and external environments, and is also the medium between the core of the human body and the external conditions (Proksch et al., 2008). Such examples have inspired architects and designers to apply these concepts to their building designs. In this study, the author is proposing an analogy between the thermo-regulation processes of the human body and buildings, to help improve the interior comfort and performance of buildings. The author believes that the building skin should be as dynamic, intelligent and efficient as the human skin in terms of function, in order to increase the thermal comfort levels in interior spaces.

1.1.3 Harnessing Wind Energy from the Building Facade

Wind plays an important factor in building ventilation and cooling for the interior of a building (Aldawoud & Clark, 2008). Developments of wind technologies for urban use are still quite new. While this technology has a great potential as an economical and sustainable design solution, studies that deal with harnessing wind energy from the building façade are limited. Most of the studies that harness energy from the building façade explores the use of photovoltaic technology design (Mandalaki et al., 2012). Still, there are some investigations in wind energy systems in urban areas that allow the architects to integrate the technology into the building (Ishugah et al., 2014). Liping et al. investigated how shading devices can be used as wind catcher. Liping recommended that the design of these devices must be located in the right place otherwise it can become a barrier to wind flow. Liping further added that careful study must be done in the design and construction of external shading devices to optimize their function. Park et al. proposed an innovative building integrated wind turbine (BIWT) system which installs directly on the building skin. The proposed system collects the incoming wind and increases its velocity to power a rotor in generate electricity. However, there are still some challenges that needs to be addressed, for instance, low turbine output, vibrations, installation challenges and noise issues, among others (Park et al., 2015). Finally, I present case studies relating to innovative and adaptive building façade in chapter 2 of this paper.

1.1.4 Investigative Inspiration: The Brise-Soleil

The use of the Brise-Soleil in the early 20th century was pioneered by the famous architect Le Corbusier (Coelho & Maes, 2009), (Melendo et al., 2008). He developed the Brise Soleil (Fig. 2) to provide protection from the harsh tropical sun and was based upon the traditional Mashrabiya of the Arab buildings, which is made of fixed perforated panels (Kamal, 2014) and the brick louvered Claustra of Morocco (Kamal, 2014). Since the Brise-Soleil is fixed on the exterior of the wall cavity, it has its various restrictions. For instance, the immovable system resulted in unlimited visual access to the outside, the decreased access of daylight inside the spaces and the inability to adapt to the changing solar exposure of the sun. The use of concrete or metal as the base material in fabricating the Brise-Soleil also contributes to thermal heating inside the building. The Brise-Soleil is also tedious and expensive to manufacture, hence this application was now abandoned by some architects. In spite of these limitations, an improved version of the Brise-Soleil was proposed by Miletic & Jovanovic (2014) which consists of movable fins that are controlled by sensors. The study resulted in savings up to 30% on energy used for cooling. However, from the environmental point of view, this type of solution is not sustainable since it relies on the use of mechanical energy.

Figure 2. Examples of the application of Brise-Soleil in architecture.

This study was partially inspired by the concept of Le Corbusier's Brise-Soleil I would like to take this architectural element a step further. The proposed *Wind Boy* is a hybrid of the Brise Soleil, and the traditional Mashrabiya element of Islamic Architecture. By re-interpreting these architectural elements and applying the concept of Bernoulli's Principle, the resulting design is a simple but effective passive cooling technique that uses natural phenomena to cool buildings without the use of mechanical devices. The following chapter therefore, presents a conceptual development of a wind driven ventilation system to improve air quality inside the building.

1.1.5 The Use of Computational Fluid Dynamics in the Building Sciences

The use of computer simulation is used in optimizing and testing building designs before construction to reduce risk and construction cost. The use of computer simulation tools also enables the testing of innovate design techniques such as the incorporation of new materials and geometries that would be too costly to test experimentally (Hong, 2000). In various literatures, the use of Computational Fluid Dynamics (CFD) models is the most accurate and popular method to predict air movement in naturally ventilated buildings (Mora et al., 2003). It can be shown that in the last decade many studies of CFD applications have existed which concerns the airflow in naturally ventilated buildings (Stavrakakis et al., 2008), (Evola & Popov, 2006), (Mochida, 2005), (Jiang et al., 2003), (Jiang & Chen., 2003).

Furthermore, computational fluid dynamics is theoretically more capable of quantifying and designing a passive system than building energy simulating software (Wong & Fan, 2013). Therefore, the challenge for the building industry is the ability to adapt the shift in building design and embrace these simulations as integral parts of the over-all design process (Jatupatwarangkul & Zapka, 2015).

To save on resources, architects and designers will want an immediate feedback of these simulation tools at the beginning of the design process. While the benefits of CFD in the building industry are numerous, so are the barriers. These restrictions associated with CFD studies have prevented designers and architects to their building projects due to several factors:

1. Time Constraints: Simulations, depending upon the complexity of the model, may consume a huge amount of time for convergence. The present architectural design process requires the simulation analysis to be conducted in a timely manner for it to be relevant (Norton, 2007);
2. Complexity: Simulation tools are sometimes complex to use and usually require the expertise of a knowledgeable CFD specialist. Models have to be simplified for CFD simulations and the validity and accuracy of these simplifications must be also be verified so that the results remain precise for use (Zhai, 2006);

3. Software Cost: Commercially available software is generally costly to acquire and sometimes only the small firms can afford to investment in the software and yearly licences (Jones & Whittle, 1992);
4. Hardware Cost: CFD simulations need a huge amount of computational time and hardware required to perform. The larger a CFD simulation, the greater the hardware cost will then be required (Zhai, 2006);

Autodesk® CFD is a verified product and compatible with design software used in the building industry. This simulation program was therefore chosen due to: Shorter time required to run the simulations; the minimal conflicts between modelling and simulation software; affordability as well as its simplicity to run the simulations without the need for a huge hardware while still providing accurate results and options for the direction, plane, and velocity of the wind flow.

Broekhuizen (2016), in his study of wind flows, found Autodesk ® CFD a more user-friendly and accurate generally purpose CFD software. The program is useful for non-FD engineers and experts and would simply want to get an over-all analysis of a product or design before it is being built. Autodesk CFD 2016 is therefore used in this study to qualitatively depict air flow patterns and quantitatively predict air velocity at certain points within the interior of the *Wind Boy*.

1.1.6 Building Envelope design based on CFD

Both he engineer and architect are able to optimize the designs of building envelope openings, analyse indoor airflow paths and make sure that air flows through seamlessly inside the building. (Yang et al., 2014). CFD can analyse the distribution of wind speeds and coordinate the design of various window and door openings without sacrificing the functions of the spaces. In order to refine the details for the wind indoor environment, the engineers and architects needs to look at the size and position of the openings (doors, windows, etc.). CFD simulations can help find indoor wind speeds and airflow distribution when different forms of shading devices are proposed during the design phase (Guo et al., 2014). Thus the process can be used during the finalization of the building design.

1.2 Statement of the Problem

In architecture, the façade plays a critical role in the functionality of the building. However, the purpose of most urban building facades is purely aesthetical to the public (Sung, 2016). The building façade will ultimately play an impact of the interior lighting, temperature and energy use of the building. Various façade types can lead to the energy performance of the building. The surfaces on the exterior of the buildings can filter air, clean water, regulate temperature, generate breeze, and contribute to public health (Sung, 2016). Additionally, limited work has been done on the potential of the building façade to harness energy. In this paper, the author hypothesizes a modular system that can improve the air ventilation inside the building. Although there have been a number of attempts to use the building envelope as wind energy generators (Aksamija, 2013), (Sharpe & Proven, 2010), they are expensive and costly. Nevertheless, the use of the building façade as a wind collector can be a potential source of free energy. I therefore hypothesise that it is a promising concept that opens up to other interdisciplinary investigation of passive cooling methods.

1.3 Research Objectives

In this research, I explored the possibility of developing a prototype device (*Wind Boy*) into a wind induced building façade. Thus, the main objective of this research is:

1. To examine and conduct airflow simulations on the different design systems of the proposed modular façade system using Computational Fluid Dynamics (CFD) in order to determine its optimum air flow performance. Additionally, to also further examine the different variables that affects the airflow.
2. To investigate air flow characteristics of the proposed *Wind Boy* and evaluate the available wind velocity at specific locations of the system.
3. To be able to determine if the various configuration and distance of the proposed façade can influence the air flow behaviour and characteristics inside a test room using CFD.
4. To explore and discuss possible applicable scenarios of the proposed façade system while providing directions for future research.

1.4 Research Hypothesis

The proposed *Wind Boy* takes advantage of the classical Bernoulli's theory, which states that fluid must increase through the narrow portion of a pipe. The proposed design has a constricted inner core (converging section) that can amplify incoming winds. The *Wind Boy* is therefore a wind induced ventilation system to improve the indoor thermal conditions of the building. This simple but effective concept of wind energy harvesting is both sustainable and opens up other possibilities of energy harvesting thru the building façade.

1.5 Research Questions

In this paper, the author wishes to identify the following questions:

1. In what way can I use Computational Fluid Dynamics (CFD) simulation in determining the optimum air flow performance of the proposed modular façade system? What are the different variables that affect the airflow?
2. How can I investigate the airflow characteristics of the proposed *Wind Boy* system and evaluate its wind velocity at a specified location?

3. Does the various configuration and distance between the building façade of the proposed system have any influence of the airflow characteristics inside a test room?
4. What are the other possible applicable scenarios and directions for future research of the proposed façade system?

1.6 Significance of the Study

The significant contribution of this research is that it attempts to analyse the proposed *Wind Boy* in improving the indoor ventilation comfort of the building. This study will also propose additional recommendations for the *Wind Boy*, for example, the use of a hybrid system (e.g. wind turbines) and cooling systems. The use of different materials will also be discussed as well as future directions of the study. This study will also reveal the capabilities of Autodesk® CFD for use in building simulations. Thus, the workflow process may be referenced by those wishing to use CFD for the design of similar building devices. The knowledge gathered in this paper will be useful for architects and designers to improve the energy performance of the buildings by developing awareness in passive natural ventilation with the use of a building skin. The author hopes that this research will inspire and motivate researchers to further investigate new sustainable solutions and innovative building facades.

1.7 Scope and Limitations of the Study

As an architect it is not always easy to understand physical phenomena and mathematical equations in the real world. Unlike other building simulations (energy and daylight), CFD requires that I must have knowledge of mathematical modelling and experience with numerical methods. It is therefore difficult for non-experts like me to conduct intensive CFD simulations. However, the computational inputs which are being used in this study were being established by previous studies as stated in literature. Whenever possible, computational results should be validated with experimental data to ensure their consistency and credibility. Wind tunnel tests are usually used for validation however, for this study only the modelling approach (CFD simulation) will be used due to the limitation of the experimental apparatus and will be reported in my future subsequent studies.

1.8 Flow of the Research Process

In order to meet the objectives of this study, the author implemented a *Flow Research Process* (Fig. 3) to serve a guide in the investigative development and to be able to satisfy the research objectives. The *Flow Research Process* was divided into four main stages: Defining the research problem; Study of related literature; Design hypothesis and proposal; CFD analysis; Results and discussions and finally, the Conclusions, Thesis statements and Recommendations for future studies.

In Chapter 1, the author provided an overview to the conditions of the sustainable building façade in its present form. The chapter also presents the research objectives and research questions of the study as well as the significant contributions to the field of knowledge.

In Chapter 2, literature reviews of selected case studies, design concepts and applications of adaptable solutions for the building designs are presented. To explore and acquire from their experience in many dimensions, the review concentrated in different concepts of promoting building sustainability, energy producing façade systems, natural ventilation and passive cooling strategies, among others. Thus, the review includes part of the building envelope and its design and functions which contributed to the study of *Wind Boy*. Furthermore, the author have reviewed some scientific papers and journals that have been using Autodesk®

CFD simulation as a tool in investigating different ventilation, airflow, thermal and comfort analysis of the built environment.

In Chapter 3, the theoretical framework of the research included the classical Bernoulli's principle and fluid systems. The different components of the framework are shown in this chapter which helped identify the *Wind Boy* system geared the study to answer the research questions. Furthermore, in this chapter the author discusses possible theoretical developments of the system as an energy and evaporative cooling element. In Chapter 4, the performance of the *Wind Boy* was investigated (CFD analysis) in a regular sized room with two windows. Here, the *Wind Boy* was configured at a given distance between the window and building envelope. Airflow analysis was done and studied if the proposed system would significantly improve the indoor conditions of the interior of a room. In Chapter 5 concludes with a discussion on the analysis and synthesis of the information gained from the study as well as the thesis statements. In Chapter 6, future directions, and recommendation for improvement of the proposed façade system is also being discussed and contended in this chapter. Finally, Chapter 7 comprises the sources of primary and secondary data that are referenced in the research paper.

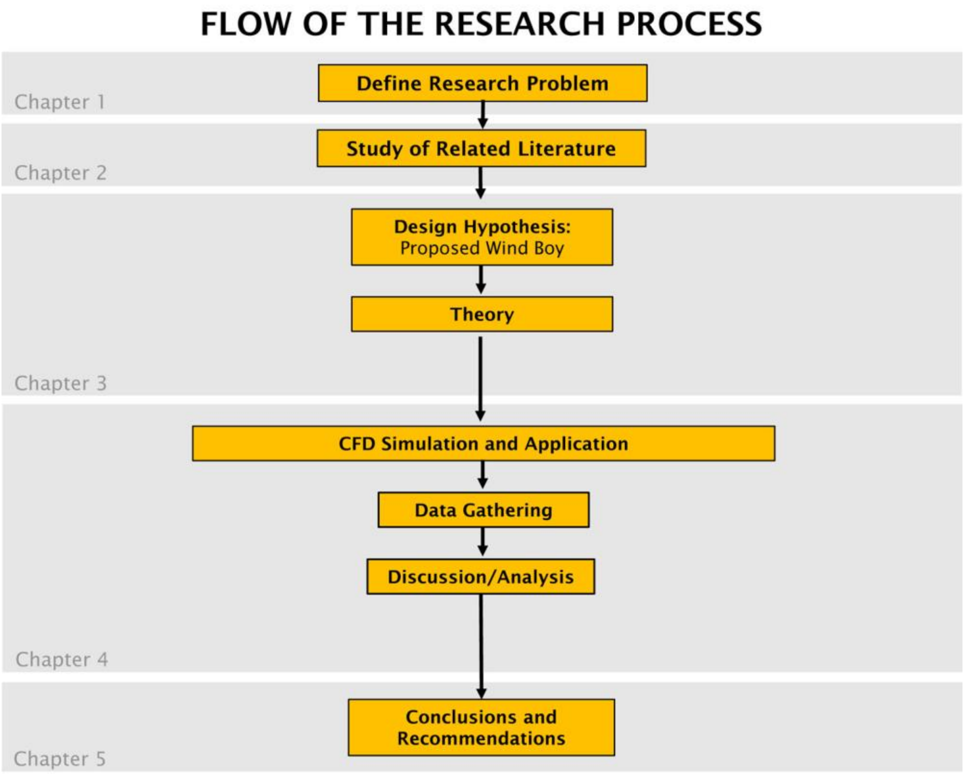


Figure 3. The Flow of the Research Process used by the author in this study.

Chapter 2. LITERATURE REVIEW

2.1 Introduction

The literature review in the following chapters aims to be broad but not exhaustive. In Chapter 2.1.1, the author presents case studies in the scope of building physics and energy efficiency with focus on improving the indoor conditions. Building facades perform two basic functions: first, they create the image of the building and second, they are barriers that separate the interior from the external environment. Adaptive facades are building systems that create comfortable spaces by utilizing the outside environment. Building facades need to respond to the specific characteristics of the local conditions. Additionally, building facades that can harness the energy, such as wind driven ventilation and solar photovoltaic cell systems have rarely been designed or studied. Nevertheless, some of the most innovative building facades and concepts presented in the succeeding chapter was the starting point for my studies presented here.

In Chapter 2.2, the author explores how both researchers and practitioners use Autodesk® CFD simulation as a tool for building science, more specifically, for naturally-ventilated and mixed mode buildings. Therefore, a literature review was conducted to outline the importance of CFD simulation and modelling tools and methods used by researchers.

2.1.1 A Review on the use of Innovative Building Façade Systems to Improve Interior Building Conditions

Case Study 1: Al Bahr Towers (Abu Dhabi, UAE). The Al Bahr Towers (Fig. 4), designed by Aedas Architects, is a responsive façade that took cultural cues from the "mashrabiya", a traditional Islamic wooden lattice shading screen. Aedas fused the concept of bio-inspiration, regional architecture and performance technology with an underlying geometric composition. The façade operates as a curtain wall which comprises of mechanical structures which can adapt to the movement of the sun, thus providing protection from direct solar rays which controlling the admission of natural diffused light. These dynamic units avoid the need for heavily treated glass and therefore reduce the need for artificial lighting and mechanical air-conditioning. This results in a decrease on energy usage and lends itself to a more sustainable solution. Recently, user satisfaction of the towers was investigated by Attia (2017) describing in detail the process of design, construction, energy performance and the use of an adaptive glass façade. During their survey of the users of the building concerning thermal comfort, 10% of the occupants felt uncomfortable. The main reason for discomfort that was recorded by females was overcooling. For concerns on natural lighting, the surveys stated that 40% are very uncomfortable. The main reason was related to the automated opening and closing of the mashrabiya. A large percentage of occupants stated that they were annoyed by the regular opening and closing of the mashrabiya that does not allow them to interact with the facade. The automation is causing a widespread occupant discomfort, which is accentuated by their passivity toward their indoor environment control. Additionally, the glass façade and unacceptable window-to-wall ratio, high cost and maintenance of the project resulted in the building failing to obtain the LEED certificate. The study further concluded that the use of an adaptive facade in this project was meaningless from a sustainability point of view (Attia, 2017). The Al Bahr Tower is a controversial project and this case study has shown the importance of user satisfaction in architecture or else the building will lose its meaning as a sustainable building and the innovative façade is nothing more but a failed decorative contraption.

Figure 4. The Bahr Towers in Abu Dhabi (Image retrieved from http://www.ahr-global.com/Al-Bahr-Towers)

Case Study 2: The BioSkin (Tokyo, Japan). Designers have been developing and using the natural forces of the wind in their building façade as solution to not only cool the interior of the building but mitigate the urban heat island effect of the surrounding environment (Shih, 2017). Such a technology was developed by the Japanese architecture firm Nikken Sekkei, used a system of ceramic pipes that absorbs and evaporates heat. The “BioSkin” was implemented on Sony’s Osaki Building in Tokyo (Fig. 5). BioSkin was inspired by the traditional practice of *uchimizu*, the sprinkling of water in Japanese gardens, temples and streets to lower ambient temperatures. The building skin is made of extruded aluminium cores, with a water-retentive terra-cotta shell. Rainwater is collected from the roof and then sent to the basement to be sterilized before it is circulated throughout the building through a series of pipes. Studies have shown that with this technology, it reduces the building temperature by as much as 21°F, and its surroundings by 3°F. Additionally, the BioSkin also screens out direct sunlight, reducing air-conditioning load for greater decreases in CO2 emissions to the environment. This case study lays out a design which follows a model that uses the natural forces as a sustainable solution to improve indoor conditions without using electrical energy.

Figure 5. Sony's Osaki Building in Tokyo which is the first building to use the BioSkin exterior system. (Retrieved from: http://www.nikken.co.jp/)

Case Study 3: The Strawscaper (Lund, Sweden). The concept of energy producing building façade using the wind has been experimented at the School of Architecture at Lund University in Sweden. Originally developed as a student project, the Strawscaper (Fig. 6) is a building with a wave of hair-like straws that produce energy through the use of piezoelectric materials. By turning the exterior of the Söder Torn building into a waving sea of hair-like straws, the building generates its own energy by converting kinetic energy into electrical energy. This means each straw, which consists of ceramic core with polymer cladding, would be gathering power to be stored by the building. Lead architect Rahel Belatchew Lerdell of Belatchew Labs believes that this technology is a new kind of wind power plant that opens possibilities of how buildings can produce energy. If Belatchew Labs succeeds the project could make a huge impact on the world of architecture. The case study presented here shows the interactive relationship between the building and nature. Although still in its conceptual stage, it shows the possibility of harnessing energy from the wind in order to reduce energy cost for the building.

Figure 6. The proposed façade of the Söder Torn building into a waving sea of hair-like straws, in which the building generates its own energy. (Retrieved from: http://thecreatorsproject.vice.com/)

Case Study 4: EcoARK (Taipei, Tawian). The EcoArk, designed by Arthung Huang in 2010, is a building of which the façade and walls are filled with non-load bearing PET bottles. The unique facade material, developed by a company called MINIWIZ, is the POLLI-Brick™ (Fig. 7). The material is made from 100% recycled Polyethylene Terephthalate Polymer. One of the advantages of using this material is its translucency and durability. The standard honeycomb design is self-interlocking which the company claims is extremely strong and weighs only around one-fifth of the standard curtain wall systems we found today. The POLLI-Brick can be manufactured on site, which reduces the carbon footprint compared to the conventional materials of glass and steel. The company claims that Polli-Brick™ cost 1/5 the price of conventional curtain wall system. Additionally, solar powered LED lighting can be integrated into the Polli-Brick™ system and therefore consolidating all-in-one green energy lighting solution. The case study here shows the possibility of a modular system that can be incorporated into the building façade while using recycled materials.

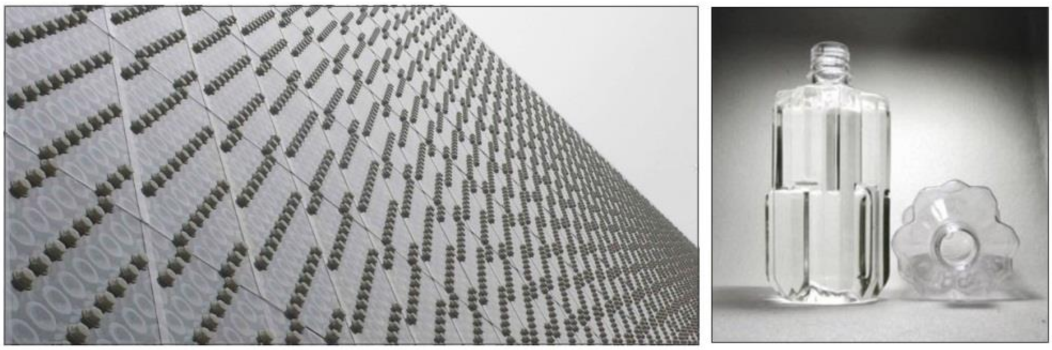


Figure 7. The use of POLLI-Brick™ as an innovative building façade system. (Retrieved from: http://www.miniwiz.com/)

Case Study 5: Pittsburgh Children's Museum (Pittsburgh, USA). *Articulated Cloud* is a "kinetic" facade covering for the Pittsburgh Children's Museum (Fig. 8) by the architects Koning/Eizenberg in collaboration with the artist Ned Kahn. The building is located in Pittsburgh and was completed in 2005. The wall is composed of thousands of translucent plastic square flaps that moved with the wind. Similar to the typical clouds that follows the paths of airflow as they penetrate through the sky, the flaps moves and flows in harmony to create the impression that the entire building is enveloped in an abstract cloud. The Museum was the largest Silver LEED museum in the northern America which features adaptive reuse, recycled materials, and passive shading in its design.

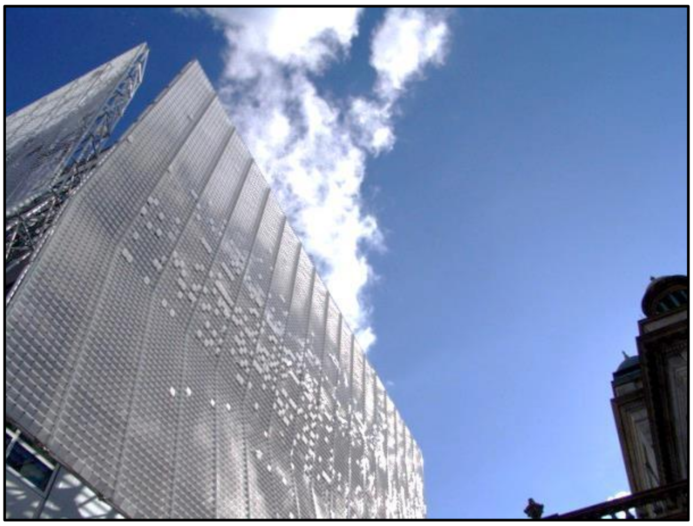


Figure 8. Articulated Cloud: An innovative Kinetic façade system. (Image retrieved from https://www.arch2o.com/articulated-cloud-ned-kahn/)

Case Study 6: Unilever Headquarters (Hamburg, Germany). The new Unilever Headquarters (Fig. 9) is located in Hamburg, Germany and is located near the river Elbe. The building, designed by Behnisch Architekten, follows the principle of holistic and sustainable architecture. The main features that have contributed to the building's exceptional environmental performance include the *Thermally Activated Cooling System*. These systems are thermally activated reinforced concrete ceilings that help to cool interior spaces. A new surface mounted device (SMD) LED system, which is up to 70% more efficient than metal halide or conventional halogen lighting, was used for interior lighting. The building's façade system consists of optimized blinds, which are made up of a single layered film that shields the blinds from the outside temperatures. Finally, the rest of the spaces are flooded with natural lighting due to the large atrium. The incorporation of simple technologies and knowledge of passive cooling (large atrium) resulted in a building that was able to reduce energy consumption.


Figure 9. The Thermally Activated Cooling System of the Unilever Headquarters in Hamburg. (Image retrieved from http://buildipedia.com)

Case Study 7: Council House 2 (Melbourne, Australia). Council House 2 (Fig. 10) is located in Melbourne, Australia and is a project led by Mick Pearce of Design Inc. The building is one of an excellent example of bio-mimicry. The façade is composed entirely of recycled timber vertical slats that cover a fully glazed wall. The vertical slats pivots vertically and operates in response to the time of day and angle of the sun. The roof is lined with bright, yellow wind turbines that harness the powerful resources of the wind. Inside the building, the combination of individual lighting and a softer overall lighting was rated highly by the users. There is also a provision for vertical frames on the north-west façade to allow plants to climb and act as living sunscreens. This building is an excellent example of the marriage of architecture and innovative engineering because almost every single design element has been resolved and integrated to form a building that create a unique solution that mimics nature. The case study of section 2.1.5, to 2.1.7 presents potential opportunities to improve buildings' energy performance by simply adding external shading and using high performance glazing systems. Likewise, solar shading could be seen as a major design element for building facades.

Figure 10. Recycled timber was being used as the building façade of the Council House 2 in Melbourne.
(Image retrieved from http://architectuul.com/architecture/)

Case Study 8: National Aquatics Center (Beijing, China). The Water Cube (Fig. 11) and was a major focal point during the 2008 Summer Olympic Games. Arup and PTW based the structural design of soap bubbles. The designers first explored how bubbles connect, which led them to the studies of an eighteen-century Belgian scientist Plateu. The solution was finally arrived a century later by Professor Weaire and his research assistant Dr Phelan at Trinity College in Dublin. The fascinating thing about Weaire Phelan foam is despite its complete regularity, when observed at different angles it appears to be organic and random. The Water Cube performs like a greenhouse due to the use of ETFE (Ethylene-Tetrafluoroethylene) material of the façade. The translucent quality of ETFE allows natural daylight to penetrate the building interior, and acts as an insulator to passively heat the building and pool water. This concept reduced energy consumption by more than 30%, which is equivalent to covering the entire roof in photovoltaic panels. Furthermore, ETFE was used because it provided an efficient means of construction. It would use minimum materials and removes the need for a secondary structure while providing excellent insulation than a single façade system.

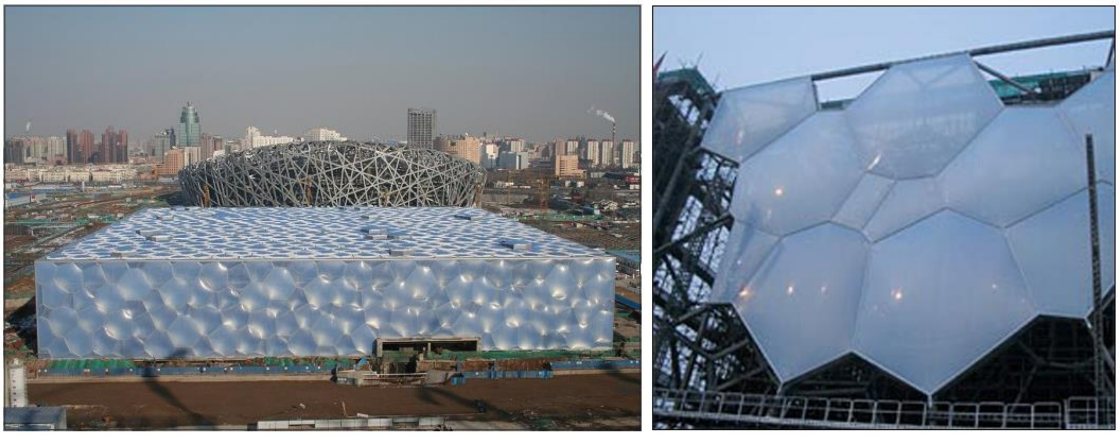


Figure 11.The use of ETFE as a façade of the Water Cube in Beijing. (Image retrieved from http://www.archello.com/)

Case Study 9: Torre de Especialidades (Mexico City, Mexico). The façade of the Torre de Especialidades was designed to capture and transmute air pollutants into harmless chemicals (Fig. 12). This innovative building facade is made up of “proSolve370e”, which according to its inventors, the Berlin-based design firm Elegant Embellishments, can neutralize the chemicals produced by 8,750 cars every day in Mexico City. Currently, Mexico City is filled with old cars belching with toxic and dangerous fumes. The secret to the hospital building's façade is in its paint, which is made from a titanium dioxide-based pigment. According to Elegant Embellishments, when ultraviolet rays of sunlight reach the titanium dioxide on the tiles, it triggers a chemical reaction between the titles and the smog breaks down into safer chemicals, such as water, carbon dioxide, and calcium nitrate. The chemical also cleans the air inside the building. Additionally, the lattice-like design of the tile shape creates turbulence and slows down air flow around the building. The lattice design of the facade also produces shadows in the inside of the building, helping to keep it cool, thus helping save electric energy.

Figure 12. Image The innovative tile material causes a chemical reaction that neutralizes smog. (Image retrieved from http://www.medicaldaily.com/)

Case Study 10: The RMIT University (Melbourne, Australia). The 2012 RMIT University's Design Hub building (Fig. 13), designed by Sean Godsell Architects and Peddle Thorp Architects, comprises of a façade which is made up of 17,000 automated, circular, sand blasted glass panels. The skin of the structure seamlessly integrates sustainable technology into the facade with evaporative cooling that improves the internal air quality and reduces energy costs. Additionally, it also has the capability to rotate and becomes transparent when expose to rain. The panels were designed to be easily adapted or replaced as solar technology advanced, and the architects proposed that the building would eventually be able to generate all of its own energy. Then in 2016, the university has announced that it will replace the circular glass panels with panels incorporating Building Integrated Photovoltaic (BIPV) technology to generate solar power. This innovative approach to incorporate new solar technologies into the building façade will continue to expand into the future, as further innovation in this strategically important area of research becomes available.

Figure 13. The circular glass panels on RMIT's Design Hub building will soon be replaced with photovoltaic panels that generate solar power. (Image retrieved from: https://architectureau.com/)

In this chapter, these literature reviews have shown us a window into the new era of smart buildings facades that have the ability to interact with the surroundings. These buildings have the can adapt their functions to promote buildings that are energy efficient and can provide healthier indoor environments. Architecture should respond to the natural, socio-cultural and economic environment of its location in the same way that an ecosystem in nature is embedded in its site, thus the prospect of adaptive rather than static façades must be pursued. Additionally, this review of related literature also shows that studies on wind energy harvesting of the building façade is limited. Innovations in building façade designs should be considered as one of the elements in solving climatic changes as it is cost and energy efficient. The research into building façade systems has great potential for decrease energy consumption in a wide range of research areas (Shameri, 2011). As shown in the summary of Table 1, these façade systems can be used in some innovative and prospective studies with multidisciplinary research opportunities.

Table 1. Summary of the case studies of building facades and their design strategies

No.	Case Study	Design Strategy
1	Al Bahr Towers (Abu Dhabi, UAE)	• Regional and responsive façade system • High maintenance cost • Unsustainable façade system • Poor user satisfaction
2	The BioSkin (Tokyo, Japan)	• Evaporative cooling façade • Rainwater collection • Ceramic pipe system
3	The Strawscaper (Lund, Sweden)	• A conceptual energy producing façade using the wind as the energy source • Power stored inside the building • Interrelationship between building and nature
4	EcoARK (Taipei, Tawian)	• Uses PET bottles as façade system • Translucency and durability • Modular facade
5	Pittsburgh Children's Museum (Pittsburgh, USA)	• Kinetic façade system • Used recycled materials for the façade • Passive shading system
6	Unilever Headquarters (Hamburg, Germany)	• Uses passive cooling principles • Façade system using blinds made up of single layered film • A holistic and sustainable architecture
7	Council House 2 (Melbourne, Australia)	• Façade uses the principle of bio-mimicry • External shading to reduce energy cost • Integrated wind turbines installed at the roof • Uses passive cooling and proper site orientation
8	National Aquatics Center (Beijing, China)	• The use of ETFE in the façade system
9	Torre de Especialidades (Mexico City, Mexico)	• Multiplicity of function: A special façade that reduces air pollution • Lattice façade design creates wind turbulence and slows down air flow around the building.
10	The RMIT University (Melbourne, Australia)	• Sustainable technology integrated into the façade system • Evaporative cooling façade • Circular façade panels replaced with solar cells to generate their own power

2.1.2 A Review of the use of Autodesk® CFD in the Building Science Research

This chapter reviews some case studies, design concepts and the use of Autodesk® CFD as a tool for building science. This is because computational fluid dynamics is theoretically more capable of quantifying and designing a passive system than building energy simulating software. Studies have shown that Autodesk® CFD already provides more accurate results than the other options, even though there is still room to improve the accuracy further (Broekhuizen, 2016). Moreover, the interface used in Autodesk CFD was intentionally kept simple to users without extensive knowledge of CFD simulations. Autodesk® CFD provides reasonably accuracy without requiring too much knowledge or experience from the user (Broekhuizen, 2016). Autodesk® CFD, due to its simplicity, brings convenience to the architectural processes and unlocks new potentials in design with a definite focus on the effects of wind around the buildings. By using Autodesk® CFD simulation technology, the architects are able to more accurately project and utilize greater performance analyses to describe the wind environment during the design scheme. This will therefore allow them to better conduct their studies based on relevant building technologies and simulation results. The user can obtain higher accuracy by spending more time on determining the best settings, based on the existing guidelines from COST and AIJ (Franke, 2011), (Tominaga et al., 2008).

CFD is a powerful tool used to routinely predict ventilation systems. The author exhibits scientific papers available on the use of Autodesk® CFD Simulation software in the field of building science. Moustafa et al. (2018) evaluated a post occupancy study of one of the prototype houses in Egypt in order to improve lighting and natural ventilation thermal comfort. The authors used Autodesk® CFD based on *k–epsilon*-based turbulence models and, for daylight simulation, Radiance v5.0 to evaluate the building performance of daylight comfort. Albatayneh et al. (2017) discusses the influence of different time steps in determining the internal air temperature of a housing test module in Newcastle. Naboni et al. (2017) carried out a study on thermal comfort analysis for a small educational building in

Copenhagen. It served as a tool in integrating energy simulation outputs to uphold design solutions for the building. Al-Omary and Muna Alsukkar (2017) used Revit® and Autodesk® CFD in investigating the possibilities of using a green wall façade system in an existing mixed-used building in Amman. The study concluded how a green wall thus reduced urban heat island effect in the surrounding area. Yildrim et al. (2017) investigated how the roof geometry influenced thermal behaviour and air conditions using Autodesk® CFD. The study revealed that conical roof transfers 30% less heat to interior side for a representative summer day, resulting in lower indoor air temperature in the house. Vitale and Ginevra (2017) did an investigative study of passive cooling on a case study of heritage Italian building in Rome. Different profiles of ventilation strategies in relation to people occupancy are analysed and the resulting CFD numerical models are used to estimate the indoor thermal comfort conditions. Barabashi et al. (2016) used both the Autodesk® Simulation CFD and Energy Plus® in a study of ventilated façade systems as a contributor to an energy-efficient building. Kumar et al. (2015) used both Autodesk® CFD and Autodesk® Revit on the protrusions of external walls in improving the process of natural ventilation. The validated study resulted in a modified wing wall design to maximize its effectiveness on circular regions and thus contributed to the design of energy efficient buildings. Thomson (2015) used Rhino® and Autodesk® CFD in testing the pressure and temperature difference in the interior building of the UWM School of Architecture [48]. The software identified methods of increasing the level of circulation that are beneficial in different building situations. Gajena et al. (2015) investigated how various building thermal mass had an impact on building energy performance and indoor air parameter stability in cold climate using Autodesk® CFD. Duke and Faisal (2014) investigated the air flow and thermal efficiency of a building integrated thermal collector and used both Autodesk® CFD and Autodesk® Multi-Physics. Numerical fluid analysis was quantified by Autodesk® CFD in order to calculate the flow rate of each fluid channel. Ong et al. (2014) used Autodesk® CFD to validate the natural ventilation of a planned Solar Living Laboratory]. Further improvements was also done on the same study by Chin et al. (2014) as a comparison for a new proposed re-design of the laboratory. Wind flow analysis was done through the new Living Lab in order to meet their targeted Green Mark certification requirements. Kristianto et al. (2014) investigated user comfort analysis using Autodesk® CFD on a vernacular Minahasa house. Simulation on several variations of openings and stilts height was conducted to measure its effectiveness in creating thermal comfort for the users. The resulting investigation provided future guidelines for architects to incorporate passive design features from vernacular architecture. Khadra and Chalfun (2014) investigated thermal comfort levels on a building façade using Autodesk® CFD, COMFEN® to evaluate energy consumption and Rhino® for shading efficiency. Based on the simulation results, the authors proposed a double skin façade system that successfully integrates passive cooling strategies within the building envelope.

A summary of the journals and other related papers using Autodesk® CFD in the building science mentioned in this paper are listed in table 2. These are the various scientific papers, academic articles and journals which have been located using electronic databases (e.g., Science Direct, Web of Science, etc.) and Google Scholar. The author paid special attention to architecture and urban design journals that were specializing in computational fluid dynamics, air analysis, natural ventilation, thermal comfort and wind load analysis. Papers that contain editorials, conceptual articles and non-research papers were not included in the literature review.

Table 2. Summary of related literature of scientific journals and papers using the Autodesk® Simulation CFD as an instrument in building science analysis

Case	Author/Year	Building Type	Measurements made
1	Moustafa et al. (2018)	Residential housing	Natural Ventilation and thermal comfort analysis
2	Albatayneh et al. (2017)	Residential housing	Thermal performance
3	Naboni et al. (2017)	Educational Building	Indoor Thermal comfort
4	Al-Omary, and Alsukkar (2017)	Mixed use buildings	Analysis of a green wall in urban setting
5	Yildrim et al. (2017)	Roofs	Thermal analysis of roof geometries
6	Vitale and Ginevra (2017)	Historical building	Passive cooling
7	Mousa et al. (2017)	Residential unit	Natural ventilation
8	Zomorodian and Tahsildoost (2017)	Commercial building	Air flow and thermal comfort
9	Ramful and Hurry (2016)	Enclosed space, concrete with roof	Ventilation analysis
10	Barbash et al. (2016)	Building Skin	Ventilation analysis
11	Kumar et al. (2015)	One story room	Natural ventilation
12	Mutaqin et al. (2016)	Room	Air flow analysis
13	Benni et al. (2016)	Greenhouse	Natural ventilation
14	Thomson (2015)	Commercial buildings	Thermal comfort
15	Gaujena et al. (2015)	Low rise conceptual buildings	Thermal mass and comfort analysis
16	Duke et al. (2014)	Commercial Building	Air flow and thermal analysis
17	Ong et al. (2014)	Laboratory	2014
18	Chin et al. (2014)	Commercial building	Ventilation analysis
19	Kristianto et al. (2014)	Vernacular house	Air flow and ventilation analysis
20	Khadra and Chalfun (2014)	Mixed use buildings	Passive cooling analysis
21	Ock et al. (2014)	Double Skin Facade	Natural ventilation analysis

Chapter 3. The Proposed *Wind Boy* Façade System

3.1 Theoretical Background

In this research, the proposed building facade is meant to integrate shading, natural ventilation and a possible evaporative cooling strategy as a passive cooling approach to optimize the occupants' thermal comfort levels, and promoting the use of day light and views to increase the visual comfort for the space users. The *Wind Boy* system proposed in this study also applies the well-known classical concept of Bernoulli's principle (Fig. 14) which conveys us that the fluid (wind) must increase through the narrow portion of the pipe (Elger & Roberson, 2016). The increase of velocity causes kinetic energy to increase at this point at the expense of pressure energy. From the continuity law, the velocity from the inlet to the outlet is given as:

Equation 1

$$\mathrm{P}_1 + \frac{1}{2}\rho V_1^2 + \rho \mathrm{g}\mathrm{h}_1 = \mathrm{P}_2 + \frac{1}{2}\rho V_2^2 + \rho \mathrm{g}\mathrm{h}_2$$

where:

P is the pressure at the chosen point,

ρ is the density of the fluid at all points in the fluid,

V is the fluid flow speed at a point in streamline,

g is the acceleration due to gravity, and

h is the elevation (height) of the fluid

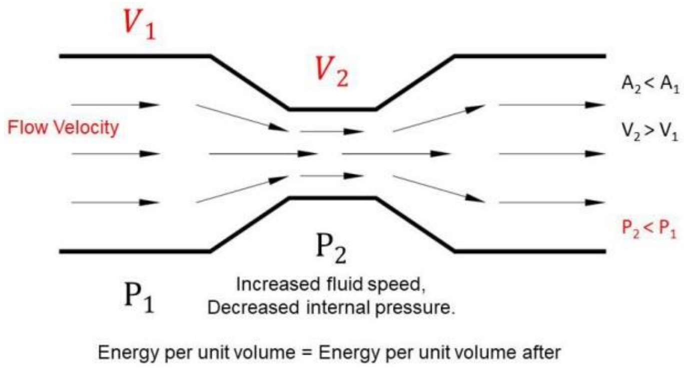


Figure 14. The Bernoulli’ Equation

As stated in this theory, the possible increase in flow velocity and decrease in pressure is therefore influenced by the contraction ratio. By exploring this phenomenon and applying the principles of building façade system, I therefore present a modular system that can improve indoor temperatures by increasing airflow. In literature, studies have shown that air movement can improve occupants' thermal comfort, especially in a warm environment. Furthermore, studies have also shown that simulated natural wind has better comfort effects than constant mechanical wind (Zhu et al., 2015).

3.1.1 Theory and Concept of Computational Fluid Dynamics

The basic concept of Computational Fluid Dynamics (CFD) is the simulation of fluids engineering systems using modelling, such as the application of mathematical physical problem formulation and numerical methods. The discretization methods, solvers, numerical parameters, and grid generations affect the output of the simulation (Zuo, 2005). The entire procedure starts with a Fluid Problem. In order to solve this problem, we must know the physical properties of fluid by using Fluid Mechanics. The mathematical equations to describe these physical properties can therefore be used. This is called the Navier-Stokes Equation and it is the governing equation of CFD (Munson et al., 2014). The Navier-Stokes Equation is an analytical equation. In order to solve this equation by computational analysis, we have to translate it to the discretized form. The translators are numerical discretization methods, such as Finite Difference, Finite Element, Finite Volume methods (Zuo, 2005). The equation must be divided into the whole problem domain into many small parts because the discretization is based on them. By using computer language programs, simulation results can be obtained. Finally, comparison and analysis on the simulation results can be compared to experiments and real world problems. If the results are not sufficient to solve the problem, we have to repeat the process until find satisfied solution. This is the complete process of CFD (Fig. 15).

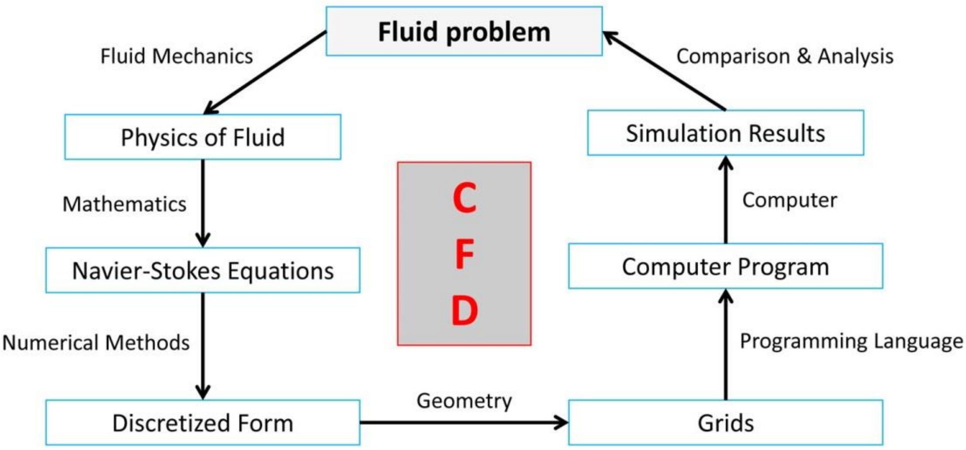


Figure 15. Basic process and concept of CFD simulation (Zou, 2005)

3.1.1.1 The Physics of Fluid

Fluid has many important properties, such as velocity, pressure, temperature, density and viscosity. If the density of fluid is constant, we call the fluid is incompressible fluid (Elger & Roberson, 2016), (Munson et al., 2014). In this study, the fluid is air and is therefore incompressible. Additionally, if the density of fluid is not constant, we call the fluid is compressible fluid. Normally, we can treat water and air as incompressible fluid. If the fluid is incompressible, we can simplify the equations for this type of fluid:

Equation 2:

$$\rho = \frac{M}{V}\left[\frac{kg}{m^3}\right]$$

The viscosity is an internal property of a fluid that offers resistance to flow:

Equation 3:

$$\mu = \left[\frac{Ns}{m^3}\right] = [Posie]$$

3.1.1.2 Conservation Law

Navier-Stokes equations are the governing equations of Computational Fluid Dynamics (Elger & Roberson, 2016), (Hirsch, 2006). It is based on the conservation law of physical properties of fluid. The principle of conservational law is the change of properties, for example mass, energy, and momentum, in an object is decided by the input and output.

For instance, the change of mass in the object is as follows:

Equation 4:

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

If $\dot{m}_{in} - \dot{m}_{out} = 0$, we have

Equation 5:

$$\frac{dM}{dt} = 0$$

Which means

$M = const$

3.1.1.3 The Navier-Stokes Equation

Applying the equation of mass, momentum and energy conservation, we can therefore derive the continuity equation, momentum equation and energy equation as follows.

Continuity Equation:

Equation 6:

$$\frac{D\rho}{Dt} + \rho\frac{\partial U_i}{\partial x_i} = 0$$

Momentum Equation:

Equation 7:

$$\underbrace{\rho\frac{\partial U_j}{\partial t}}_{I}+\underbrace{\rho U_i\frac{\partial U_j}{\partial x_i}}_{II}=-\underbrace{\frac{\partial P}{\partial x_j}}_{III}-\underbrace{\frac{\partial \tau_{ij}}{\partial x_i}}_{IV}+\underbrace{\rho g_j}_{V}$$

Where

Equation 8:

$$\tau_{ij}=-\mu\left(\frac{\partial U_j}{\partial x_i}+\frac{\partial U_i}{\partial x_j}\right)+\frac{2}{3}\delta_{ij}\mu\frac{\partial U_k}{\partial x_k}$$

I: Local change with time

II: Momentum convection

III: Surface force

IV: Molecular-dependent momentum exchange (diffusion)

V: Mass force

Energy Equation:

Equation 9:

$$\underbrace{\rho c_\mu\frac{\partial T}{\partial t}}_{I}+\underbrace{\rho c_\mu U_i\frac{\partial T}{\partial x_i}}_{II}=-\underbrace{P\frac{\partial U_i}{\partial x_i}}_{III}+\underbrace{\lambda\frac{\partial^2 T}{\partial x_i^2}}_{IV}-\underbrace{\tau_{ij}\frac{\partial U_j}{\partial x_i}}_{V}$$

I : Local energy change with time

II: Convective term

III: Pressure work

IV: Heat flux (diffusion)

V: Irreversible transfer of mechanical energy into heat

If the fluid id compressible, we can simplify the continuity equation and momentum equation as follows.

Continuity Equation:

Equation 10:

$$\frac{\partial U_i}{\partial x_i}=0$$

Momentum Equation:

Equation 11:

$$\rho \frac{\partial U_j}{\partial t} + \rho U_i \frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_j} - \mu \frac{\partial^2 U_j}{\partial x_i^2} + \rho g_j$$

Therefore, the General Form of Navier-Stokes Equation:

Finally, to simplify the Navier-Stokes equations, we can rewrite them as the general form:

Equation 12:

$$\frac{\partial(\rho\Phi)}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho U_i \Phi - \Gamma_\Phi \frac{\partial \Phi}{\partial x_i}\right) = q_\Phi$$

When $\Phi = 1, U_j, T$, we can respectively get continuity equation, momentum equation and energy equation. These are the basic concepts on the mathematical analysis on CFD that are found in various literatures.

3.2 Design Description of *Wind Boy*

Figure 15 illustrates the basic geometry of the proposed *Wind Boy* module. The system consisted of three parts, the Inlet, the Converging Section and the Throat. The basic dimensions of are L=350mm, W=200mm and Thickness=10mm. The Inlet receives the incoming wind, merging at the Converging Section and exits at the Throat. It is here at the throat of the proposed system where, according to Bernoulli's theorem, wind will increase due to the narrow portion of the throat and pressure differences (Fig. 17).

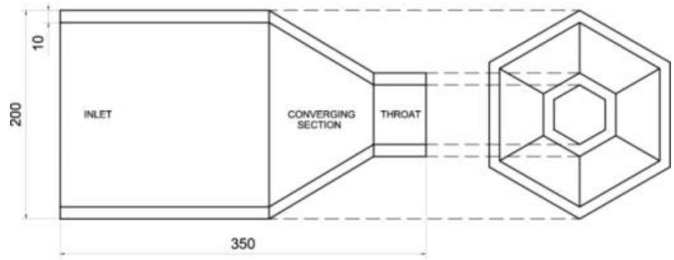


Figure 16. The basic schematic diagram of the proposed *Wind Boy*.

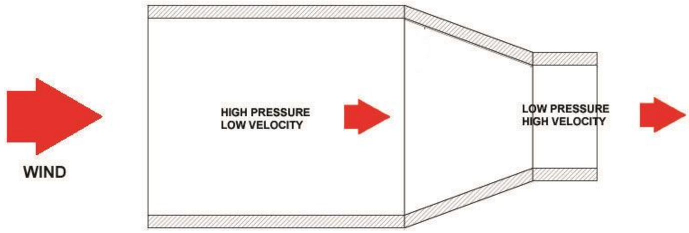


Figure 17. Wind direction, pressure and velocity areas of the proposed *Wind Boy*.

The sustainable aspect of the design was the desire for aesthetics as well as performance. The proposed system also has no moving parts, thus greatly reducing the need for maintenance. The system is not directly connected to the façade, and the cavity between the window and the can cool the surface of the glass windows, thus becoming an integral part of the passive cooling system of the building (Fig. 18).

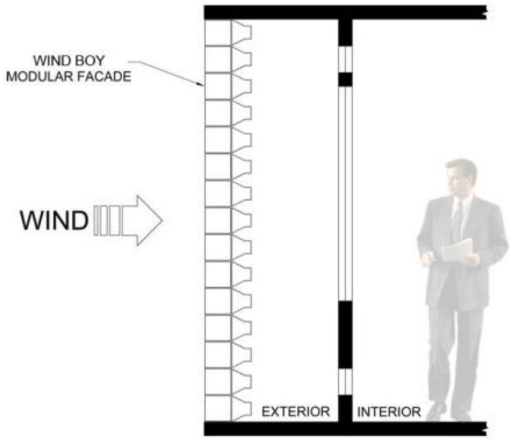


Figure 18. Possible installable area of the proposed *Wind Boy*.

The design of *Wind Boy* is comparable to the concept of the nozzle, which has been studied comprehensively on various literatures. There are various numerical studies on the flow through various nozzle geometries and shapes. Schmidt (1959) investigated airflow pattern in nozzle spray holes. Payri et al. (2002) discusses the numerical study of nozzle geometry and the inner caveating flow. Chen et al. (2009) investigated pressure differences for different nozzle geometries. Schmidt et al. (1997) investigated different geometries of diesel fuel injector nozzles using a two-dimensional, two-phase, transient model. Han et al. (2002) investigated the internal flow through various nozzle geometries using commercial CFD software. CFD verified that internal flow is depended on the nozzle internal geometries. Von Kuensberg Sarre et al. (1999) discusses the effects of nozzle geometry on fuel injection and spray process. Yang et al. (2012) numerically investigated the effects of different nozzle structures on the flow performance of a steam ejector using computational fluid dynamics (CFD). Five different nozzle structures were investigated: conical, elliptical, square, rectangular and cross-shaped nozzles. Ruangtrakoon et al. (2013) examined the effects of the primary throat and exit diameter of nozzle shapes of a steam ejector using CFD. From these studies, different variations of *Wind Boy* can further be analysed, including minimizing the contraction area and throat. In any case, an almost unlimited number of design variations can be studied and analysed for optimum performance. In this façade system, the author proposed system the author proposed four different properties for *Wind Boy*: *modularity, multi-ability, adaptability, simplicity* and *prefabrication*. The following subsections explain these properties in detail.

3.2.1 Modularity

The important feature for *Wind Boy* is that of modularity. A diagram of the proposed system is shown in figure 19. The form of *Wind Boy* was based on the beehive hexagon structure.

Studies have shown that the beehive hexagonal structure has the characteristics of higher structural strength, compact layout, thinner thickness of wall and low material consumption (Meng, 2015).

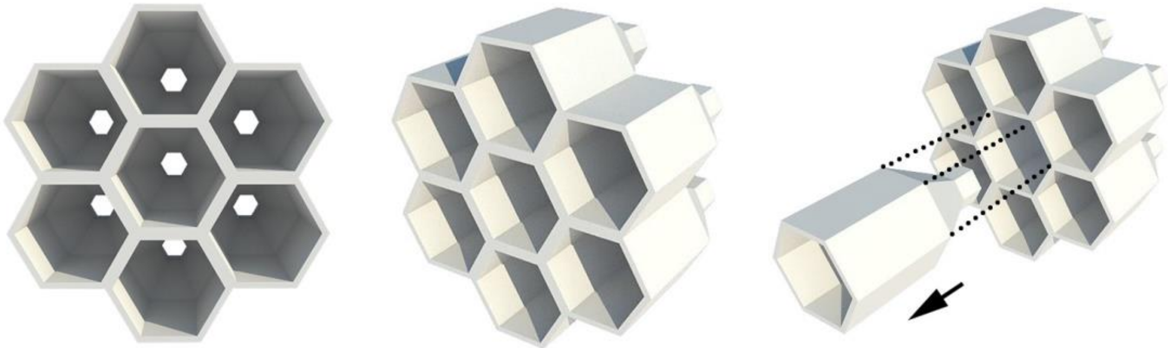


Figure 19. Modularity and adaptability feature of *Wind Boy*.

Similarly, the intent behind *Wind Boy* is to produce a relatively small modular device while minimizing structural loads. As shown in the figure 20, the entire component is an assemblage of many modules to fill the building skin, specifically in front of the window fenestration.

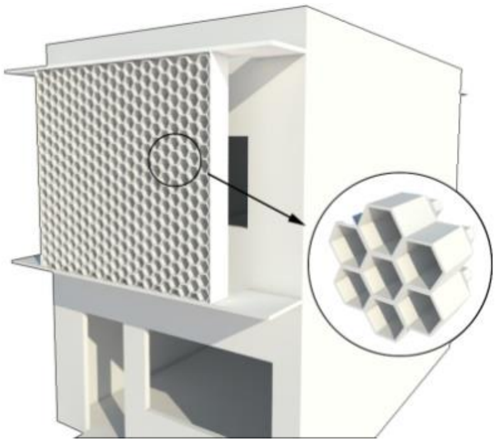


Figure 20. The *Wind Boy* as a modular facade system.

This modularization enables the system to be easily applied to various types of existing buildings and make it convenient for *Wind Boy* to be installed and can easily be replaced or removed. Modularity also leads to economies of scale derived from reduced cost in manufacturing and installation systems. Additionally, this also enables interchangeable components for easy maintenance or change in appearance. The proposed *Wind Boy* is also small enough to be easily handled, replaced and assembled in situ. Finally, the entire module can be used with existing structures without any significant structural strengthening. The only significant consideration is a structurally solid assembly between each modules and the building façade.

3.2.2 Multi-Ability

The concept of *Wind Boy* as a versatile façade component means it was designed not to satisfy a single set of conditions but for addressing change via a plurality of optimized states (Fig. 20, Fig. 22). Unlike other conventional systems, the *Wind Boy* concept was designed not to only satisfy a single set of condition but for addressing change via a multiplicity of optimized states. The multi-Ability function of the *Wind Boy* is further discussed in sub-section 3.5.

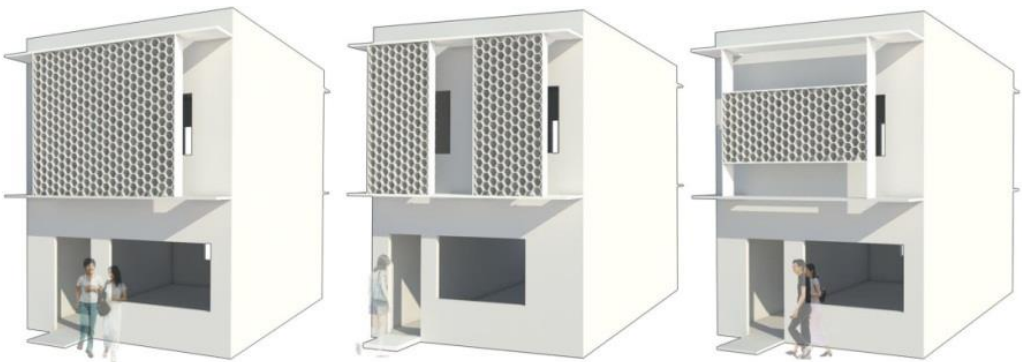


Figure 21. The different possible variations of *Wind Boy* on a horizontal facade.

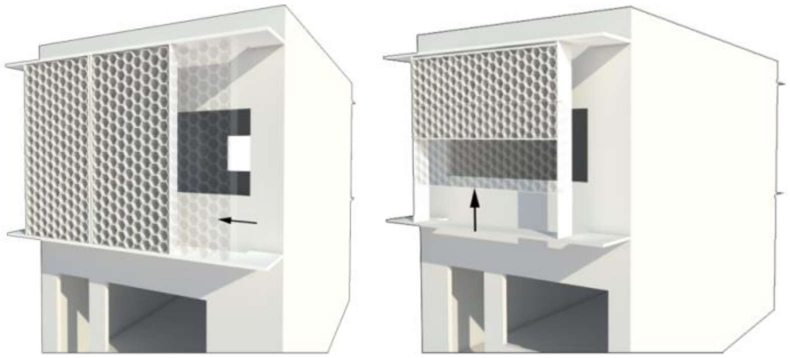


Figure 22. The modular *Wind Boy* as a movable and responsive element.

3.2.3 Adaptability

The *Wind Boy* façade system is a movable and adaptable system that can make a transition over time to meet new requirements and cope with uncertainty. This will therefore result in an ease of modification for each of the individual components. *Wind Boy* is not static but is rather responsive. The proposed system has the capability to respond to different wind conditions by exploiting the different variations of the building façade and the environment (Fig. 23). This system can therefore offer satisfactory performance if the environment changes over time.

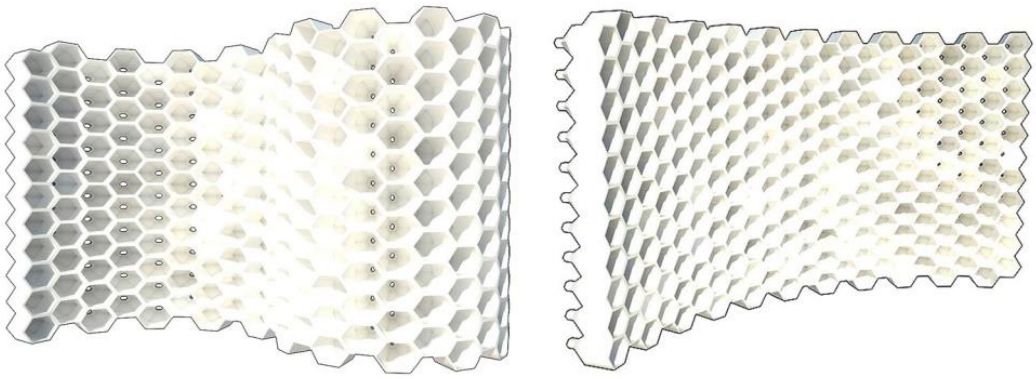


Figure 23. The different possible variations on an arched façade.

3.2.4 Simplicity

The foremost characteristic of the proposed system is that it has no complicated movable parts. Additionally, unlike other façade systems, the proposed *Wind Boy* does not need electrical energy to function. An intricate façade system is more likely to have complications and will therefore be very expensive to maintain. Since *Wind Boy* is easily removed, it can be easily replaced without additional cost. Although it is beyond the scope of this paper, different materials can be further explored as further discussed in the sub-section 3.4.

3.2.5 Prefabrication

Wind Boy can easily be prefabricated in off site. Therefore, a ready set of components and parts are easily available. With the advent of 3D printing, *Wind Boy* can easily be produced locally and therefore reduce the environmental impact of transport. 3D printing *Wind Boy* is also better than CNC (Computer Numerical Control) because there is no waste of material and produce what is only needed. In this study, I highly recommended the use of polymer materials such as ETFE (Ethylene-Tetra-Fluro-Ethylene) (Fig. 24). This material is lightweight, has a relatively high melting temperature, excellent chemical, electrical and high energy radiation property. Another advantage of using ETFE is its high translucency, transmitting up to 95% of light (Robinson, 2005). In addition to being the main architectural feature, by using ETFE, *Wind Boy* is open to light, air and views. ETFE films can be printed or fritted with intelligent patterns of varied transmittance properties that can be used to reduce solar gain without sacrificing its transparency to light. The recent use of this relatively new lightweight material in buildings is primarily due to its lightweight properties, its high daylight transmission and associated potential for energy savings as well as its reduced weight in contrast with the use of glass (Lau, 2016).

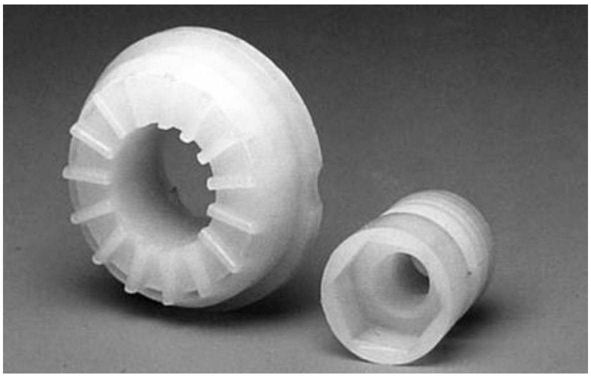


Figure 24. Moulded parts from ETFE. (Image courtesy of DuPont Fluoroplymers).

3.5 Theoretical Developments of *Wind Boy* as a Hybrid Façade System

In this chapter, the option of using Wind Boy as an evaporative cooler and wind energy harvesting system and are discussed. The possibility of using direct evaporative cooling techniques to improve indoor ventilation and comfort can be a possible future direction of the *Wind Boy*. Additionally, the knowledge in wind energy for natural ventilation, pollution dispersion and energy generation has a great potential to be fully explored and developed.

3.5.1 Theoretical Developments of Evaporative Cooling Systems

By definition, evaporative cooling is the process by which the surrounding air temperature is reduced through the evaporation of water in an airstream (Emdadi et al., 2016). Using water for evaporation as a mean of decreasing air temperature is considerably the most environmentally friendly and effective cooling system. Using water to reduce indoor temperature is not a new concept and has been used for many centuries (Jain, 2012), (Emdadi et al., 2016). The concept of evaporative cooling has the same benefits as mechanical evaporative cooling systems without the complexity of ductwork and equipment (Proksch, et al., 2008). The increased interest in sustainable architecture resulted in a number of innovative concepts on evaporative cooling. For instance, London based firm Postler-Ferguson have conceptualized the 3D printed pods which can cool the surroundings using evaporation. These units can be installed in public spaces to create comfortable micro-climates. Water is drawn inside the pods and then it would evaporate, thus cooling the air as it passes through the pods. Further taking advantage of the flexibility of 3D printing, an innovative 3D porous ceramic brick was conceptualized by the group called Emerging Objects. Their project, named *CoolBrick*, used evaporative cooling concepts which every brick absorbs water that allows air to pass through the wall. When air passes through the 3D printed brick, the water that is held inside the micro pores evaporates which brings cool air into the interior. Numerous evaporative cooling systems utilize the porous evaporators as their wetting media. A ceramic *Ecooler* by Mey and Boaz Kahn is an innovative concept which cools the air using a system of hollow tiles which is filled with water. The *Ecooler* was inspired by the *mashrabiya* and *jara*, two popular Middle Eastern elements.

3.5.1.1 Theory to Design

As stated in earlier chapters, the possibilities of using evaporative cooling techniques to reduce indoor temperatures have been in used for many centuries. With this in mind, there has been a renewed interest in evaporative cooling techniques in recent years (Heidarinejad & Moshari, 2012). Using water as a key element of passive evaporative cooling has the same benefits as mechanical evaporative cooling systems without the complexity of ductwork and equipment (Jain & Hindoliya, 2012). In this study, the author also hypothesizes that the *Wind Boy* system can be used as an evaporative cooling solution to reduce indoor temperature. The author therefore proposed that since evaporative cooling occurs when air passes over a wet surface, the wetting of the external wall is an effective strategy to attain the desired room conditions, without resorting to air-conditioning. *Wind Boy* can be integrated on the building façade and recycled rainwater can be gravity fed and flow directly through the building envelope (Fig. 25). The rainwater collected and stored in the storage tanks at the rooftop will run through the Wind Boy façade using gravity feeds and will be pumped back to the storage tank to be reused. The pump can be powered by the solar panel that is installed at the rooftop. The proposed system will be directly integrated into the existing building façade that acts as a secondary building skin and this cycle will then sustain itself for a long period of time. By using wind power and recycled rainwater, this new concept will help minimize the thermal gain of the building façade while still providing adequate solar shading, natural lighting and ventilation. Thus, the use of this new modular system can lead to considerable energy savings for buildings in windy climates. However, the use of the right kind of materials that can effectively collect harvested rainwater for *Wind Boy* must be further explored and analysed as a potential for future investigation.

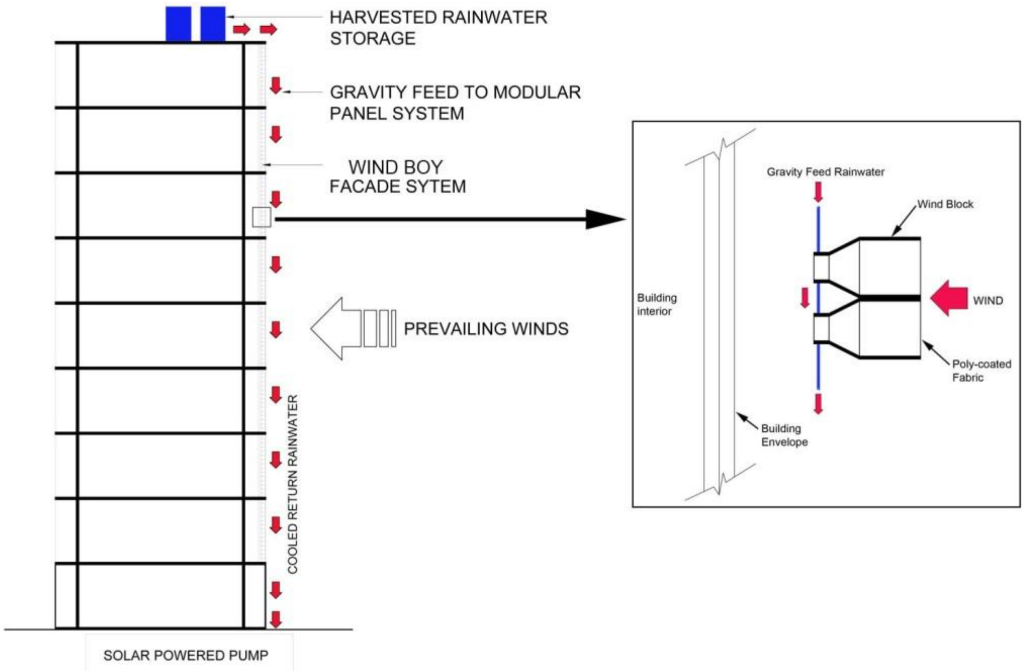


Figure 25. A concept of using the *Wind Boy* as an evaporative cooling facade.

Furthermore, such technology for water retention has already been studied by architects and students of the Institute for Advanced Architecture in Barcelona. The research team have created a composite façade material made of clay and hydrogel called *Hydroceramic*, which is capable of cooling building interiors by up to 6 degrees Celsius. According to the research team, they claimed that the new hydrogel material has the ability to absorb water

500 times its own weight. By absorbing large quantities of water, the hydrogel pellets expose a surface area for evaporation to occur, which both decreases the temperature and increases the humidity of the surrounding air. Such a concept can also be integrated to the *Wind Boy* (Fig. 26) for regions where rain water is scarce. During the testing, the students recommended that the best material to complement the hydrogel was clay, which performed more effectively than acrylic and aluminium owing to its porous nature, which assists the evaporation of the hydrogel pellets. Therefore, the proposed system is responsive, which means that the cooling effect is greatest when the surrounding environment is warm, but when the surrounding is cool little evaporation occurs.

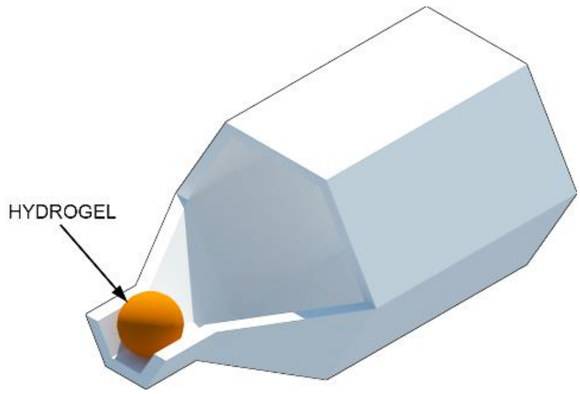


Figure 26. A proposed "Hydrogel" inside *Wind Boy*.

3.5.3 Theoretical Developments of *Wind Boy* as a Wind Energy Harnessing System

Small scale wind turbines installed within the built environment is classified as micro-generation technology (Bahaj, 2007). I propose such micro-turbines can be installed inside Wind Boy to produce energy (Fig. 27). When installed the micro-wind turbines can rotate much faster due to the increase of velocity inside the system. However, the speed at which these a micro-turbine rotates must be controlled for efficient power generation and to keep the turbine components within designed speed and torque limits. Investigations have already shown that the centrifugal force on the spinning blades increases as the square of the rotation speed, which makes this structure sensitive to over-speed (Howell, 2010). In spite of this, a study by Bajaj (2007) claims that micro-wind technology has the potential to make a significant impact on reducing electrical consumption when installed in gusty locations (Mills et al., 2009). The probability of using these turbines in the urban setting is low but at coastal or inland high elevation sites the technology appears to have a promising future (Bahaj et al., 2007).

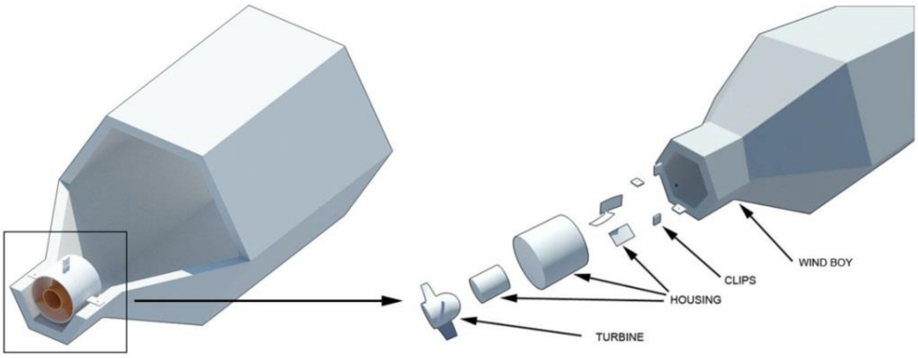


Figure 27. A proposed micro wind turbine generator inside *Wind Boy*.

A similar investigation have been done by Sokolovsky & Rotkin (2017) on the use of a *confusor* with an internal wind turbine to improve the energy performance of wind turbines (Fig. 28)

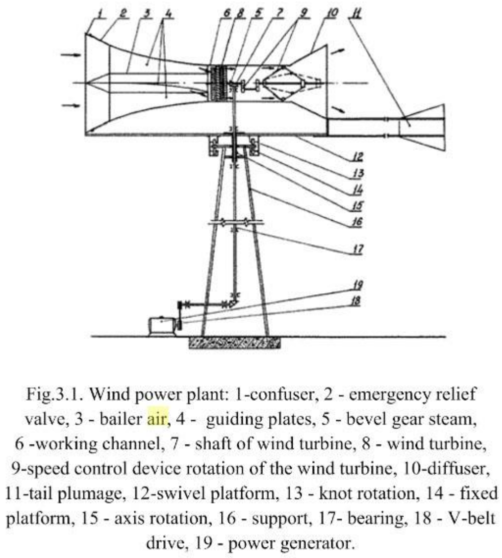


Figure 28. A theoretical analysis to optimize the wind turbine system. Image from Sokolovsky & Rotkin (2017).

Chapter 4. Research Methodology

4.1 Introduction

This chapter provides a description of the processes and methodology used throughout this study. The research follows the process of exploratory-design based research which focuses more on gaining insights and familiarity when research problems are in a preliminary state of investigation (Mills et al., 2009). An exploratory design research is conducted about a research problem when there are few or no earlier studies to refer to or reply upon to predict an outcome. Thus, exploratory design research is often used in the development of tentative theories or hypotheses and determines whether a study is feasible in the future (Babbie, 2015). Furthermore, this study will use Computational Fluid Dynamics (CFD) as a tool in validating the *Wind Boy* designs.

In CFD, it is a common approach to divide the fluid domain into a number of topologically simple regions. Three dimensional (3-D) fluid domain is then further divided into polyhedrons (called cells), each polyhedron is limited by faces with vertices (called nodes), forming a mesh. The N–S equations are then solved for each cell which results in a substantial amount of computing resources. The huge computational costs for 3-D flow simulations are still a major limiting factor for using CFD tools in industry, in particular for unsteady calculations (Olsen, 2000). Nevertheless, due to the increasing power of present computers in the last few decades, it is now conceivable to simulate fluid mechanics using personal computers (Olsen, 2000).

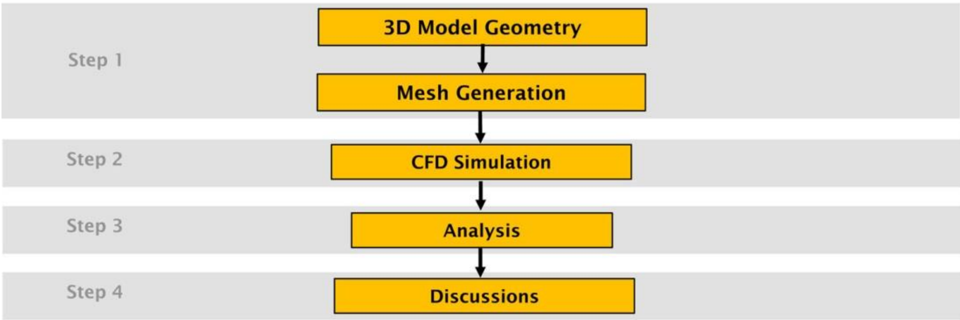


Figure 29. The *Methodology Workflow Process* for the design analysis of *Wind Boy*.

In this study, the author follows a four step *Methodology Workflow Process* (Fig. 29) in order to determine which design options variables affect airflow inside the test room using the *Wind Boy façade* system. In Step 1, the 3D model geometry of the façade system and test room will be generated using Autodesk® AutoCAD. The model will then be imported into Autodesk® CFD, in which the Flow Domain, Boundary Conditions will be established. Grid/Mesh generation will be generated by the software. In Step 2, the simulation scene was performed and monitored for completion. In Step 3, the simulation results were examined and analysed. Finally, in Step 4, the performance of the proposed system was evaluated and discussed. The studies are intended at examining the efficiency of the *Wind Boy* in different configurations of the test room, wind and velocity magnitude distribution under constant approaching wind speed.

4.2 The *Wind Boy* 3D Model Geometry

The geometry and configuration of *Wind Boy* is intended to create a negative pressure in the narrowest section which can be used to partly or completely drive the incoming wind. In this first study, all of the proposed *Wind Boy* designs have the basic Inlet Diameter (D=200 mm) and Outlet Length (L3=50 mm). The various design configurations consist of different specific geometrical change to the Outlet Diameter (d), Taper Angle (a), Inlet Length (L1) and Throat Length (L2) (Fig. 30).

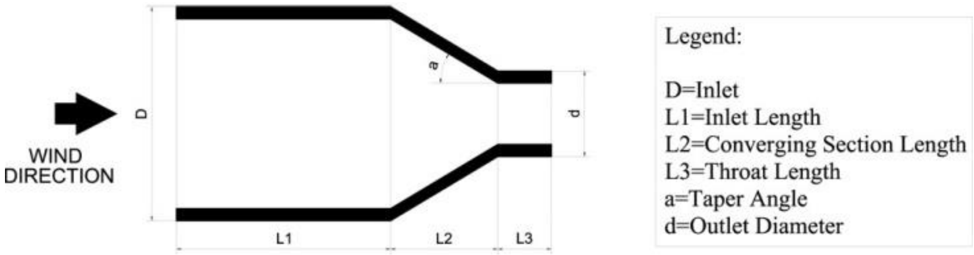


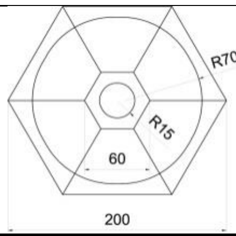
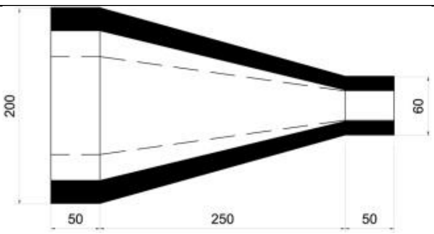
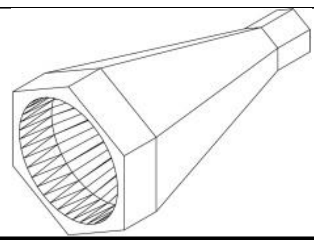
Figure 30. The basic parts of the proposed *Wind Boy* module.

In order to examine the air velocity and performance of *Wind Boy*, the author proposed four (4) different design configurations. In literature, there are various numerical studies on the flow through various nozzle geometries and shapes, especially in round inlets. The studies have verified that cylindrical and tapered geometry nozzles have better internal airflow characteristics than squared-edged nozzle inlet Han et al. (2002), (Kent & Brown, 1983). Therefore, in this paper, all of the proposed system has *round hollow* sections (Table 3 and Table 4) with similar hexagonal exterior structure. However, the Inlet length (L1), the Converging Section Length (L2) and Outlet Diameter (d) are modified. As expected, the new *Wind Boy* designs will result in different velocity magnitude. A 3D geometry for the four (4) proposed system was then generated using the program Autodesk® CAD program and imported into Autodesk® CFD software for analysis.

Table 3. Dimensions of the proposed *Wind Boy* Design

Design No.	**D (Inlet)**	**L1 (Inlet Length)**	**L2 (Converging Section length**	**L3 (Throat Length)**	**d (Outlet Diameter)**
1	200	50	250	50	60

Table 4. The proposed *Wind Boy* designs considered in this study.

Design no.	**Cross Section**	**Longitudinal Section**	**Isometric**
1			

4.3 Simulation in a Test Room

In this chapter, five (5) different *Wind Boy* façade configurations (Fig. 31) are examined in a theoretical test room using CFD analysis (Table 5). These configurations are listed as Study 1 to 5:

- Study 1 is the control variable in which it is held constant and in this case, the CFD simulation does not include the *Wind Boy* façade on the window of the room;
- Study 2 has the *Wind Boy* Inlet (D) *flushed* into the window of the room at the windward side of the wind at 3 m/s;
- Study 3 has the *Wind Boy* Outlet (d) flushed into the window of the room. This means that there is no distance between the window and the Outlet of the proposed façade. This is the 0 mm distance from the windward window;
- Study 4 has the façade distance at 100 mm of the window of the room in respect to the Outlet (d) of *Wind Boy*;
- Study 5 has the façade distance of 600 mm of the window of the room in respect to the Outlet (d) of *Wind Boy*.

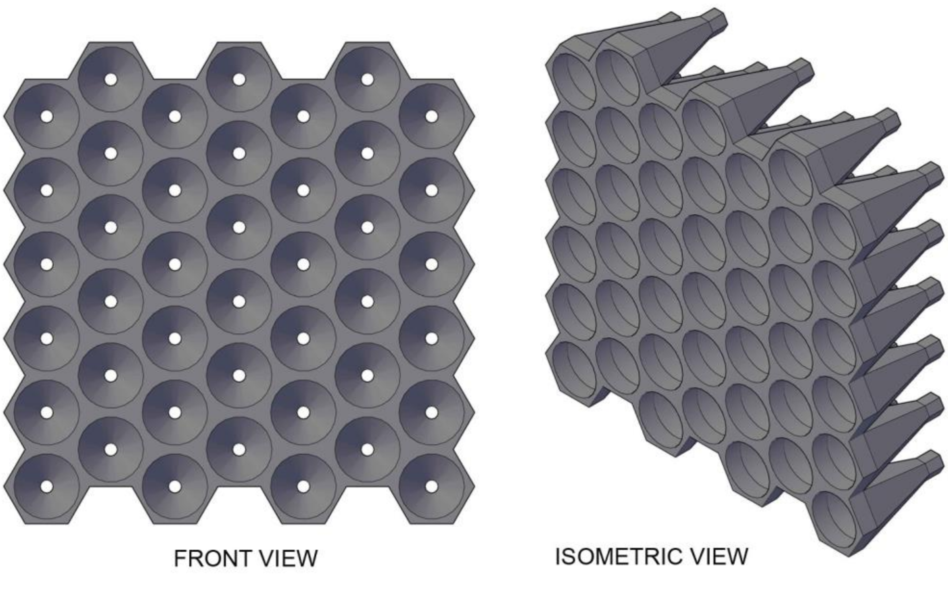
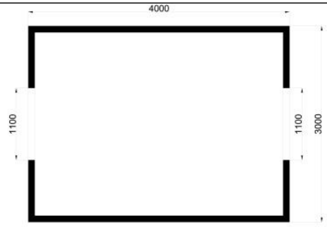
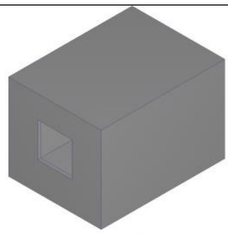
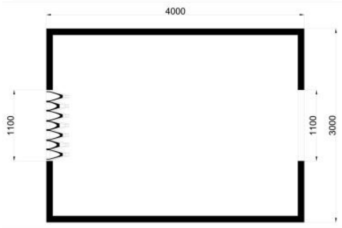
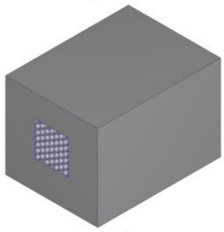
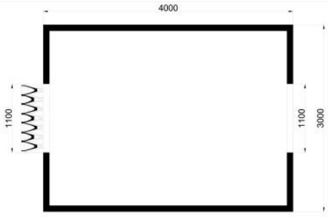
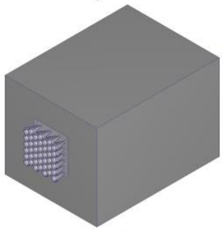
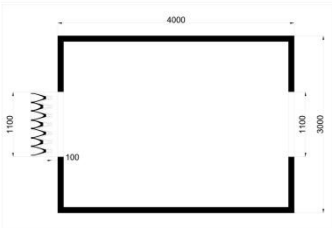
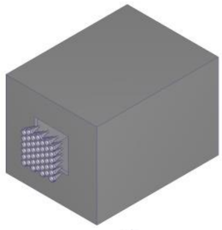
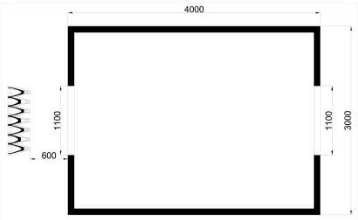
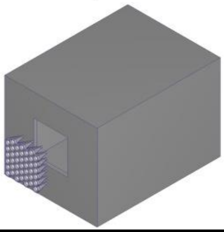


Figure 31. Front and Isometric view of the proposed *Wind Boy* arrangement

Table 5. The Proposed configurations of *Wind Boy* for airflow analysis in a test room using CFD

Study No.	Distance to the window	Plan	Isometric
1	No facade		
2	Flushed		
3	0 mm		
4	100 mm		
5	600 mm		

4.3.1 The 3D Model Geometry

A 3D geometry of the test room (Fig. 32) was generated using the program Autodesk® CAD program and imported into Autodesk® CFD software for analysis. The length of the test room is 4000 millimetres with a width of 3000 millimetres. Both of the windows at windward and leeward side are 1126 x 1100 (L x W). The height of the test room is 2800 millimetres.

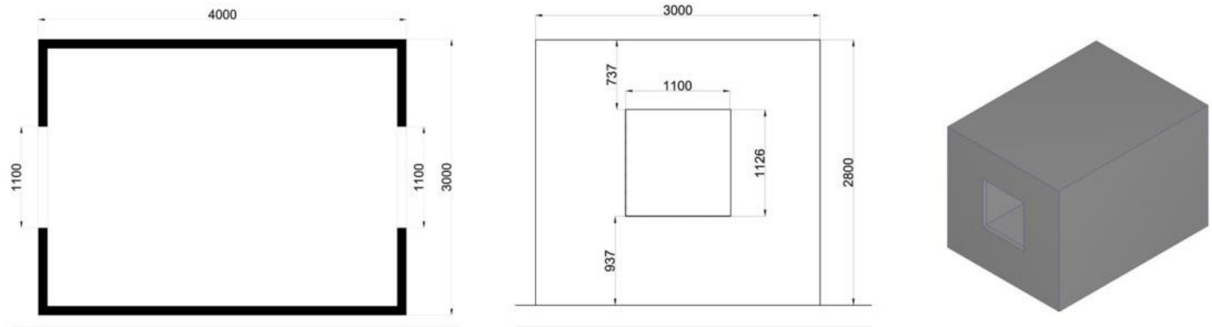


Figure 32. Plan, front elevation and isometric of the test room

4.3.2 Computational grid and Boundary Conditions

In order to investigate the velocity performance inside the room, the computational domain of the CFD simulation had to be extended to include part of the environment. The external air volume must be large enough to allow both fully developed air velocity profiles. Therefore, in order for the inlet flow velocity to be fully developed, the upstream part of the domain was set at 3D, where D is the total length of the room, for a final distance of 1200. The downstream part of the domain was 4D, for a distance of 1600. The height and width of the domain was set at 1d, where d is the height of the room. The over-all computational domain has dimensions L x W x H = 32000 x 5600 x 5600 mm as shown in Fig. 38. The dimensions of the computational domain were chosen based on the best practice guidelines recommended by Franke et al. [66] and Tominaga et al. [67] and the Autodesk® Knowledge Network. The material “air” was assigned as the fluid to the computational domain while the material “Concrete” was assigned to the walls and *Wind Boy* as the solid material for the proposed system. The material does not affect the velocity performance since this study does not deal with thermal heat transfers. The boundary condition of the inlet was assigned as the velocity of 3 m/s (the average wind speed in the Philippines) and set as *Variable*. The three wall regions were assigned as “Slip/Symmetry” to simulate a free-space environment. Finally, the outlet was assigned the Pressure value of 0 Pa Gage (Fig. 33).

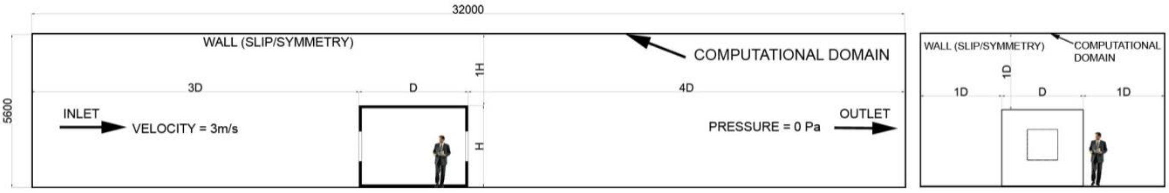
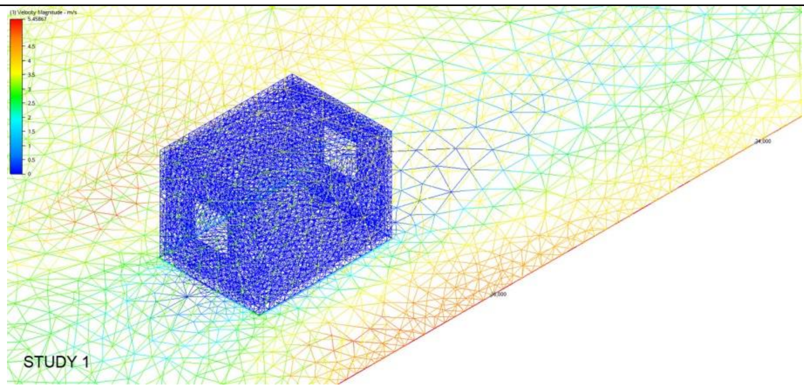
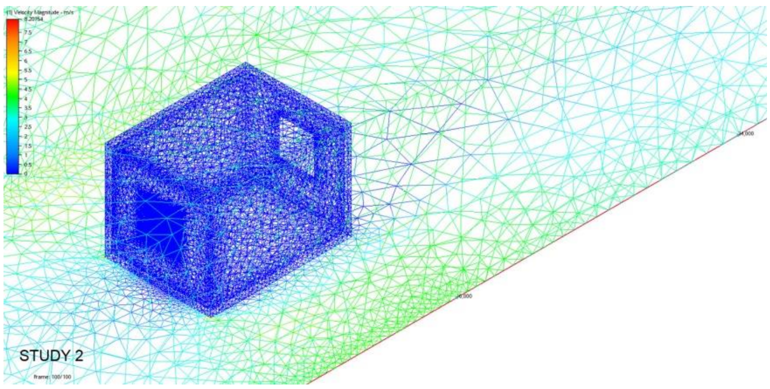


Figure 33. The computational Domain and Boundary Conditions of the test room: Side and front view.

4.3.3 Mesh Generation (Design 1)

In Autodesk® CFD the manual mesh generation was assigned to the boundary. The mesh size for the boundary was refined at a numerical value of .5 and evenly applied. The mesh size for the proposed Wind Boy designs were also refined at a numerical value of *.5, evenly applied* and these *changes are spread*. The final Mesh Definitions and Mesh Sizes outputs for the five (5) studies are shown in Table 6 and Table 7, respectively.

Table 6. Mesh Definition for study 1-5

Distance	Mesh Definition
None	
Flushed	

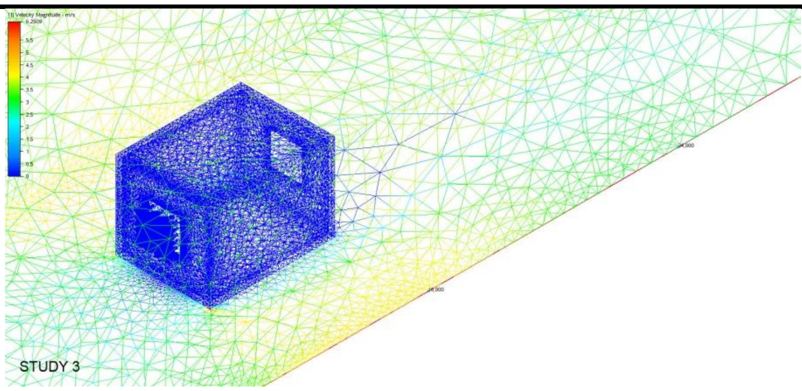
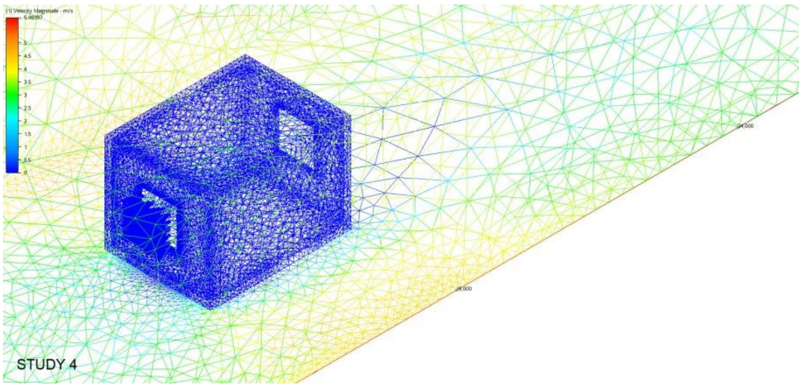
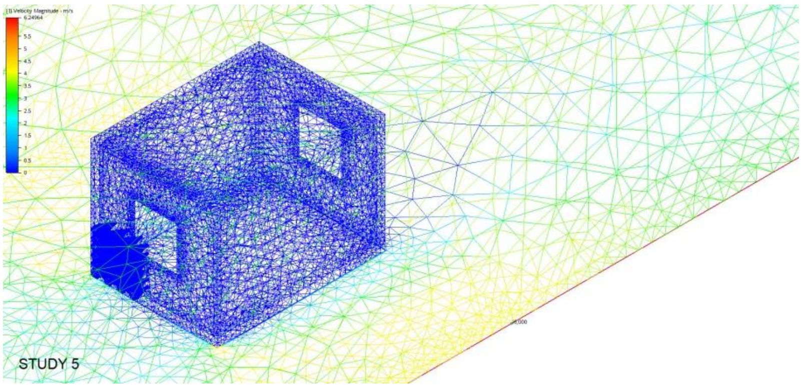
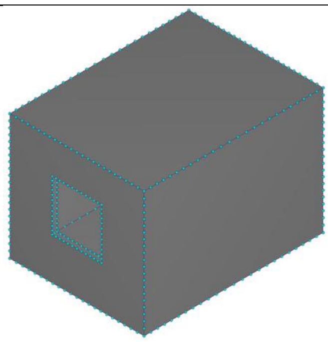
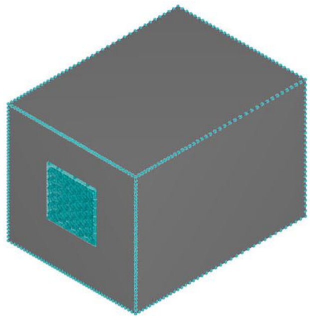
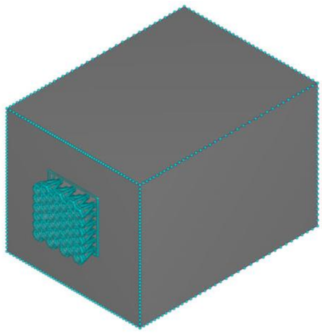
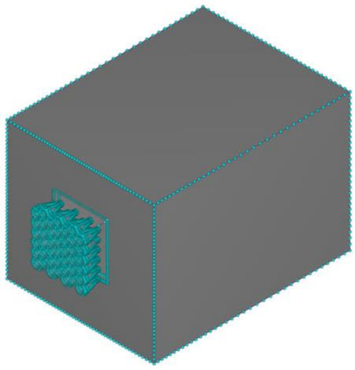
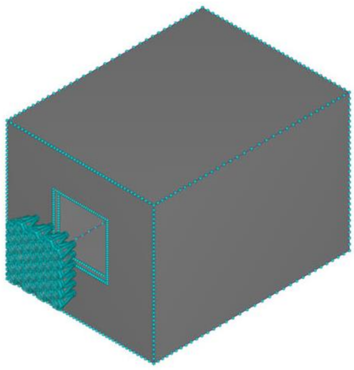
0 mm	
100 mm	
600 mm	

Table 7. Mesh Sizing for study 1-5

Distance of facade	Mesh
None	 STUDY 1

Flushed	 STUDY 2
0 mm	 STUDY 3
100 mm	 STUDY 4
600 mm	 STUDY 5

Before the CFD analysis, the geometry was broken into small pieces called *elements***.** The corner of each element is a *node*. The calculation was performed at the nodes. These elements and nodes make up the *mesh*. The CFD program performed a comprehensive topological interrogation of the 3D geometry and therefore, determines the mesh size on the 3D model's edges and surface. Furthermore, the geometric curvature, gradients, and proximity to the neighbouring 3D geometry model were considered by the program when assigning element sizes and mesh distributions. The resulting numerical nodes and elements of the studies are presented in Table 8.

Table 8. The resulting numerical nodes and elements of the five (5) studies.

Study	Total nodes	Fluid nodes	Solid nodes	Total elements	Fluid elements	Solid elements
1	37409	37011	398	152868	137318	15550
2	238069	235312	2757	963209	844392	118817
3	254665	250033	4632	1033528	898499	135029
4	244701	241593	3108	999254	879699	119555
5	224012	223310	792	900904	798706	102198

4.3.4 Solver Settings

In this study, the selection of the turbulence model has a significant effect on the reproduction of the flow structure around buildings (Tominaga & Stathopoulos, 2010). The solver settings for the room test simulations were therefore performed using the 3D steady Reynolds-averaged Navier-Stokes (RANS) equations. The standard *RANS K-ε turbulent model* with enhanced wall treatment was selected to model the velocity flow, as with previous studies, by Montazeri and Blocken (2013), Blocken et al. (2012), Chavez et al. (2011) and Montazeri et al. (2013), (Kim, 2014), in which they also employed the k-turbulence model in order to predict wind flow and dispersion around a building. Convergence is assumed to be obtained when all the scaled residuals levelled off. The numbers of iterations specified were *400*. The pressure drop, flow rates and velocity across the interior of the room was calculated using the code for the five (5) different studies. The CFD simulation conditions are described in Table 9.

Table 9. CFD simulation solver settings and conditions for the test room.

Variable	Value
Fluid Material of the boundary	Air
One Velocity Inlet	3 m/s
One Pressure Outlet	0
Wall	Slip/Symmetry
Solution Method	Incompressible flows
Solutions Mode	Steady State
Number of Iterations	400
Physics Flow	On
Turbulent Incompressible Flow	On
Intelligent Wall Formulation	Off
Turbulence Model	Standard RANS k-epsilon
Scalar	Off
Heat Transfer	Off
Allow Coarsening	Off
Flow Angularity	On
Growth Rate	1.3
Boundary Layer Growth	1.05
Refinement Limit	0.001
Resolution factor	0.75

4.3.5 Measuring Points

For this investigation, the wind is assumed to be towards the direction of the front window. The measurement points created by the simulation program are distributed in a horizontal plane. In this investigation, only the horizontal plane *x/y* with limited number of points was considered in this analysis. A total of seven (7) measuring points was positioned on the horizontal plane. These points were positioned along a straight horizontal line that pass through the velocity inlet, the window of the test room, the interior of the test room and in the direction of the velocity outlet (Fig. 34). These points are indicated in Table 10. Autodesk® Simulation CFD 2016 automatically subdivided the given points into 101 points on the horizontal *x/y* plane. These points were used to measure the mean velocity through the computational domain of the test room.

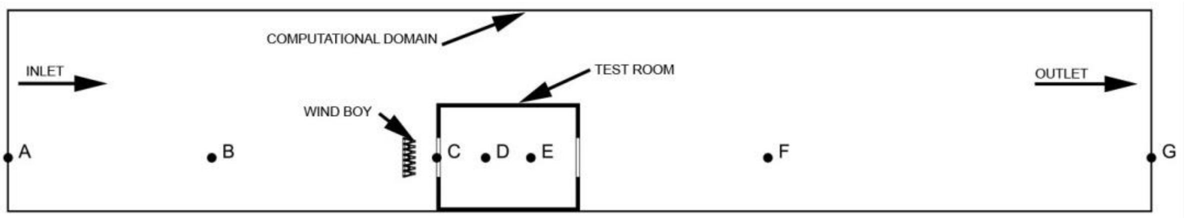


Figure 34. Measuring Points on the *x/y* plane

Table 10. The measuring point coordinates of the horizontal *x/y* sectional plane.

Point	x	y	z
A	0	4500	1456
B	5700	4500	1456
C	12000	4500	1456
D	13366	4500	1456
E	14633	4500	1456
F	21266	4500	1456
G	32000	4500	1456

4.3.6 Results and Discussions

The airflow characteristics inside the test room, with different configurations of the façade, as a way to introduce natural ventilation was analysed by means of CFD analysis. In the visual analysis, air flow in the room is shown with the help of vectors and corresponds to actual indoor air flow exchange. From the results, I have found the following:

- In Study 1 (control room), the wind velocity is constant until it exits at the leeward side of the room, in which due to pressure differences, the velocity decreases

(Fig.35). From the visualization (Fig. 36), the airflow distribution is evenly distributed.

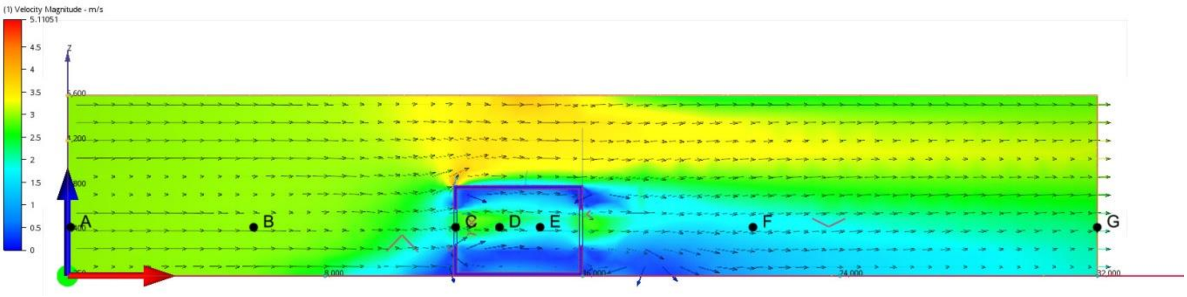


Figure 35. Velocity Vectors along the x/y plane with no *Wind Boy* applied to the window

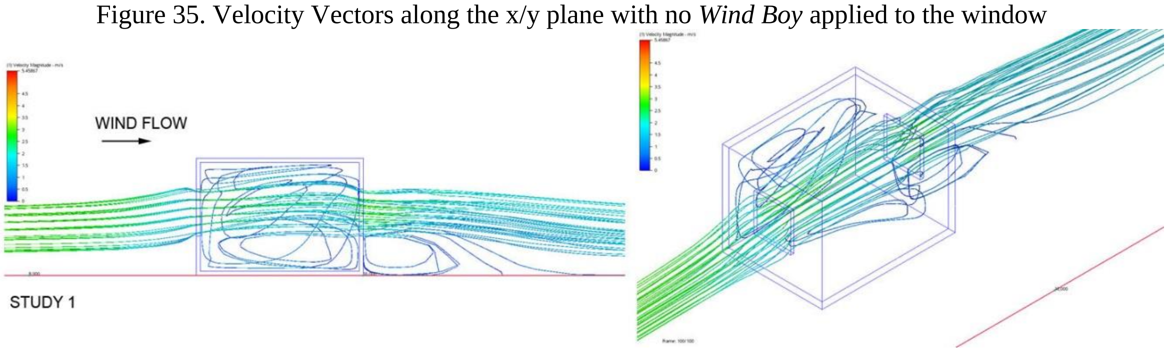


Figure 36. Velocity traces for the test room with no façade

- In Study 2, the wind velocity drastically decreases at point C due to the presence of the flushed *Wind Boy* façade. The velocity gradually increases at point D and continues to drop at the leeward side to pressure differences (Fig.37). From the visualization Fig. 38, this configuration has the highest velocity output of 4.5 m/s at point *x=1234.1*, *y=4500*, *z=1456*.

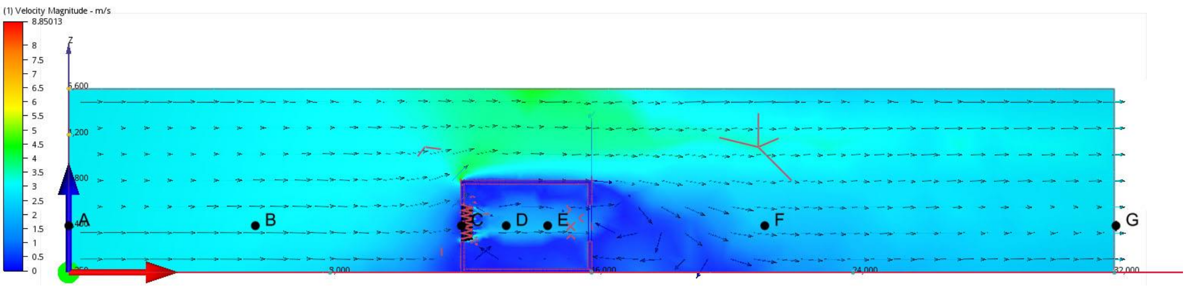


Figure 37. Velocity Vectors along the x/y plane with *Wind Boy* flushed the window.

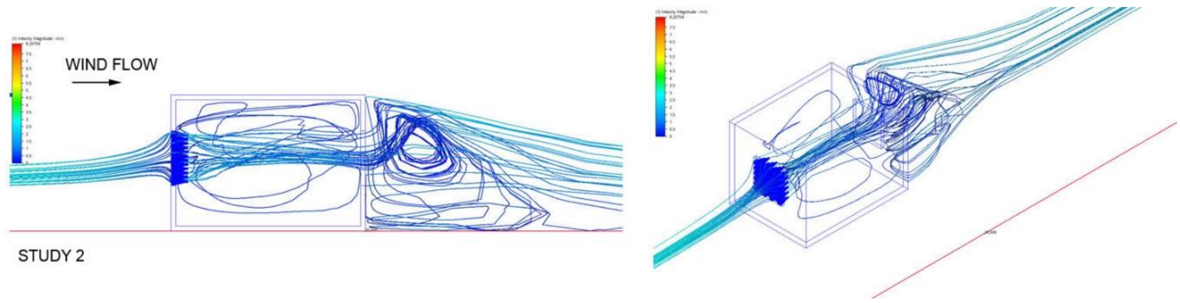


Figure 38. Velocity Traces for the test room with *Wind Boy* flushed into the window.

- In Study 3, where the façade is at 0 mm from the window, there is a high increase of incoming wind velocity upon entering the test room. There is a sudden drop in velocity in points D and E and a gradual increase of the air velocity upon exit at the leeward side of the test room (Fig. 39). From the visualization shown in Fig. 40, there is a huge amount of air distribution inside the test room. This configuration distance resulted in the second highest velocity output of the experiment at 3.5 m/s at point *x=1200, y=4500, z=1456*.

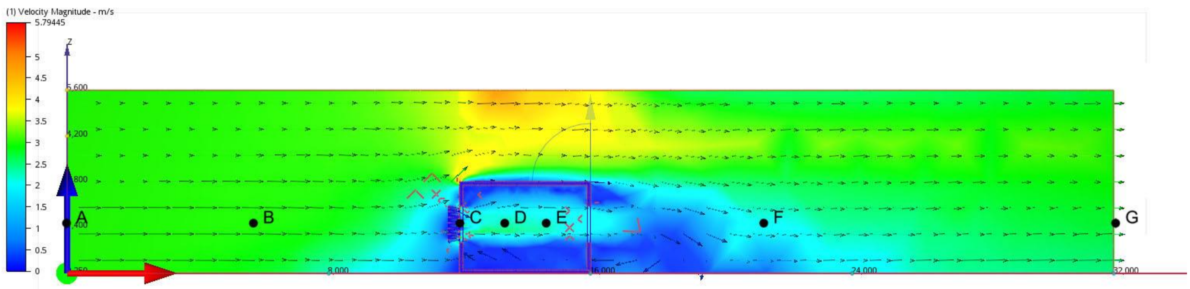


Figure 39. Velocity Vectors along the x/y plane with *Wind Boy* at 0 mm from the window.

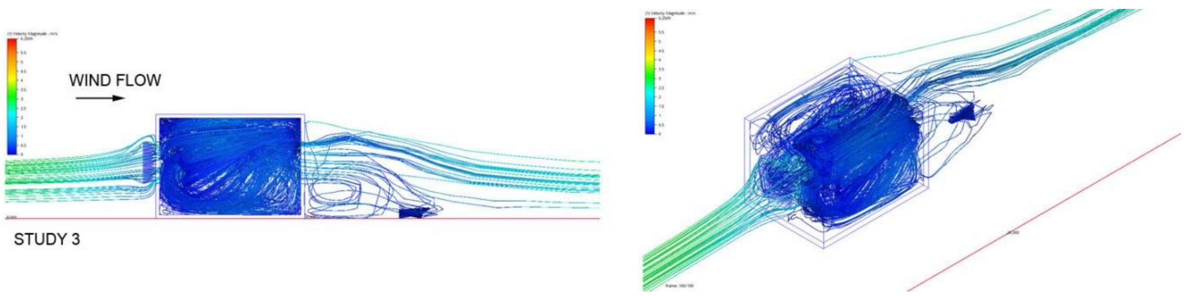


Figure 40. Velocity Traces for the test room with *Wind Boy* at 0 mm from the window.

- In Study 4, air flow velocity was reduced upon entering the façade at point C. At this point the airflow decreased gradually due to the different pressure variables and continues to increase upon exit at the leeward side of the window (Fig. 41). From the visualization (Fig. 42) this configuration resulted in the lowest airflow velocity at 2.3 m/s at point *x=11900*, *y=4500*, *z=1456*.

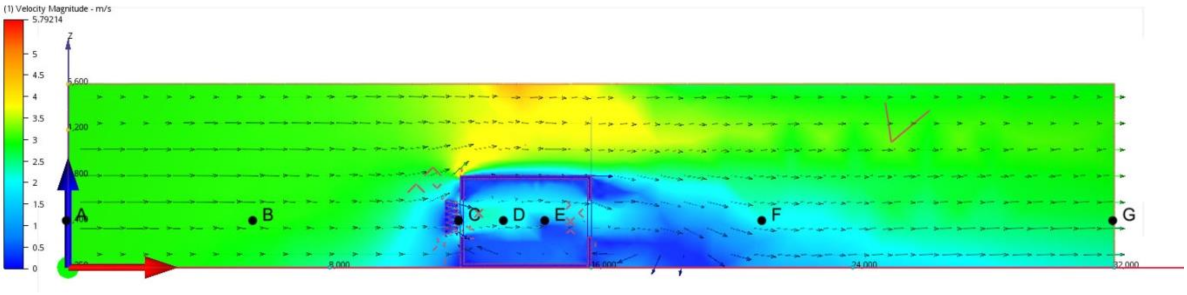


Figure 41. Velocity Vectors along the x/y plane with *Wind Boy* at 100 mm from the window.

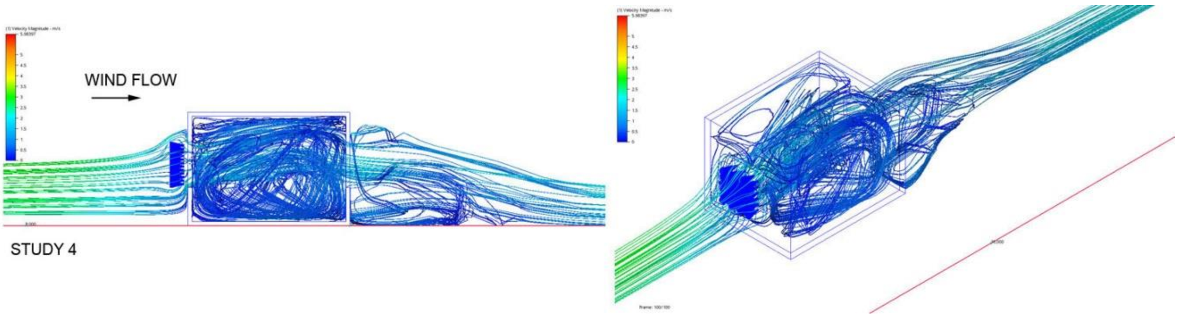


Figure 42. Velocity Traces for the test room with *Wind Boy* at 100 mm from the window

- In Study 5, airflow velocity reduced dramatically upon entering point C. The descending velocity airflow continues until it began to exit at the leeward side of the room (Fig. 43). From the visual analysis (Fig. 44), this configuration distance resulted in the third highest velocity output at 3.2 m/s at point *x=11370, y=4500, z=1456*.

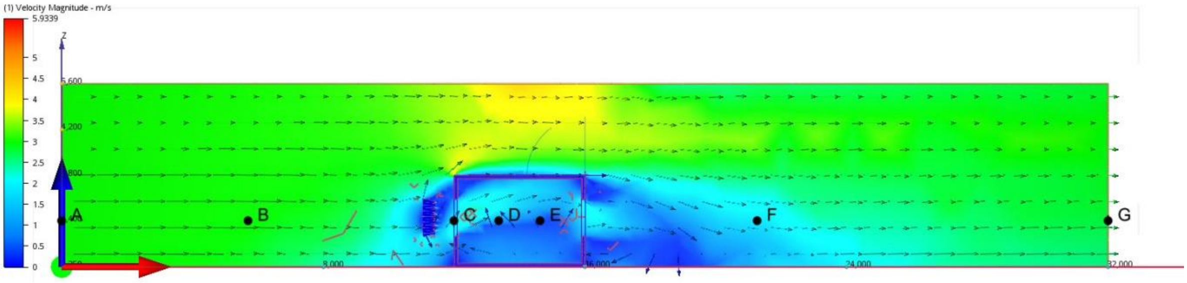


Figure 43. Velocity Vectors along the x/y plane with *Wind Boy* at 600 mm from the window.

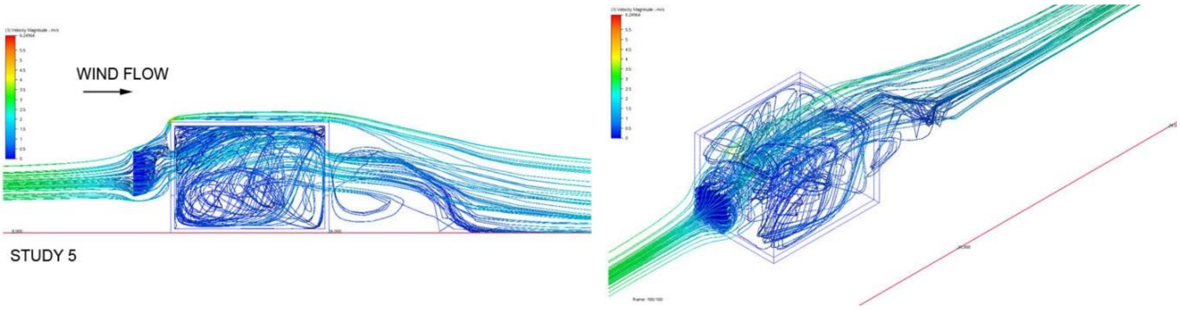


Figure 44. Velocity Traces for the test room with *Wind Boy* at 600 mm from the window.

Table 11. Summary of the Velocity along the measuring points of the test room

Study No.	Measuring Points						
	A	B	C	D	E	F	G
1	300	2977	2430	2512	2060	1623	2227
2	300	2967	162	1536	1383	1977	2724
3	300	2981	3258	2216	2015	2026	2743
4	300	2969	1733	2064	857	1913	2684
5	300	2978	1695	1120	600	1730	2784

From the given results stated above it is apparent that the indoor air flow and distribution was influenced by the location of the wind boy façade system. The analysis also showed the efficiency of cross ventilation as opposed to single sided ventilation in a room. Furthermore, the results revealed that the location of Wind Boy resulted to different characteristic air flow patterns. Different airflow rates into the test room could be anticipated whenever the location or distance of Wind Boy is mounted.

Chapter 5. Conclusions and Thesis Statements

In this study, Computational Fluid Dynamic (CFD) software was used to predict the airflow inside a test room with a wind induced façade system. The investigation measured the distribution of air velocity and airflow distribution for four different façade configurations. As a consequence of my investigation, I have come to the following conclusions:

- The simulation results indicate that natural ventilation, with the required driving force, can have optimal mode and maximum wind circulation in the interior space. However, the application and distance of the façade can have an over-all effect on the internal airflow and distribution inside the room. This is evident from the graph shown in Fig. 45 and Fig. 46. In Fig. 45, when the façade is located at 100 mm distance between the building façade windows, there is a very minimal change in the maximum velocity that the system can deliver in terms of wind velocity.

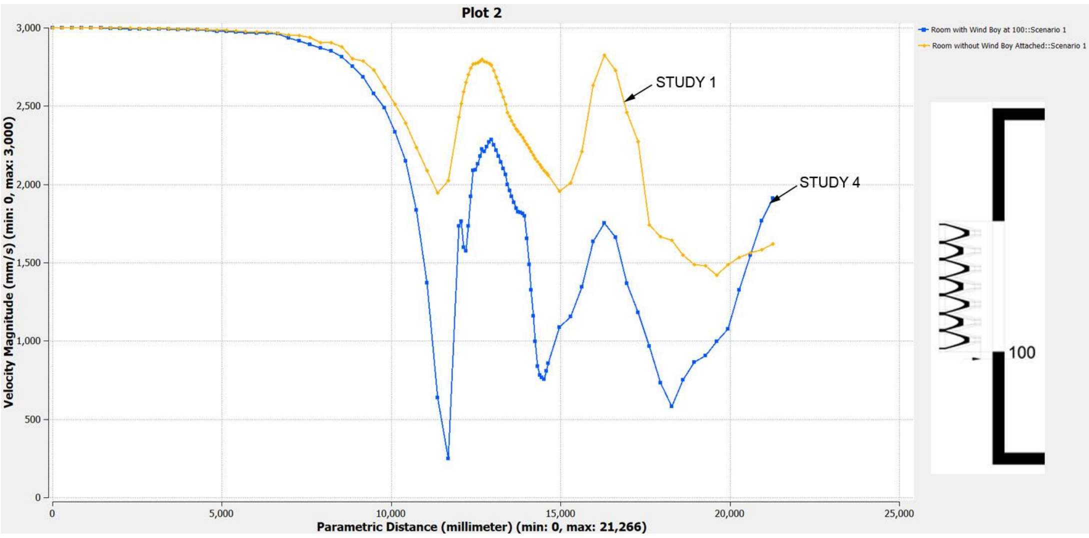


Figure 45. The Velocity trend between the control room and *Wind Boy* façade at 100 mm distance.

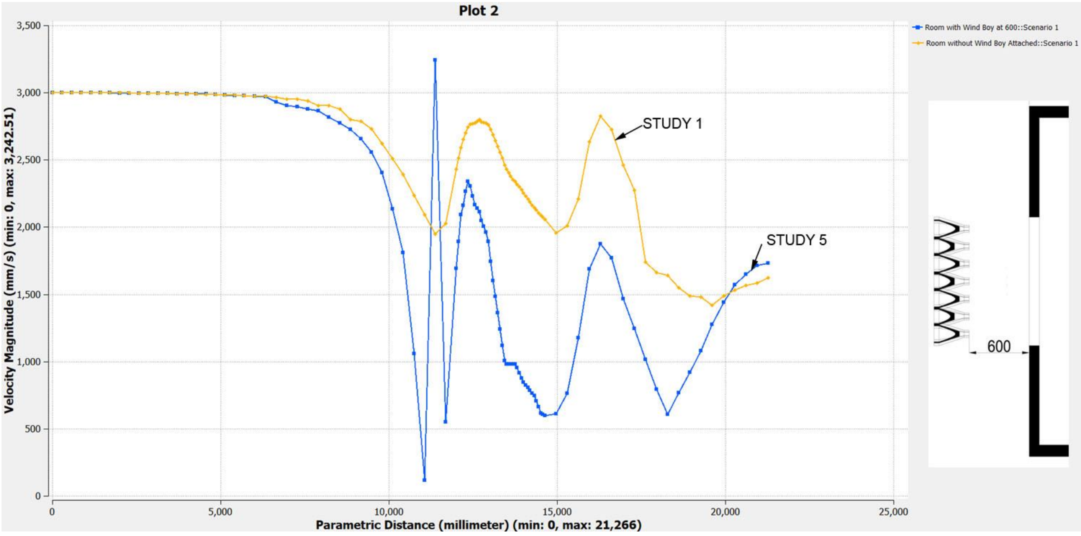


Figure 46. The Velocity trend between the control room and *Wind Boy* façade at 600 mm distance.

- The distance between the *Wind Boy* and façade of the room had an effect on the internal airflow velocity, direction as well as the air distribution inside the room. The velocity output of *Wind Boy* was drastically reduced if it is farthest from the façade. This analysis can be seen in the summary of the velocity trend magnitude plot (Fig. 47).

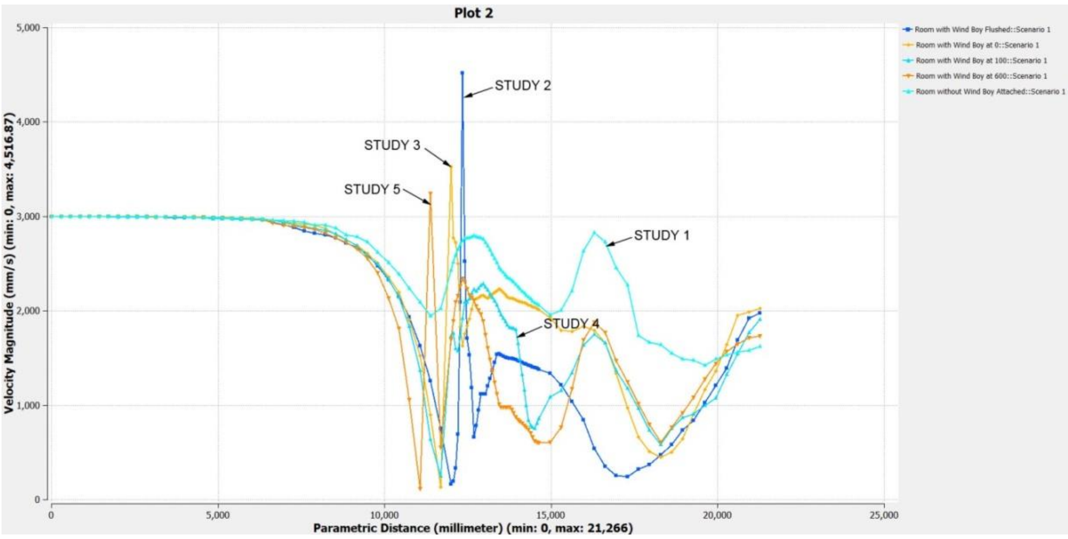


Figure 47. Summary of the Velocity Trend Magnitude Plot with the test room simulation

- From this investigation, the façade with the *Wind Boy* at 0 mm (Study 3) from the windward window had the highest airflow distribution. Therefore, by integrating an evaporative cooling system, this façade configuration has the ability to improve thermal conditions through airflow dispersion as shown in Figure 48.

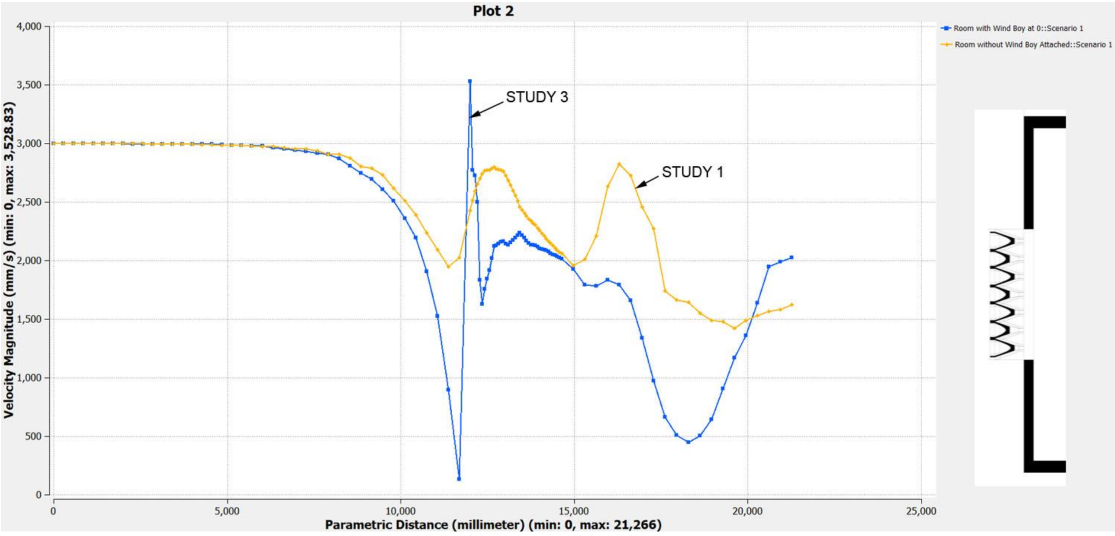


Figure 48. The Velocity trend between the control room and *Wind Boy* façade at 0 mm distance.

- The façade configuration with the facade flushed from the windward window resulted in the highest velocity output of Wind Boy. Due to this high velocity output, this alignment output can be used to integrate a system that can harness wind energy (Fig. 49).

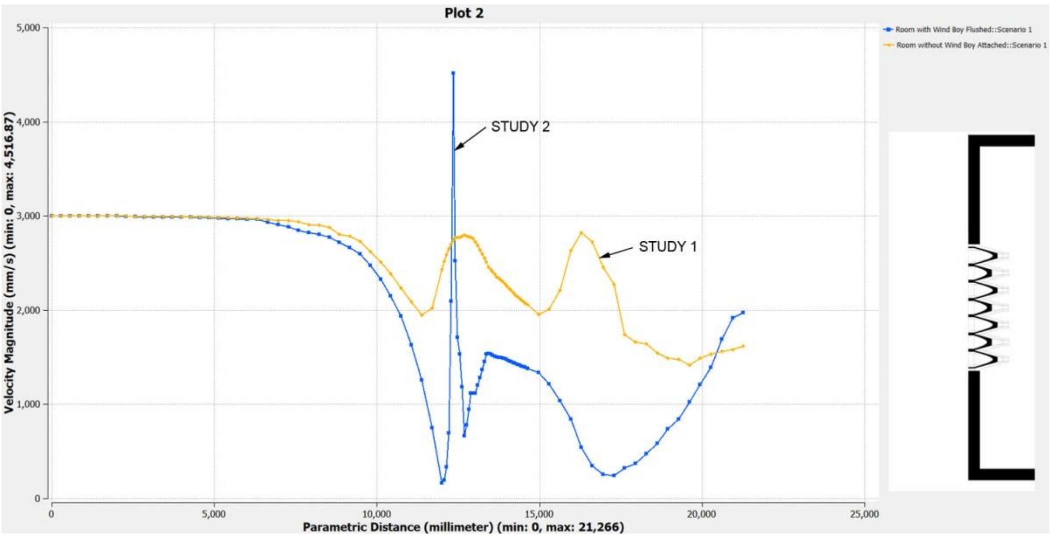


Figure 49. The Velocity trend between the control room and flushed *Wind Boy* façade.

Finally, this study was carried out to explore the fundamental connection between building façade and natural ventilation, so as to make the best use of natural wind resources. As architects, we must further explore natural ventilation as the key element in sustaining the built environment. With suitable combinations of distance and location, the ventilation rate can therefore be achieved.

Chapter 6. Recommendations for future studies

This study wanted to convey a starting point for the implementation of a wind driven façade system. The future direction of this study could further be developed in the form of a more comprehensive experimental investigation in order to expand the knowledge of facade systems that can improve indoor building conditions. The performance of *Wind Boy* depends largely on several factors such as prevailing winds, location and materials, among others. For future studies, the application of *Wind Boy* can be further studied in the areas of temperature and thermal analysis, among others. The design concept of Wind Boy can further be explored, such as the effect of investigating the effects of the inlet dimensions and the varying the thickness of the system. Different materials can also be further studied, such as the use of adobe, concrete or recycled plastics. The proposed scheme can also be used as a stand-alone system, meaning it does not have to be installed into the building envelope itself but as a separate unit.

Furthermore, it is also essential to note that using *Wind Boy* alone could not provide or fully eliminate our requirements for active mechanical systems. The use of passive design methodologies and our responsiveness to building orientation, shape, composition and local microclimate conditions must still be applied in order to improve occupant comfort inside our buildings. It is therefore imperative that through knowledge of the local climate and well applied passive design principles, we can greatly decrease building energy requirements before we even consider using mechanical systems. This paper will hopefully add to the knowledge and understanding of indoor airflows and guide future research for architects and to influence a future of sustainable development.

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APPENDICES

A. 3D printed image of the proposed Wind Boy

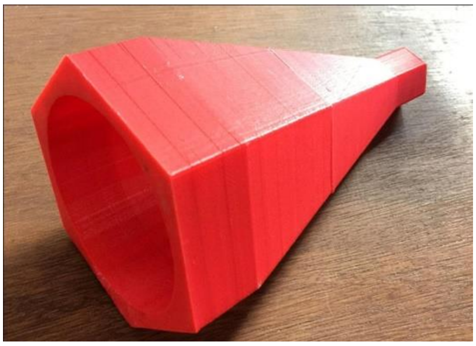

Image 1. A 3D printed output of the proposed Wind Boy.

Image 2. A 3D printed Cross section of a Wind Boy with an option for liquid cooling.

B. A visualization of the Wind Boy façade system

Image 3. The application of Wind Boy on a façade of an office building.

Image 4. Application of Wind Boy on a mid-rise residential building.

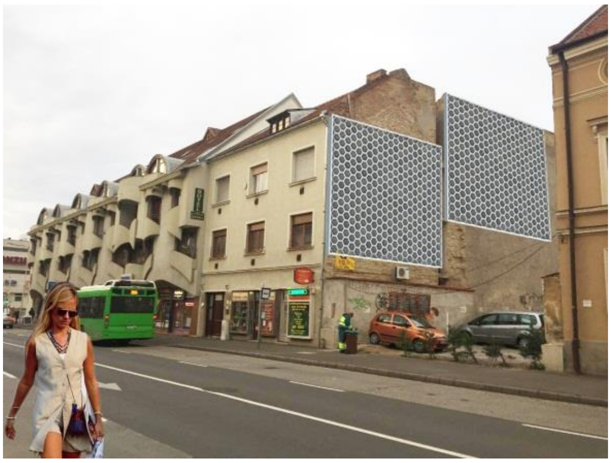

Image 5. The application of Wind Boys on an empty wall of a building.

C. List of Published Papers

(As of March 12, 2018)

1. **The Urban Heat Island (UHI) Phenomenon in Cebu City, Philippines: An Initial Study.**
   Author: Rowell Ray Lim Shih and Dr. Danilo T. Dy
   Journal: Espasyo Journal (Philippines) ISSN 2094-3725 (January 2013, Volume 5, Issue 1).

2. **The Visual Perception and Human Cognition of Urban Environments Using Semantic Scales.**
   Author: Rowell Ray Lim Shih and Dr. Runddy D. Ramilo
   Journal/Peer-Reviewed Conference Paper: The 7th International ASCAAD Conference (Effat University, Jeddah, Kingdom of Saudi Arabia) December 16-18, 2013.

3. **Investigating the Night-time Urban Heat Island (Canopy Layer) Using Mobile Transverse Method: A Case Study of Colon Street in Cebu City, Philippines.**
   Author: Rowell Ray Lim Shih and Dr. István Kistelegdi
   Journal: Pollack Periodica (Dec 2017, Vol. 12, Issue 3)

4. **A Shelter for the Victims of the Typhoon Haiyan in the Philippines: The Design and Methodology of Construction.**
   Authors: Danilo Ravina and Rowell Ray Lim Shih
   Journal: Pollack Periodica (Aug. 2017, Vol. 12, Issue 2)

5. **Bakwitanan: Design of a Blackboard Convertible to an Evacuation Center Partition by Participative Design Method.**
   Authors: Danilo Ravina, Marc Ruz, Rowell Ray Lim Shih and Dr. István Kistelegdi
   Journal: To be published in Pollack Periodica (Aug. 2018, Vol 13, Issue 2)

6. **Community Architecture: The Use of Participatory Design in the Development of a Community Housing Project in the Philippines.**
   Authors: Danilo Ravina, Rowell Ray Lim Shih and Dr. Gabriella Medvegy
   Journal: Pollack Periodica (Aug. 2018, Vol 13, Issue 2)

D. Conferences and Workshops

1. **11th International Miklós Iványi PhD & DLA Symposium**

   Date: October 19–20, 2015

   University of Pécs (faculty of Information and Engineering)

   Paper title: *Commercial Developments and Urban Sprawl in Cebu City: How Far Can We Go?*

2. **13th Miklós Iványi International PhD & DLA Symposium**

   November 3–4, 2017

   University of Pécs (faculty of Information and Engineering)

Paper title: *Community architecture: Case studies of Participatory Design in the Philippines.*

3. **Architectural Education Conference (**Paks Conference: Konferencia- időbeosztás, tudnivalók)
   Date: October 25, 2017
   Paks, Hungary
   Paper title: Architectural Education in the Philippines

4. **Annual Conference on Architectural Research and Education (ACARE-15)**
   Date: August 22-24, 2016
   Iloilo City, Iloilo (University of San Agustin) Philippines
   Paper title: Investigating the Nocturnal Micro-Urban Heat Island Phenomenon Using Mobile Traverse Method: A Case Study of Colon Street in Cebu City, Philippines.

5. **Annual Conference on Architectural Research and Education (ACARE-13)**
   Date: May 15-16, 2014
   Mintal, Davao City, Philippines
   Paper title: Urban Sprawl: Urban Sprawl and Strip Development: The Case of Study of the Banilad-Talamban Corridor

6. **Annual Conference on Architectural Research and Education (ACARE-12)**
   Date: February 7-8, 2013
   Legazpi City, Philippines (Bicol University College of Arts and Letters)
   Paper title: The Visual Perception and Human Cognition of Urban Environments Using Semantic Scales.

7. **University Architecture Week 2013 (Principal Speaker)**
   Date: December 2, 2013
   University of Southern Philippines-Foundation (USP-F)
   Paper title: The Urban Heat Island Phenomenon

E. Workshops and Team teaching engagements:

1. *“This Is Me Now”* Workshop
   Date: October 27-30, 2015

2. Team teaching with Prof. Mark Zagoracz
   Date: September 29, 2015
   Location: Research Center at Room A414
   Subject: Introduction to Basic AutoCAD for Civil Engineering students.

3. Team teaching with Prof. Dr. Xin Jing
   Date: September 11, 2015
   Location: Room A-206
   Subject: Architecture Model “A”.

F. International Competitions with the DLA students

1. *“Set Foot in Sittard”* (Phidias Community Cooking) International Competition
   Date: November 1 to December 4, 2015

G. The Author

Rowell Ray Lim Shih is an architect based in Cebu, Philippines. He took up Masters in Architecture (Major in urban Design) at the University of San Carlos in 2012. Rowell has been active in the academe since 2011 and has already published several peer-reviewed research papers at both local and international journals. His major is interest is urban design, sustainable architecture and urban climate studies. This study has been undertaken at the University of Pécs in Hungary. One of the basic objectives of the study is the application of an exploratory design and scientific analysis into architectural solutions.